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The Use of a Parabolic Solar Concentrator in Nasiriya city, Iraq

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Abstract

In this paper, it presents a detailed analysis of the use of the parabolic solar concentrator in heating and boiling water, as the parabolic solar concentrator was manufactured with a diameter of (96 cm), the focal length of the dish is (72 cm), and the focus depth of the dish is (8 cm). It was made using a parabolic dish with a diameter of (96 cm) and using glossy aluminum foil as a reflective sun ray after being cut into strips 10 cm wide and glued to the inner surface of the dish. Metal tin cans with two capacities (1L and 2L) were used as the absorbent receiver. Experiments were conducted to boil water from the roof of the house in Nassiriya city. The study calculated the optical efficiency of the equivalent solar concentrator, the amount of heat output as a result of the fall of concentrated solar radiation on the receiver, the amount of useful heat gained, the thermal losses from the receiver, the collector efficiency. Many tests were conducted in Nassiriya city weather conditions.

The results of the experiments showed that the efficiency of the solar center mainly depends on the diameter of the concentrator dish, the quality of the reflector used, the time of heating the water, and the closing to midday. While the high ambient air velocity leads to a decrease in the receiver temperature by increasing the heat loses to ambient air by convection, thus reducing the efficiency of the solar concentrator; as well as the accuracy of directing the dish towards the sun and determining the focus accurately also affects the efficiency of the solar concentrator.

Keywords: Solar energy, Parabolic, Concentrator, Absorbent receiver, Collector efficiency.

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1. Introduction

For a long time, researchers presented research studies and many practical experiments on the topic of using solar concentrators in heating, boiling water, and producing steam, and how to improve the efficiency of solar concentrators and reduce heat losses. There was a lot of research conducted on solar concentrators, as the idea of using solar energy to boil water and cook food is not new, as the first scientist to test solar cooking was a German physicist named Tschirnhausen (1651-1708) [1]. Use a large lens to focus the sun's rays and boil water in a clay bowl filled with water for boiling. Subsequently, a lot of research was done on the exploitation of solar energy in cooking and water heating, and improving the efficiency of these concentrators and the rest of their important parameters. **[2]** Designed, made, and evaluated a solar parabolic dish with a diameter of (2.2 m) and an aperture area of (3.8 m^2). To improve thermal efficiency, reduce heat loss, and realize steam production from concentrated solar energy, this solar collector is equipped with manual tracking. The sun's heat was concentrated on a black absorbent that was placed in the focal point of a dish concentrator. The researchers found that for the beam solar intensity (800 $\mathrm{W/m^2}$) at noon, the direct heat that can be obtained was 200 W, and they found that the temperature of the oil outlet reaches 50 ℃ at the beginning of the experiment and then increases after 30 minutes until it reaches the maximum value (80 ℃). The average concentration ratio and average energy efficiency are respectively about (150) and between 40% to 77%. This device can be used in various applications such as pasteurization and detoxification. **[3]** designed and manufactured a solar concentrator dish with a diameter of (1.6 m), depth of the dish (18 cm), and Focal distance (84 cm) to heat water and produce steam, and its inner surface is covered with a reflective layer with a reflection rate of (76%) they used a stainless-steel receiver with a helical absorber inside. They also used a tracking system to ensure the vertical sunlight fell on the reflector, and the dish was also equipped with a temperature measurement system and solar energy. They found that the water temperature had risen to 80 ℃ and that the system's efficiency had increased by 30% at midday. **[4]** Designed and built a parabolic concentration dish for heating water. They used polyester resin reinforced with fiberglass mat and inner surface lined with aluminum foil as a reflector. The design consisted of a parabolic dish with a diameter of 246 cm, a height of 58.2 cm, and a concentration factor of (54). The absorption

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area was $0.0173m^2$. This project aimed to heat the water between (82-121℃), and they concluded that the water was heated from (27℃) to (85℃) within 20 minutes, and this solar concentrator can be used for home use to heat and boil water.

[5] experimentally studied the thermal performance of a solar concentrator dish with a conical spiral absorber. A dish with a diameter of (1.4 m) and a focal length of (0.3223 m) and covered with a reflective material with a reflection of (0.86), with truncated cone-shaped helical coiled receiver made up of copper and coated with nickel-chrome at a focal point, the lower and upper diameter of the receiver were (0.135 m) and (0.095 m), respectively. The researchers concluded that the light energy captured by the receiver increased by 41% during the day, the average rise in heat losses was 76% compared to the increase in solar radiation and wind speed by 41% and 42%, respectively, the collector instantaneous efficiency decreased by 12.3% during the day and an instantaneous efficiency of 63.9% was achieved.

[6] studied the utilization of solar energy to produce steam using a (1.7 m) diameter concentrator dish. The diameter of the dish was (1.7 m). A brass spiral absorbent with a diameter of (20 cm), a length of (3 m) and a diameter of (12.5 mm) was used. The solar radiation falls on the plate and is reflected in the absorbent vessel which contains the coil that carries the water. The results of this experimental work gave a good indication of the production of steam with a temperature of about 115.7 °C during a short time from the concentration of sunlight (in Iraq). Also, it is possible to produce very hot steam when increasing the length of the copper receiver coil. **[7]** studied the thermal performance of a parabolic concentrator with a diameter of (200 cm) and a focal length of (66.5 cm) was studied as an asymmetric parabolic concentrator covered with a reflective aluminum foil of (0.9) reflectivity, they use absorbent volumetric SiC honeycomb size (105 mm^3). Which used atmospheric air as a heat transfer fluid experimentally. The preliminary results show that at the target temperature range, the collector efficiency remained above 70% and that the higher the mass flow rate, the lower the air exiting the collector temperature. Besides, the two flow rates gave a good collector thermal efficiency of about (70%). The results of this study show, for both high temperatures and efficiency, that an air-based solar concentrator is feasible. **[8]** studied cylindrical parabolic solar collectors with a length (2.4 m), a width (0.8 m). A reflective aluminum foil was affixed to the inner surface of the

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collector to concentrate the rays on two types of copper absorption tubes with a length of 2.4 m, one of which has an outer diameter of (3 cm) and the inner (2.8 cm) painted black, the other dyed black and covered with an outer diameter glass tube (3.6 cm) and an inner vacuum tube (3.4 cm). The device was equipped with automatic tracking of the sun. The study aimed to obtain the necessary heat to heat the water and to study the thermal performance of the solar collector. The results showed that the system efficiency and the beneficial heat energy obtained with the evacuated glass tube were higher than that obtained from the copper tube and were directly proportional to the water mass flow rate and the amount of solar radiation incident on the surface.

2. Physical Geometry of The Parabolic Solar concentrator.

2.1 Optical Analysis Model:

The parabolic collector geometry is fundamental to guarantee the proper functioning of the prototype; an error during the geometric calculation would represent the deviation of the solar the parabolic collector geometry is fundamental to guarantee the proper functioning of the prototype; an error during the geometric calculation would represent the deviation of the solar rays; consequently, the absence of temperature at the focal point, which would give way to obtaining low thermal efficiency.

To calculate the parabola, mathematical analysis was performed to find the values that satisfy the design criteria, like: of a parabolic dish (d), Depth of concentrator dish (h), Focal length of a dish (f), Aperture area of dish (A_a) Rim angle of a dish (Υ_{rim}), and concentration ratio. The scheme used for the analysis is shown in Figure (1).

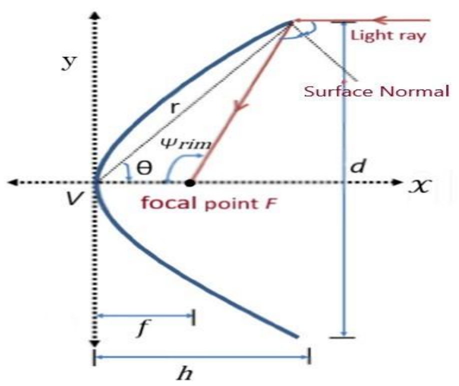

Fig. (1): Geometrical parameters [9].

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The surface area of this parabola is given by the following equation [2, 10]:

$$S = \frac{8\pi}{3} f^2 \{[1+(\frac{d}{4f})^2]^{3/2} -1\} \quad (1)$$

Where:

(f) is the focal length

(d) is the opening diameter of the dish

The aperture area of the dish is [11]:

$$A_a=\frac{\pi}{4} d^2 \quad (2)$$

The focal length of the dish is given by the following equation [12]:

$$\frac{f}{d} = \frac{1}{4\tan(\Psi rim/2)} \quad (3)$$

Where Ψ_{rim} a rim angle of the dish. The effect of the rim angle on the focal point position at the same diameter can be shown in Figure (2). It is shown that the focal length is decreased when the rim angle increases [13]. Figure (1) shows the main parameters of parabolic dish geometry [12].

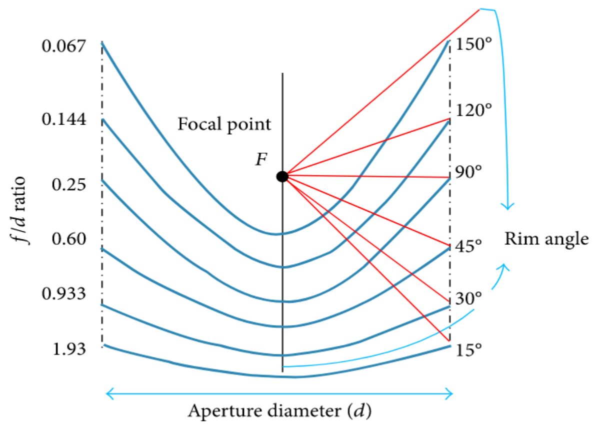

Fig. (2): Relation between the focal length and the rim angle for a constant reflector diameter [14].

The depth of the dish is described by the following equation [3]:

$$\boldsymbol{h}=\frac{d^2}{16f} \quad (4)$$

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This part is specialized with set equations of the optical behavior of parabolic solar concentrator (PSC). The two main parameters in optical design are optical and geometrical concentration ratios .

The first is defined as the ratio between solar heat flux over on absorber (Iabs) and solar flux (beam solar intensity) falling on an aperture area of a dish (Ib) as shown in the following equation:

$$C_{RO} = I_{abs}/I_b \tag{5}$$

It is considered a true concentration ratio because it indicates the optical losses [15]. The optical concentration ratio is not related to thermal losses and efficiency because not indicate the absorber area.

The geometrical concentration ratio is defined as a ratio between aperture area (Aa)to the absorber area (A_{abs}). It affects the choice of the receiver area which affects thermal losses. The geometric concentration ratio can be represented in the following equation [16]:

$$C_R = A_a/A_{abs} \tag{6}$$

The optical efficiency is defined as a ratio between the radiation absorbed by the receiver ($Q_{\boldsymbol{abs}}$) to the radiation captured by the aperture area of the concentrator ($Q_{\boldsymbol{s}}$) [16,17]. The following equation describes the optical efficiency:

$$\eta_o = Q_{abs}/Q_s \tag{7}$$

Where:

$$Q_s = I_b \times A_a \tag{8}$$

Q s: Energy captured by the reflector.

The other definition of optical efficiency is a product of many properties of dish and absorber surface such as reflectivity of material, absorptivity and transmissivity of absorber material, shape factor (interception factor), and the effect of incident angle of solar radiation [10,17].

which can write be in the following equation:

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$$\eta_o = \lambda\rho\, \tau\alpha\boldsymbol{\gamma}\ \cos\theta \qquad (9)$$

Where λ is the factor of un-shading or shape factor [11]:

$$\lambda = \frac{Aa - At}{Aa} \qquad (10)$$

Where:

Aa: Aperture area.

At= $area$ that shaded by the receiver on the concentrator

ρ is dish reflectance, τα is transmittance– absorptance product [13]

$\boldsymbol{\gamma}$ is the intercept factor of a receiver, which is defined as the ratio of the energy intercepted by the receiver to the energy reflected by the focusing device [18]

$$\gamma = 1 - exp[-820\left(0.7\frac{r}{f}\right)^2\ (1 + \cos\psi)\ ] \qquad (11)$$

For all the concentrates and receivers used in our research: $\boldsymbol{\gamma}\approx 1$

And ($\boldsymbol{\theta}$) is the angle of incidence. As the solar parabolic dish concentrator maintains its optical axis always pointing directly towards the sun to reflect the beam, which means the incidence angle of the solar beam into the dish is zero degrees, and the cosine loss equals zero.

$$\eta_o = \lambda\rho\ \tau\alpha \qquad (12)$$

The reflectivity of aluminum foil which is used in this project was 0.72. And The reflectivity of pieces of the mirror was (0.70-0.84) The transmissivity–absorptivity product was 0.94 for black paint [10]. The effect of incident angle can be neglected [10]. The range of the optical efficiency is between (0.85 – 0.9) for high reflective mirrors [3, 10].

2.2. Thermal Analysis:

Useful heat that was exploited by the receiver Q_u is equal to the heat absorbed by water in the receiver. It can be calculated by subtracting the heat energy losses of the receiver Q_{loss} from the heat

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energy absorbed by the receiver wall Q_{abs} [13.18] which can be represented in the following equation:

$$Q_{abs} = \eta_{opt}\, Q_s \tag{13}$$

Net energy is transmitted by the area catching the radiation concentrated by the reflector. The net energy for a solar thermal absorber is the amount of thermal energy leaving the absorber, which generally means the amount of energy being added to a fluid by thermal transfer through passing into the receptor or the converter that is [18]:

$$Q_{useful} = Q_{abs} - Q_{loss} \tag{14}$$

The rate of thermal losses is separated into radiation (Q_{rad}) and convection (Q_{con}) losses. Equations (17) and (15) give the formulas for estimating these quantities [3]:

$$Q_{loss} = Q_{rad} + Q_{conv} \tag{15}$$

$$Q_{conv} = A_{abs} \times h_{air}\,(T_{abs} - T_{am}) \tag{16}$$

The heat convection coefficient between absorber and ambient can be calculated by the following equation [19]:

$$h_{air} = 2.8 + 3 \cdot V_{air} \tag{17}$$

A mathematical model of the radiation heat losses from the absorber surface can describe in the following equation (18).

$$Q_{rad} = \varepsilon_{abs}\, \sigma A_{abs}\,(T_{abs}^{4} - T_{am}^{4}) \tag{18}$$

So that, the collector efficiency of the system can be written in the following equation [17].

$$\eta_c = \frac{Q_{useful}}{Q_s} \tag{19}$$

Q_{useful}: useful energy delivered to the working fluid.

Q_s: the energy incident on the concentrator's aperture.

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3. Practical Modeling Analysis:

Below we list the calculations of samples of experiments in which a parabolic solar concentrator model was used, which was manufactured using a satellite dish, the diameter of the dish is 96 cm, and aluminum reflective paper was affixed with a reflectivity rate of 72%, and using a receiver with two different capacities (1 liter, 2 liters) are metal cans that had been painted black. Table (1) presents the dimensions used for the design of the parabolic solar concentrator.

Table (1): Data and dimensions used for the design of the parabolic solar concentrator.

Parameter	Value	Unit
Diameter of a parabolic dish (d)	0.96	m
Depth of concentrator dish (h)	0.0.08	m
The focal length of a dish (f)	0.72	m
Material of parabolic dish	Galvanized steel	-
Material of the reflector	Glossy Aluminum foil	
Aperture area of a dish (A_a)	0.724	m^2
Rim angle of a dish (ψ_{rim})	36.87	degree
Geometric concentration ratio: $C_R = {}^{Aa}/_{Aabs}$ Aa=36.87 m^2	When A_{abs} =0.0184 m^2 ⇒C_R = 39.35 When A_{abs} =0.02145 m^2⇒C_R = 33.753	-
Ratio (Focal length/Diameter of the dish)	0.75	-
rim angle of the dish (Ψ)	63.32	degree
dish reflectance ρ	0.72	-
transmittance– absorptance $\tau\alpha$	0.97	-
The emissivity of the absorber ε	0.97	-
specific heat of water Cp_W	4.23	kJ/kg K
Stefan–Boltzmann constant σ	5:670367×10^{-8}	$W/m^2\ K^4$

After performing the theoretical analysis to construct the parabolic solar concentrator model, a thermal and optical analysis was performed for two experiments when using a thermal

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receiver with a volumetric capacity (1 liter) as shown in Table (2) and Table (3), and two other experiments when using a thermal receiver with a volumetric capacity (2 liters) as shown in Table (4) and Table (5). To summarize, the results of the experimental parameters calculations for the four experiments were listed in Table (6).

Table (2): Data of the experiment used a concentrating dish with d (96 cm) with a 1-liter receiver on Tuesday 2 /3/2021.

Time	Ib (W/m^2)	Tw (°C)	Tabs (°C)	Tamb (°C)	Vair (m/s)
9:50	941	17	366	25.4	0.2
10:10	907	97	321	25.8	0.2
10:14	950	101	339	26.2	0.2

Table (3): Data of the experiment used a concentrating dish with d (96 cm) with a 1-liter receiver on Thursday 11/2/2021.

Time	Ib (W/m^2)	Tw (°C)	Tabs (°C)	Tamb (°C)	Vair (m/s)
2:18	1048	22	478	35.4	0.3
2:31	1068	101	488	32.2	0.3

Table (4): Data of the experiment used a concentrating dish with d (96 cm) with 2 liters receiver on Thursday 21/1/2021.

Time	Ib (W/m^2)	Tw (°C)	Tabs (°C)	Tamb (°C)	Vair (m/s)
10:20	1002	12	280	15.5	1.1
10:40	991	83	248	16.2	0.9
10:55	1013	102	387	15.9	1

Table (5): Data of the experiment used a concentrating dish with d (96 cm) with 2 liters receiver on Tuesday 2 /3/2021.

Time	Ib (W/m^2)	Tw (°C)	Tabs (°C)	Tamb (°C)	Vair (m/s)
1:35	949	22	355	29.6	0.3
1:55	980	88	291	31.7	0.4
2:04	974	101	341	29.8	0.3

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Table (6): Results of experiments when the receiver was (1-liter, 2-liter)

Experiment time	receiver capacity (L)	λ	η_o (%)	Qs (W)	Q_{loss} (W)	Q_{useful} (W)	η_c (%)
9:50 am-10:14 am at Tuesday 2 /3/2021	1	1	69.84	675.25	48.65	443	65.6
2:18 pm-2:31 pm at Thursday 11/2/2021	1	0.9949	69.48	766	74.78	457.42	59.7
10:20am- 10:55 am at Thursday 21/1/2021	2	1	69.84	725.45	109.54	397.11	54.74
1:35 pm- 2:04 pm	2	1	69.48	700.6	73.96	415.34	59.28

4. Experimental Results and Discussion:

The parabolic solar concentrator was tested in Nasiriyah, southern Iraq, at the site (31.058° N 46.2573° E) [20]. Two experiments were conducted before midday, in which the solar concentrator with a diameter of (96 cm) was used once with a receiver with a volumetric capacity of (1 liter), and the second experiment was conducted with a receiver with a volumetric capacity of (2 liters. Also, two other experiments were conducted after midday with the same solar concentrator and receivers under a clear sky as shown in Figure (3) and Figure (4).

Fig. (3): Experiments when used parabolic solar concentrator d (96 cm) with a 1-liter receiver.

Fig. (4): Experiments when used parabolic solar concentrator d (96 cm) with 2- liters receiver.

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The following outputs were calculated: The optical efficiency of the parabolic solar concentrator (η_{opt}), energy captured by the reflector (Q_s), the heat lost due to the heat radiation convection (Q_{loss}), the amount of heat gained (Q_{useful}), as well as the measurement of the efficiency of the solar cooker(η_c). This requires recording the important experimental parameters that we need in computing the important outputs: such as solar beam intensity (I_b) falling on an aperture area of the dish A_a, which is measured with a solar meter, and water temperature (T_w), the receiver surface temperature at the location of the concentrated ray incidence (T_{abs}), the ambient temperature (T_{amb}), these temperatures are measured by thermocouples, as well as the ambient air velocity around the working device (V_{air}), which is measured by an anemometer. This data is calculated and recorded every 20 minutes, and using this data for calculating the above parameters (η_{opt}, Q_s, Q_{loss}, Q_{useful}, and η_c). And then draw curves that show the change of these variables during the period for heating water from its initial temperature until reaching the boiling point.

Fig. (5-8) show that T_w and T_{abs} increase with the increase in the solar beam intensity (I_b), as well as the period for boiling water, decreases with the increase in the solar beam intensity and the accuracy of directing the parabolic dish towards the sun, when the amount of water that was to be boiled increases, this leads to an increase in the boiling period, which leads to a decrease in the efficiency of the solar concentrator, as well as an increase in the velocity of the movement of ambient air surrounding the solar cooker, which leads to an increase in the heat losses by convection, especially at high surface temperatures of the receiver.

Figure (5) where the receiver capacity was One liter shows that (T_w) rose from 17 °C at 9:50 am until it reached its maximum value of 101 °C where the water was boiling at 10:14 am. And that (I_b) decreased from 941 $\mathrm{W/m^2}$ at 9:50 am to 907 $\mathrm{W/m^2}$ at 10:10 am because of the inaccuracy of tracking the sun, then after this, it starts to increase to 950 $\mathrm{W/m^2}$. The absorber temperature (T_{abs}) decreased from 366 °C to 321°C as the solar beam intensity (I_b) decreased, then it raised to 339°C. As for (T_{am}) it had a slight increase, as it raised 0.8 °C and because this rise was small, the change in T_{am} appeared in the form of a horizontal line very close to the horizontal axis, as for the velocity of the ambient air, being was fixed and appeared as a horizontal line.

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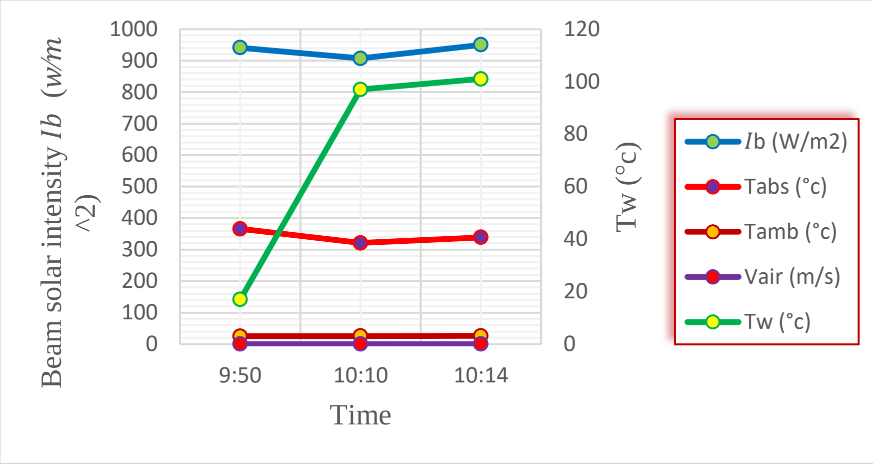

Fig. (5): The experiment using parabolic solar concentrator d= 96 cm with 1-liter receiver at (9:50 am-10:14 am).

As for Figure (6), where the receiver capacity was One liter too, (T_w) started to rise from 22°C at 2:18 pm until it reached the boiling temperature at 2:31 pm and after that, the water continued to boil. The beam solar intensity started rising from 1048 W/m^2 at (2:18 pm) until it got to 1068 W/m^2 at (2:31 pm). As for the absorbing receiver temperature (T_{abs}), it was 478°C at the start of heating at 2:31 pm and then increased to 488°C at 2:31 pm, which was very high temperatures as a result of the high beam solar intensity in this period. (T_{am}) was 35.4°C at the beginning of the heating at (2:18 pm) and at the boil it was 32.2°C, so the result was that the drawing was almost a horizontal line, as well as the case for the velocity of the ambient air, it stayed almost constant during the experiment period at $(0.3 m/s)$, so its graph represented a horizontal line very close to the horizontal axis.

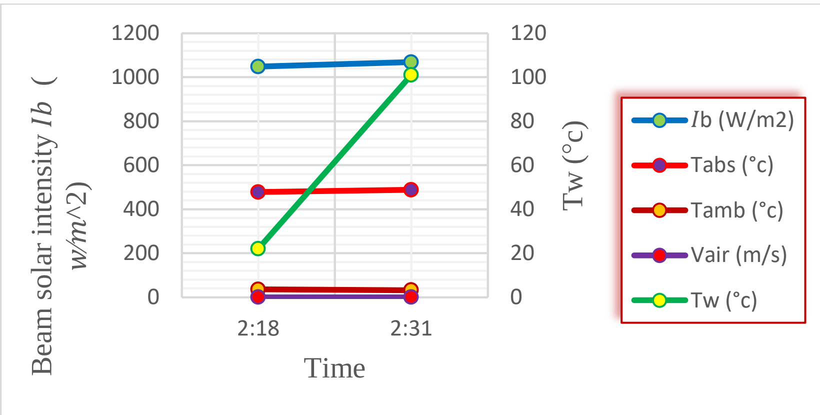

Fig. (6): The experiment using parabolic solar concentrator d= 96 cm with 1-liter receiver at (2:18 pm-2:31 pm).

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Figure (7), where the receiver capacity was two liters, the water temperature (T_w) started to rise from 12°C at 10:20 am, until it reached 102°C at 10:55 am where the water was boiling. Then beam solar intensity was 978 W/m^2 at 11:34 am, then increased to 1002 W/m^2 at 10:20 am, then it went down to 991 W/m^2 at 10:40 pm due to the inaccuracy of tracking the sun and the movement of ambient air, and then increased until it reached 1013 W/m^2 at 10:55 am. As for the T_{abs}, it was 280°C at the start at 10:20 am and then decreased to 248°C at 10:40 am, and that's the result of inaccuracy tracking the sun and the movement of the ambient air, then it increased to 387°C at 10:55 am. The ambient air temperatures were close to each other at the time of measurement, as it was 15.5°C at the beginning of the heating and at the boil it was 15.9°C, so the result was that the drawing was almost a horizontal line, the ambient air velocity was ranged between (0.9 – 1.1 m/s), its graph appeared in the form of a horizontal line close to the horizontal axis.

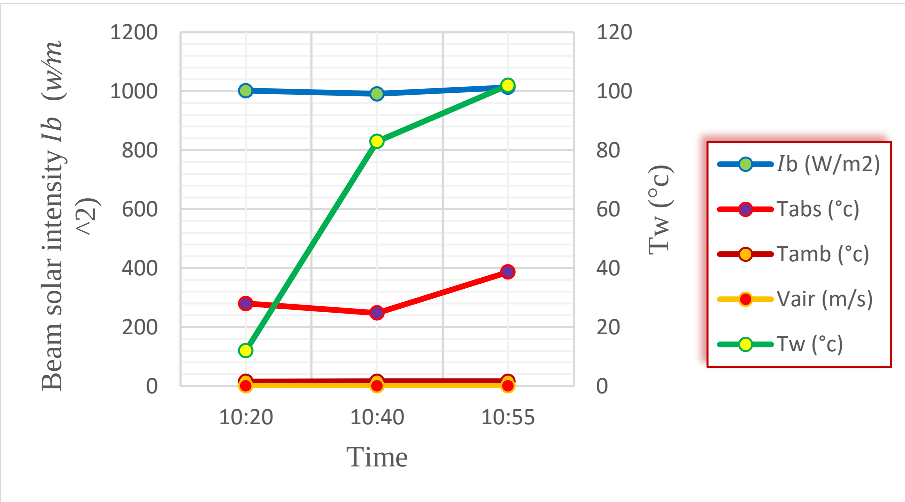

Fig. (7): The experiment using parabolic solar concentrator d= 96 cm with 1-liter receiver at (10:20 am-10:55 am).

As for Figure (8), where the receiver capacity was two liters, (T_w) began to rise from 22°C at 1:35 pm until it reached 101°C at 2:04 pm where the water was boiling. The beam solar intensity was 949 W/m2 at 1:35 pm, and then it began to increase until it reached 980 W/m^2 at 1:55 pm and decreased until it reached 974W/m^2 at 2:04 pm due to the inaccuracy of directing the concentrating dish towards the sun and movement ambient air. As for the absorbing receiver temperature T_{abs}, it was 355°C at the beginning of heating at 1:35 pm and

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then it got down until it got to 291℃ at 1:55 pm, then it increased until it got to 341℃ at 2:04 pm. The ambient air temperature was 29.6°C at 1:35 pm then it increased to 31.7°C at 1:55 pm, then it decreased to 29.8°C at 2:04 pm, the result was that the drawing was almost a horizontal line, as the same case for the ambient air velocity was not that high and because it was low it ranged between (0.3-0.4 m/s) and was almost a horizontal line close to the horizontal axis.

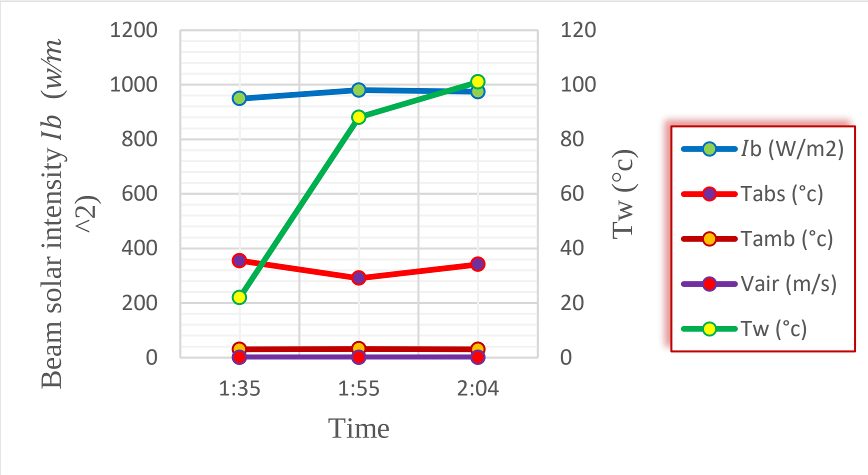

Fig. (8): The experiment using parabolic solar concentrator d= 96 cm with 1-liter receiver at (1:53 pm-2:04 pm).

5. Conclusions:

This research paper presented a practical study on the use of the parabolic solar concentrator in heating and boiling water in Nasiriyah city, southern Iraq, where the model of this concentrator was designed using simple and cheap materials that are available in the local market. The following conclusions were reached:

1. The shape factor depends on the area of the thermal receiver shade reflected on the solar concentrator and it does not depend on the time of the experiment nor the volumetric capacity of the thermal receiver.
2. The optical efficiency can be improved and thus increase the amount of concentrated heat by using a high-reflection reflector and using a thermal receiver with high absorptivity, low emissivity, and reflectivity, and does not depend on the volumetric capacity of the receiver nor on the time of the experiment.

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3. To reduce the thermal losses from the thermal receiver, the focus area on the receiver surface should be reduced and the solar concentrator should be used to boil water when the ambient air velocity is low, and the thermal losses depend on the focus area, the receiver surface temperature, size, and quality of the receiver and the experiment time.
4. The increase in the amount of useful heat used by the receiver and the collector efficiency depends on the diameter of the concentration dish, its optical efficiency, the size and quality of the receiver, the amount of concentrated heat reflected from the concentrator, and the thermal losses of the receiver.

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