Construction of Central Receiver -Type Field of Solar Power Plant Model

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Abstract

The use of central receiver (or Power-Tower type) of heliostat as concentrators on absorber plate (target), used practically as boiler, proved convenient and favorable both in performance and cost.

In this work a model of solar thermal power plant field was designed, analyzed, fabricated and studied in details using central receiver type. The model is constructed on flat, smooth, rigid and strong plywood board used as a base for the model fixed on an inclined base at an angle of 20º. The field area was set on quarter circle to arrange the heliostats; and at the centre of a circle the tower is carrying a copper plate target was fixed. Two sets of heliostat field [(540) and (1097) mirror] were tested experimentally.

Experimental data and results obtained showed that the use of solar energy in power generation is a very promising application .The temperatures achieved for target were in the range of steam boilers operation temperatures (268- 578)C˚.

The number of heliostat has a major effect on the target temperature; the power concentration factor and the overall efficiency of the system.

بناء نموذج محطة حرارية شمسية من نوع المستلم المركزي

المستخلص

إن استخدام محطات توليد الطاقة الكهربائية من نوع المستلم المركزي أو ما يسمى برج القدرة الذي يركز الأشعة بواسطة المرايا المتحركة على السطح الماص (الهدف) والذي يستخدم عمليًا كمرجل قد اثبت ملائمته وأفضليته من جانبي الكفاءة والكلفة.

في هذا البحث تم تصميم وتحليل و تصنيع ودراسة نموذج حقل محطة حرارية شمسية لتوليد الكهرباء باستخدام المستلم المركزي. تم تصنيع النموذج على صفيحة خشبية ملساء صلبة وقوية كقاعدة لأجزاء النموذج مائلة بزاوية 20 درجة عن الأفق. تم تثبيت حقل المرايا على شكل ربع دائرة ، ثبتت صفيحة نحاسية ماصة للحرارة في مركز هذه الدائرة. وأجري اختبار العمل على حقلين يتكونان من 540 مرآة و 1097 مرآة.

أثبتت نتائج البحث ان استخدام الطاقة الشمسية في توليد الطاقة الكهربائية هي من التطبيقات الواعدة، حيث كانت مديات درجات حرارة الهدف تتراوح بين (268-578) درجة مئوية وهي ضمن مديات توليد البخار لمراحل محطات التوليد. وكان لعدد المرايا تأثير أساسي على درجة حرارة الهدف ومعامل تركيز القدرة والكفاءة الكلية للمنظومة.

1. Introduction

Efforts to design devices for supplying renewable energy through use of the sun's ray began at least 1774[1], when the French chemist Lavoisier and the English scientist Joseph Priestley discovered oxygen. Also during the same year an impressive picture of Lavoisier was published in which he stands on a platform near the focus of a large glass lens and is carrying out other experiments with focused sunlight.

Joe [2] investigated an absorbing cavity or collector of solar energy mounted on a tower which is assumed to be erected over horizontal terrain, located about the base of the tower are many relatively small mirrors of predetermined size..These results are combined with a simple cost model to obtain a lower bound on the minimum cost per unit of redirected energy as a function of the unit mirror cost.

Sobin *et.al* [3] discussed the application of the compact steam generator technology to the design and fabrication of central receivers for solar energy powered electrical power plants. They discussed receiver design for tower – mounted applications where size and weight are important, they found the heat flux rates necessary for central solar receivers are nearly identical to the design heat fluxes for the compact steam generator, fabrication of the central receiver is discussed as well as design details and applicable materials.

Aparisi *et.al.*[4] examined the calculation of the radiation densities on the surfaces of flat and cylindrical receivers of tower- type solar power stations (SPS). They found, this calculation method is characterized by an accuracy of 20%, and in individual unfavorable cases the error may reach 30 -40%, and the results obtained using these methods were used as the basis for designing one of the variants of a cylindrical steam generator of an SPS with electric capacity about 60 MW.

Zakhidov and Ismanzhanov [5] investigated the effect of atmospheric dust particles on the reflectance of solar – installation mirrors with front and rear reflection, investigated as a function of particle time, speed, dimensions and angle of attack. They found that the atmospheric dust borne in the air and transported by the mountain – valley circulation winds characteristic of Central Asia present no danger to mirrors, strong winds with driven dust (dust storms) cause damage to the surfaces of mirrors, especially those using front reflection, so, it is undesirable to locate solar installations in areas with frequent jet winds and loose soil (sand).

Zakhidov [6] discussed the principles of modeling in the design of solar power station mirror concentrating systems (MCS) and analyzed the various model types: substantial, structural, functional and mixed.

Teplyakov and Aparisi [7] presented a paper with the experimental solar electric station (SES-5) in light of the USSR's energy program. The paper included:
(1) Purpose of SES-5.(2) Structure of SES-5.(3) The operating principle. (4) Distinctive features. (5) Basic characteristics (Electrical output (nominal) = 5MW, Area of mirror surface =40000 m^2, Dimensions of a single heliostat =5×5m, Number of heliostat =1600, Area of the receiving surface =154 m^2, Pressure of saturated steam =25 bar, temperature of steam =250 C°, Annual electric power production =5-7 million kWh).

Saiylov and Nazarov [8] determined the slope of a heliostat's primary axis which makes it possible to track the sun's apparent movement with a constant angular rate of rotation around the axis and a zero rotation around the secondary axis during the working day.

Fricker [9] investigated some 30 MW-demonstration solar power stations by using heliostat field and central receiver type. He deduced that all the systems investigated are feasible, the sodium system can probably be excluded for further investigations. He explained that the air system appears to provide the simplest, lowest risk operation; it has also by far the smallest electricity generation costs. The lower values can be attained by increasing the size of the plant into the 100MW range.

Mancini *et.al* [10, 11, 12] presented an annual review of search and development. They found that solar thermal power technologies are in different stages of development. Trough technology is commercially available today, with 355 MW currently operating in the Mojave Desert in California. Power towers are in the demonstration phase, with the 10 MW Solar Two pilot plant located in Barstow, CA, currently undergoing at least two years of testing and power production. Dish /engine technology has been demonstrated. Buck *et.al.*[13] investigated with Solar- hybrid gas turbine-based power tower systems (REFOS). They presented design and manufacturing of central receiver.

Terrado [14] investigated the economics and the finance of solar thermal power plant , he took the case study ,SEGS plant in California, he explained that California in the 1980's represented an optimum location for the development of the world 's first commercial solar thermal electric system ,high radiation an on-peak rate for electricity in summer afternoons , and tax incentives for investment in renewable energy combined initially with high fossil fuel prices, were the pre conditions for the creation of nine solar electricity generating plants (SEGS)with a total of 355 MW_e capacity.

Henry Price [15] presented paper of concentrating solar power systems (analysis & implications).It explains some of principles with market assessment important and integrated analysis tools which are essential.

Steinhagen and Trieb [16] explained the principles and development of concentrated solar-thermal power and outline its considerable potential for alleviating the constant pressure on our existing resources. They explained various types of single & dual-purpose plants have been analyzed and tested in the field. In addition, experience has been gained from the first commercial installations in use worldwide since the beginning of the 1980. Solar thermal power plants will provide a significant contribution to an efficient, economical and environmentally benign energy supply.

Fluri and Von Backstrom [17] analyzed the performance of the power conversion unit of large solar chimney power plant and compared three configurations from efficiency and energy yield point. The efficiency was 80% and increased with decreasing the diffuser area.

Rolim *et.al.* [18] developed an analytic model for a solar thermal electric generating system with parabolic trough collectors which were installed in Mojave Desert. They concluded that a large maximum of the overall cycle efficiency was found for evaporation temperatures around 320 ^oC with good agreement of results when comparing this model with experimental data with an attractive tool for simulation and design of solar power stations.

This paper is concerned with the study and design of a system which will concentrate direct sunlight in order to produce high temperature for the target (such as a boiler in thermal power plants). This system is made up of field of mirrors and a tower which is made for the first time in Iraq. The model includes the following items:

(1) Parts of model, and the materials which are used in manufacturing.
(2) Method of work and measurements.
(3) Study of the effect of atmospheric air.
(4) The model construction was assumed at solar noon time.

2. Theoretical analysis

In this design, the square shape area of mirror is (2*2) cm^2 .The distance to be 2cm taken between two adjacent arcs because the places of heliostat with shape of zig- zag, and for one arc, one place of heliostat between two adjacent heliostats was neglected. Therefore, the distances between them became 2cm.

To calculate the number of heliostats in each arc by using the equation (2) (the first radius of arc of heliostats 34 cm was used to decrease the area of field for experimental use only):

$$length\ of\ arc\ L_a = \frac{2pR}{4}$$

$$length\ of\ first\ arc = \frac{2p*34}{4} = 53.4cm \tag{1}$$

$$Number\ of\ mirrors\ N = \frac{L_a}{2L_m} + 1 \tag{2}$$

Number of heliostats in first arc $N_i = \frac{53.4}{2\times 2} + 1 = 14.35 \cong 14\ mirror$

-After calculating the number of heliostats, their positions were drawn on paper. The number of heliostat for adjacent arcs are equalized or increased by one and decreased by one. One arc was created to isolate the arcs group among them to increase the number of heliostat at increasing the radius of arc and avoid the shading .At manufacturing the model the first radius of arc become 34cm to decrease the area of field and the problems of trend. The field is arranged as shown in Table (1) which explains the mirrors field arrangement calculations for two models. The first column shows the arc number begins near the tower of central receiver with arc number (1), the second column gives the radius of arc which contains the positions of mirrors. Also, the third column shows the length of arc (one quarter of circle). The forth column shows the number of mirrors in each radius. The arcs numbers (5, 11, 17, 23, 30, and 37) were used to increase the mirrors number between two adjacent arcs and to avoid the shading.

The field of heliostats was applied to the dimensions of Table (1) in figure (1) as top view of the model rig.

For designing a solar power plant, the temperature at which it will operate must be known normally in the range of (500C° - 600C°) approximately for steam power plant and in many other power plants.[21]

Therefore, for our model, a target of copper plate of dimensions (3.5*3.5*0.15) cm , the energy which is reflected from the mirrors of the solar field , is absorbed by the target , therefore, the following analysis for the heat balance of the target applies.

-Ambient air temperature =20 C°=293K

Sky temperature T_s=0.552 $T_\infty^{1.5}$

$$\therefore Ts = 0.0552 * (273+20)^{1.5} = 276.85K = 3.85C^{\circ} \approx 4C^{\circ}$$

$$\begin{aligned} q_r &= sA\left(T_p^4 - T_s^4\right) \\ &= 5.67\times10^{-8} * \left(3.5\times3.5\times10^{-4}\right)\left(873^4 - 277^4\right) \\ &= 39.93 \quad W \end{aligned} \tag{3}$$

$$\begin{aligned} h_\infty &= c(T_p - T_\infty)^{\frac{1}{4}} \\ &= 1.77(600-20)^{\frac{1}{4}} \\ &= 8.686\, W/m^2.C^{\circ} \end{aligned} \tag{4}$$

This coefficient is for zero wind velocity. For wind speed is higher than 5 m/s , h_∞=20W/m^2. C°. Then ,

$$\begin{aligned} \therefore q_c &= h_\infty A\left(T_{p-}T_\infty\right) \\ &= 20 * \left(3.5\times3.5\times10^{-4}\right)(600-20) \\ &= 14.21 \quad W \end{aligned} \tag{5}$$

$$\begin{aligned} \therefore q_{total} &= q_r + q_c \\ \therefore q_{total} &= 39.93 + 14.21 \\ &= 54.14 \quad W \end{aligned} \tag{6}$$

Assuming [23],[24]:

(1) The reflection coefficient of mirror $h_p = 0.75$ (for commercially available).

(2) The guidance efficiency for heliostats $h_e = 0.8$.

(3)The optical efficiency of heliostat $h_{eo} = 0.9$.

(4)The average solar flux through one year $I_b = 700\, W/m^2$

(5)The field angle is 90° when θ=135° to 180°,and (-135° to 180°)

(6)The power factor or cosine factor (cos i,or η_{co}) ,(due to the fact that the perpendicular to the heliostat is not the same as the incident ray vector), approximately equal to (0.8) taken from the previous experiments.

(7)The absorptance of sunlight by target plate is 0.9

-As in the analysis presented by [22], it was found that:

Dimension of mirror $\cong$ dimension of target plate ×Cos 22.5

=3.5×cos 22.5=3.23Cm

-When the angle 22.5º is the inclination angle of the target plate from the reflected radiation from rim mirror of the field, it is half the angle of rim mirror from the horizontal plane.

-Another hint, there is declination of the solar rays with a value of 16 second of degree ,measured between solar disc edge ray and center ray.

-There are some difficulties in the trend of mirrors practically. Therefore, the dimension of mirror is (2×2) cm was chosen , for the above reasons and also to lessen the dimensions of model.

Table (1). Field of mirrors arrangement calculations for two models. First model for arc number 1 – 27

Arc No.	Arc radius cm	Length of arc cm	Mirror No.	Arc No.	Arc radius cm	Length of arc cm	M No.	Arc No.	Arc radius cm	Length of Arc cm	M No.
1	34	53.4	14	15	62	97.4	22	29	90	141.4	31
2	36	56.5	15	16	64	100.5	21	30	92	144.5	25
3	38	59.7	14	17	66	103.7	7	31	94	147.7	38
4	40	62.8	15	18	68	106.8	27	32	96	150.8	37
5	42	66	6	19	70	110	26	33	98	153.9	38
6	44	69.1	17	20	72	113.1	27	34	100	157.1	37
7	46	72.3	17	21	74	116.2	26	35	102	160.2	38
8	48	75.4	17	22	76	119.4	27	36	104	163.4	37
9	50	78.5	17	23	78	122.5	12	37	106	166.5	30
10	52	81.7	17	24	80	125.7	31	38	108	169.6	43
11	54	84.8	8	25	82	128.8	31	39	110	172.8	43
12	56	88	21	26	84	132	31	40	112	175.9	43
13	58	91.1	22	27	86	135.1	31	41	114	179	43
14	60	94.2	21	28	88	138.2	31	42	116	182.2	43

Then the power calculated here is compared with the theoretical power equation which was analyzed by [22] ,i.e.

$$q = h_1 a I_b N A_m Cos\ i$$

$$54.14 = 0.75 \times 0.8 \times 0.9 \times 0.9 \times 700 \times N \times (2 \times 2 \times 10^{-4}) * 0.8$$

$$N = 497.3 \cong 498 \quad mirror$$

But the designer must add twice a multiple number of mirrors [23],[24] to secure power plant working for all conditions such as rain, fog, wind and dust…etc(at the absence of direct solar ray),by using special devices for storage.

Therefore the study used 540 mirrors in the first model because of problems of trend and manufacturing .Then using (1097) mirrors in the fabrication of the second model.

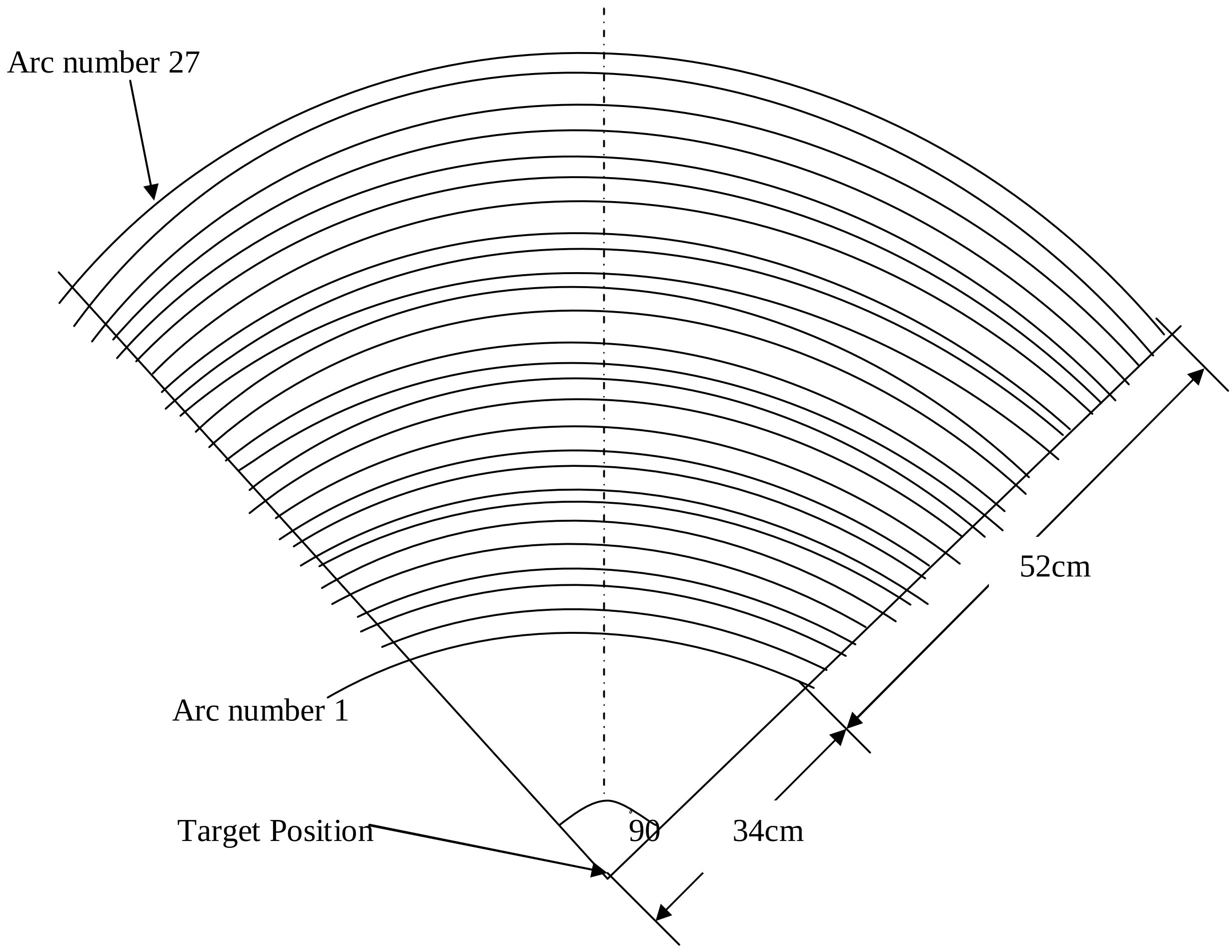


Figure (1). Heliostats Field.

3. Manufacturing of field of solar power plant

3.1. The Base of model

(1)Dimensions

Before the start of manufacturing the model base plate, its dimensions must be specified from the following measurements for the first model:

-width=the radius of outer arc of heliostat+ Factor (1)

=86+14=100 cm

-length =The radius of outer arc of heliostat ×Sin 45×2+Factor (2)

=86×Sin 45×2+28.4=150 cm

The plan of arcs radii must be done and the positions of blocking the heliostats on graph paper as in Figure (1) were applied on the model. (Factor (1) and Factor (2) mean the distance between two adjacent mirrors to avoid the shading which assumed to be the total length or width of plate as integer value).

(2)Choice of plate

A base plate must be chosen with special specifications such as:

a- Water resist: to resist the effect of rain at winter season.

b- Temperature resist: to resist the change of temperature at different seasons without changing of its properties.

c- Rigid wood with low flexibility to bear the heliostat and target tower and accessories without changing the trend and direction of heliostat and target.

d- Smooth surface.

(3) Manufacturing of plate

The wood plate with dimensions (150×100) cm, is supported by a wood piece of angle 20° to the horizontal to decrease the distance between the heliostats and the absorber. Then, engineering drawing on wooden base is achieved with the following manner:-

(a) Limiting the position of tower at the lower edge of plate, after graphing the two perpendicular axes (West-East and South-North), the tower is fixed at the center point.

(b) Drawing the arcs of heliostat by using a pencil and limited by rim lines of field of angle 90°.

(c) Pointing the places of blocking the heliostats on the arcs by obvious mesh points of pencil lines.

(d) Drilling the pointed places above with diameter of 3mm by using handle driller with drill depth of 5-7mm approximately.

3.2. Target and tower

Target plate is manufactured from pure copper plate with dimensions of (3.5×3.5) cm with thickness of 1.5mm and coated with black, non shine and non gloss paint. The choice of pure copper was get because of its high melting point, high conductivity for heat (K=385 W/m.°C)which leads to high response to heat change, specific heat(C_p=383J/kg.K), and density(ρ=8795 kg/m^3), melting point temperature is(1356 K) but the melting point of Aluminum is (933 K)[19]. When the copper coated with black paint, the absorptance α becomes 0.91 and the emittance €= (0.2-0.05) [20].

The net height of vertical target tower is 50cm measured from the upper plate to the surface of wood plate (the height of tower was chosen as 50cm to ensure no shading and to be higher than the maximum height of field).

The target plate is supported tightly at the upper of tower using connecting steel flexible rod with diameter of 1mm and isolating the target plate and the tower steel by using glass wool and wood insulation to insure no direct contact between them and heat transfer between the target plate and the tower steel to be insignificant.

The target plate surface is facing the mirrors in the field of mirrors.

3.3. Manufacturing of heliostat

The heliostat in this model composed from two main components, the mirror and bearer (supporting rod).

The reflecting mirror selected from small glass thickness cover to decrease the distortion of sunlight and the absorption of the solar energy spectrum when the glass includes a portion of Fe_2O_3 compositions, which appears as greenish appearance. Therefore, (water white) appearance of mirror which is pure were chosen. So, mirror type 2mm thickness with dimensions (2×2) cm.

The supporting rod of heliostat is manufactured from 1mm thickness steel flexible rod (which used to connection of steel rods in concrete casting) because of its resistance to corrosion (oxidization). The length of rod is about 5cm, curved from one side as elbow bend to help at adhesion of mirror tightly, the other side is also curved with smaller elbow bend to utilize in supporting the heliostat on the base plate.

3.4 .Trend method and measurement

The trend of the model must be accurate when starting the work. It is achieved by using a known length rod placed near the model, fit perpendicular by using the bulb device which used in building work for measuring the levels, put the rod at different time , before, after and at the solar noon. Then, the direction of shading of rod at solar noon, points the South –North axis, and then the model trended to this direction.

The trend of heliostats made the model at solar noon all time by changing the angle of model. It starts at solar noon, limiting the shade of tower to be perpendicular and limiting the length of shade to remain at these features all time of trend and measurements, and then the direction of mirrors was moved smoothly to see the shine of mirror accurately on the target area, and repeat this process for all mirrors. It was continued to change the angle of wooden plate at all time (each five minutes approximately) to secure remaining the model at solar noon with monitoring the shade of tower (length and angle).

After the end of trend process, replacing the movable heliostat was done and then supports it with the same procedure.

So, the measurement process was started, in this paper it is able to measure the temperature of front surface of target plate by using a digital clamp thermometer type K, by welding the ball of the end of compensating wires to the target plate surface at the center to measure the temperature. This process was repeated at every hour start to remain the model at solar noon by trending the field to different slope perpendicular to sun direction (azimuth angle is 90̊.

The solar noon was used in designing this model because:

(1) This time is known at every day.

(2) Simplicity in procedure.

(3) Avoiding the shading or masking effects.

4. Discussion

(1) A sample of experimental results for target temperature during the day are presented in Table (2) and Figure (3) for the period 28-12-2008 to 20-3-2009 for the first model and the period 17-4-2009 to 21-5-2009 for the second model. Data accumulated for 41 experiments.

As shown in Figure (4), the trend for the target temperature change is nearly the same for both models. The band width for the temperature of the first model is (103-211)C° at 8 AM and (162 – 258) C° at 12 AM , while for the second model is (292 – 411) C° at 8 AM and (375 – 578) C° at 12 AM . These results are in a good agreement with the published results for experimental solar electric station [7]. It is worth mentioning that target temperature reaches its value at the specific measuring hour within 3 minutes from the start of the experimental measurements. Figure (3) shows the variation in the band width for the two models (i.e ΔT_1=108 C°, ΔT_2=119 C° at morning and ΔT_1=96 C°, ΔT_2=203 C°, at noon) is mainly due to the change in atmospheric temperature during the tests (winter for the first model and late spring, early summer for the second model). Figure (3) shows the trend of measured data for the two models (Target temperatures variation during the hours of experiments) .The trend is nearly the same, however, variation in the second model is nearly twice that of the first model, and the highest temperature reached in both models was at noon .The scatter of the data is shown in Figure (4). The maximum temperature measured at noon for the first model was (258C°), while the minimum was (122 C°).

For the second model, the minimum temperature recorded at 8a.m was (292C°), this indicates clearly that the second model starting temperature at 8am is much higher than the maximum temperature recorded for the first model. Also the overall temperature range recorded for the second model is in the normal range of steam operating temperature. At the same time the recorded data shows that the lowest temperature recorded for the second model at 5pm was (268 C°), this gives as operational temperatures for a period of nine hours.

(2) Figure(5) shows the average target temperature for the two models during the days of measurements, although , the hourly average was calculated as the arithmetic average of readings at that hour , the shape of two curves resembles the behavior of temperature change during the day of the two models.

(3) Daily Efficiency $= \dfrac{\sum Actual\ q}{\sum Measured\ q} \times 100\%$ for the two models (18.9% for first model) and (31.7% for the second model).

(4) The average measured power calculated approximately (through one day) , (through nine hours) for second model reaching the target is :

$\sum$(measured q)= 1292.1 W/day

while the actual power, calculated according to the model is:

$\sum$(actual q)=368.2W/day

therefore, the total average daily efficiency is:

$$h_{day} = \frac{\sum q_{actual}}{\sum q_{measuredl}} \times 100\%$$

$$= \frac{368.2}{1292.1} \times 100\% = 28.5\%$$

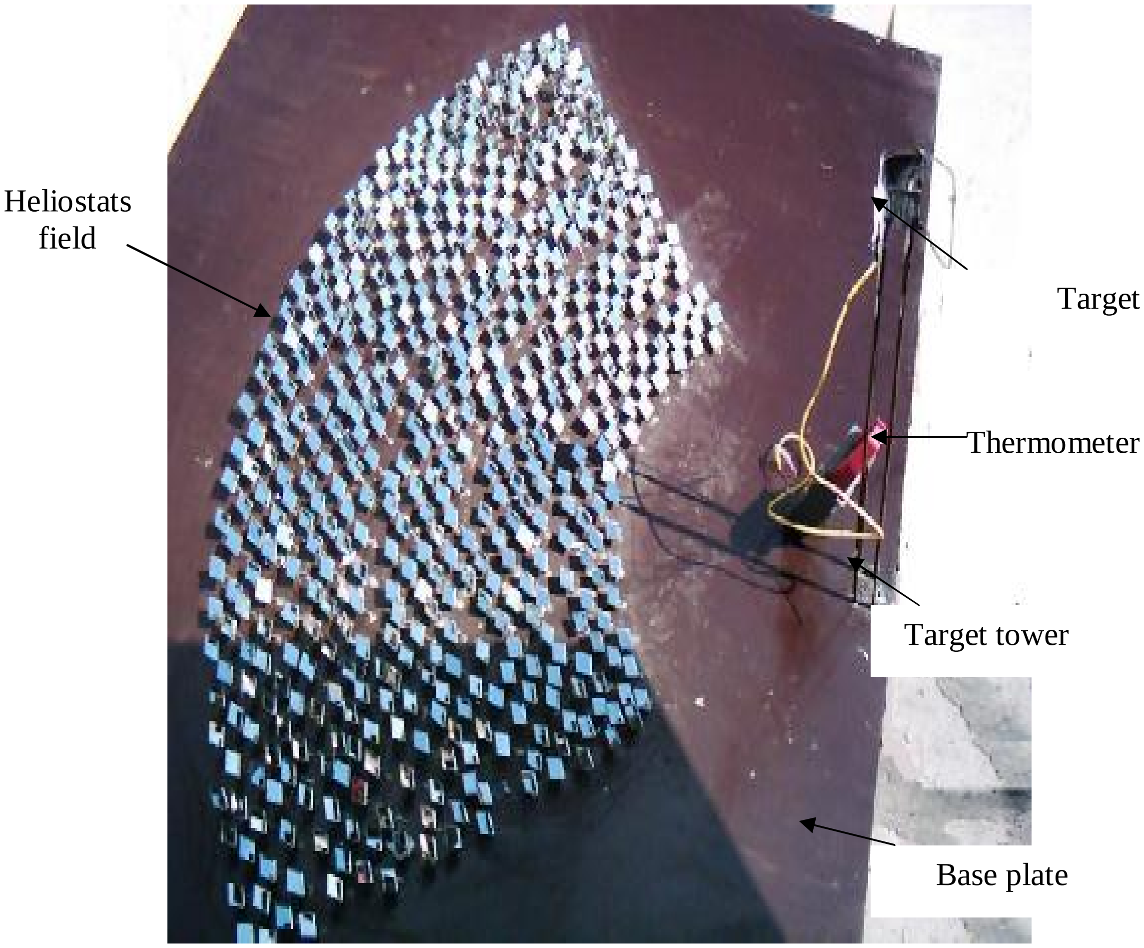
But for the first model; the average measured power is (407.6/day) , the actual power is (71.36W/day), the total daily efficiency is (17.5%).

(5) From the actual and measured power were illustrated in the same values calculated in (4) above , the losses of system can be determined by using System Losses=$q_{(measured)} - q_{(actual)}$

$$\text{Percentage Losses} = \frac{\text{system losses}}{q_{(measured)}} \times 100\%$$

(average losses = 336.24 W for first model, and average losses= 923.9 W for second model).

The percentage losses were calculated by applying the above equations to be (82.5%) for first model and it was (71.5%) for second model.



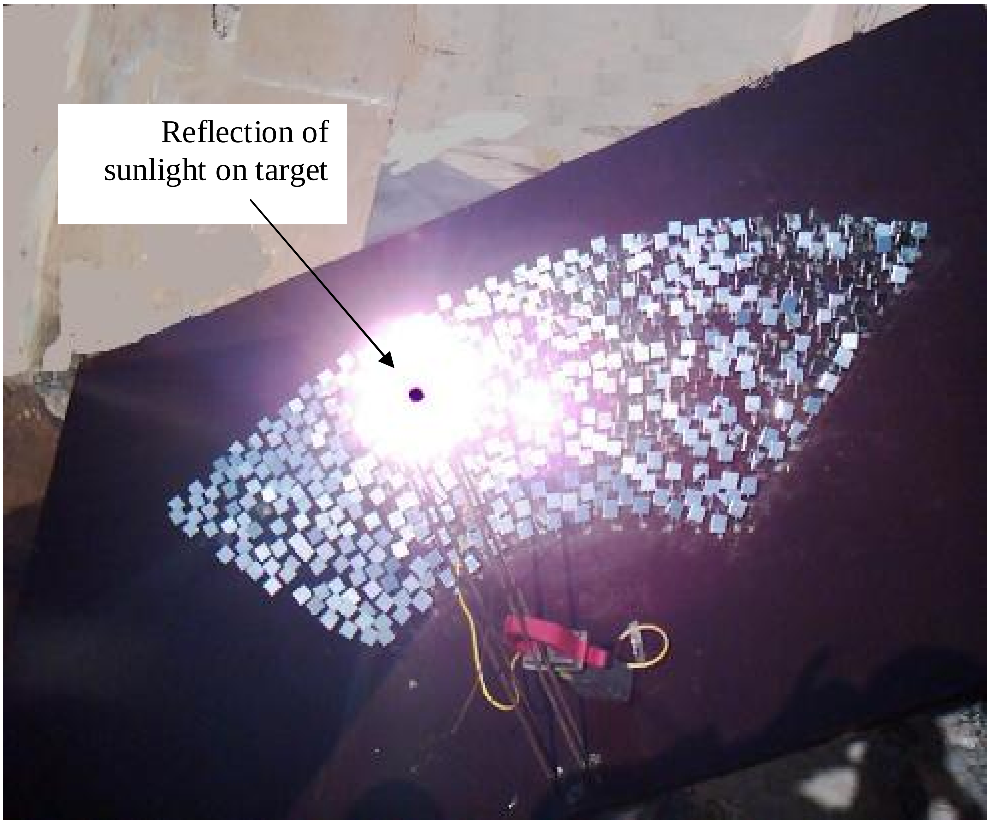


Figure (2). Shows two photographs for the first model.

Table (2). Temperature readings in ^oC for the first model.

Daily time (hour)	12-Jan	13-Jan	15-Jan	20-Jan	19-Mar	20-Mar	29-Dec
8					174	194	
9					191	211	65
10	155	163	145	175	206	228	95
11	175	198	191	225	215	242	145
12	189	276	242	231	228	258	199.8
13	181	206	175	203	214	244	186
14	145	150	fog	154	201	231	145
15					191	219	
16					173	203	
17					161	190	

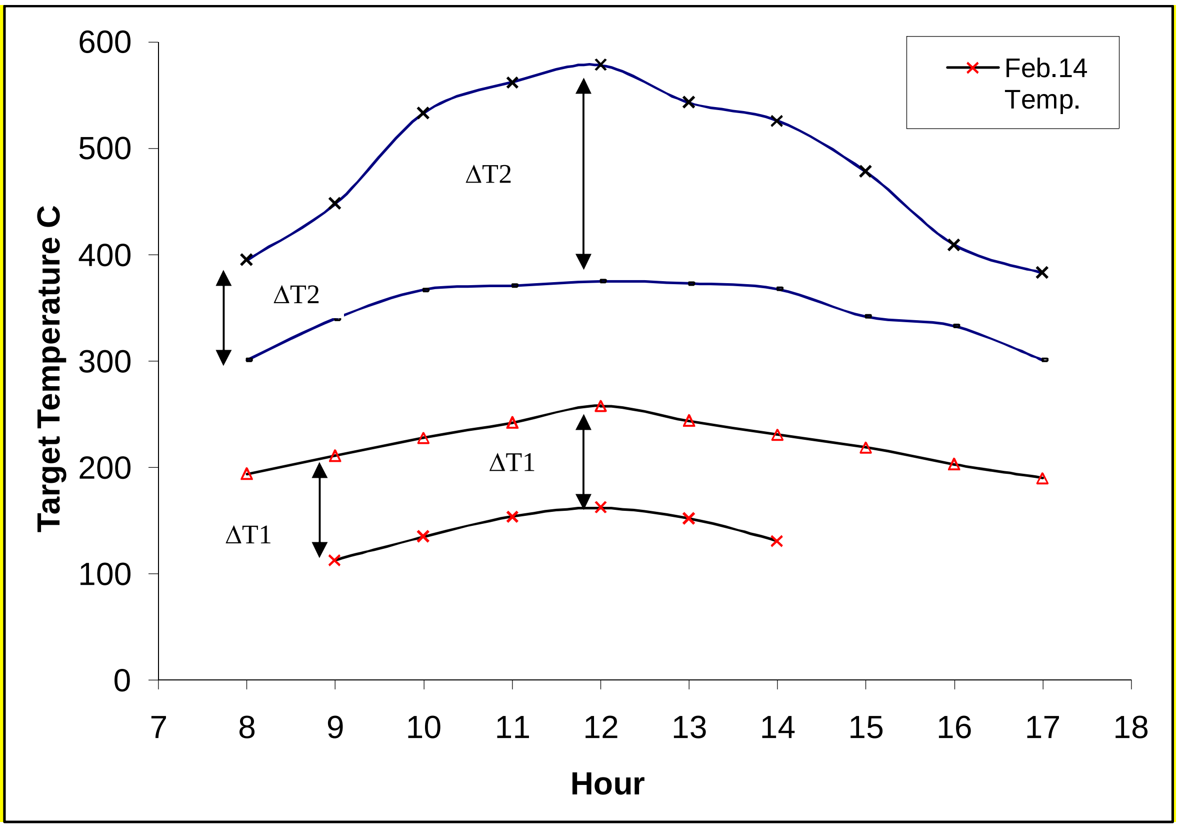


Figure (3). Target temperature difference (ΔT_1 for first model measured at 20-3 & 14-2-2009 & ΔT_2 for second model measured at 9-5 & 17-4-2009).

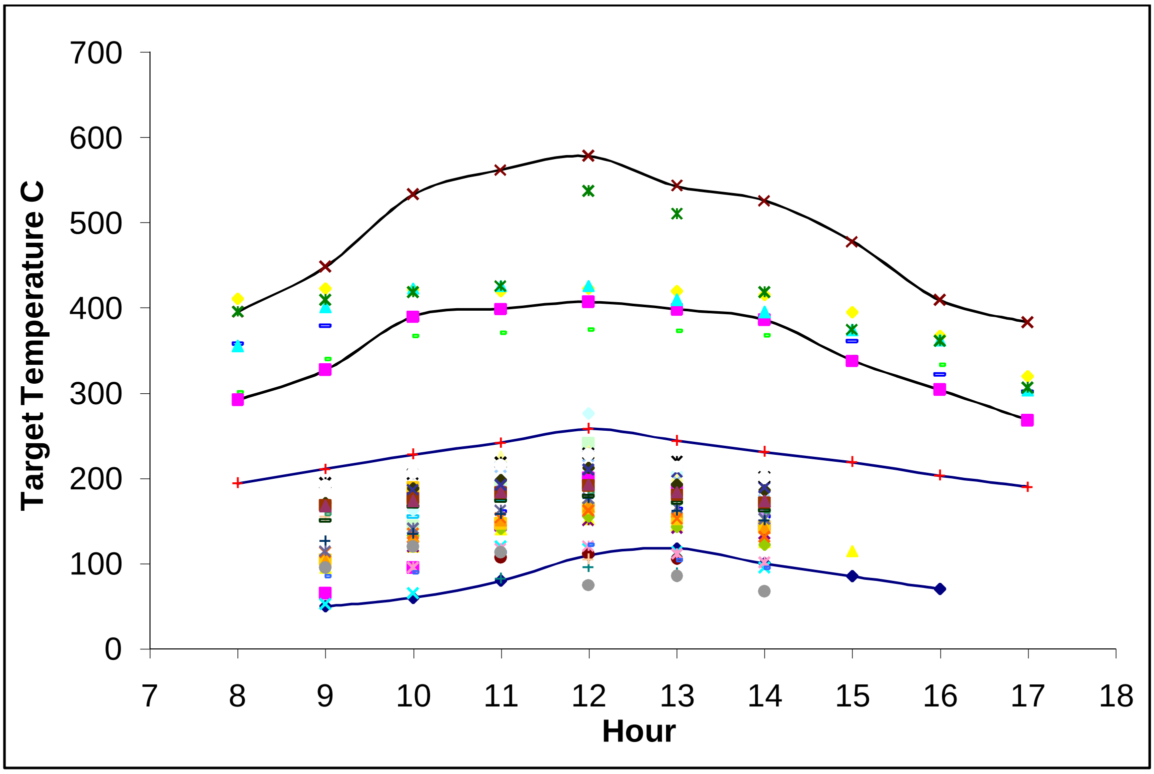


Figure (4). Target measured temperature of two models(the upper for second model & beneath for first model)through the period 28-12-2008 to 21-5-2009.

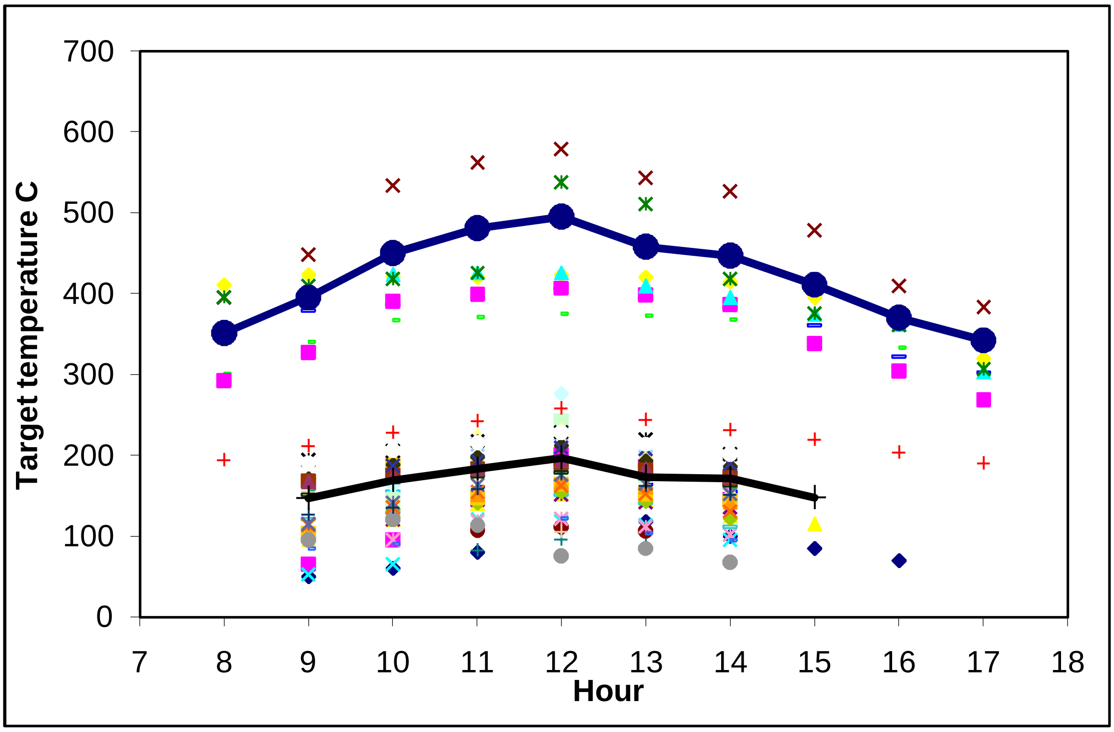


Figure (5). Average target temperature calculated for two models (upper curve for second model and beneath for first model, the other points are temperature measurements of 41 test day).

5. Conclusions

There are some notes in designing and constructing the model:

(1) The measurements of temperature suffered from the effects of weather conditions, speed of wind, temperature of sky and air, dust, fog ….etc.

(2) When the wind is slow, plate temperature increases and the solar power absorbed by target is observed.

(3) When the weather is pure and no dust and fog the solar power absorbed is high.

(4) When the ambient temperature is low then sky temperature is low, therefore, that leads to decrease the power absorbed.

(5) Increasing the insulation layer thickness under the absorber plate will increase the absorbed power absorbed because of decreasing the losses.

(6) At the measurement and trend of model in the direction to follow the sun, the angle of incidence and altitude angle change, therefore, the trend changes.

(7) The study assumed that the altitude angle is constant for all day design in measurement.

(8) The designer lost the utilization of solar power from about 6 mirrors because of target shading.

6. References

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7. Nomenclature

symbol	Definition	Unit
A'	Absorber area	m^2
A_m	Mirror area	m^2
C_p	Specific heat of plate with constant pressure	J/Kg.K
h_∞	convection heat transfer coefficient	$W/m^2.C^\circ$
i	Solar incidence angle	Degree
N	Number of mirrors	-
q	Power	Watt
q_c	convective heat	Watt
q_e	electrical power	Watt
q_r	radiated heat	Watt
q_s	storage heat	Watt
t	Time	Second
T	Temperature	C°
T_p	Plate temperature	C°
T_s	Sky temperature	C°
T_∞	Ambient air temperature	C°
α	Absorptance of target plate	-
ε	Emissivity of target plate	-
η	Efficiency of system	%
σ	Stefan- Boltzmann constant	$W/m^2.K^4$