



An Investigation of Hybrid Solar-Steam Power Plant: A case study in Iraq

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Abstract:

In this work integrating Al-Zubaydia (Kut-Iraq) thermal power plant with solar thermal system is studied for heating feed water by solar energy to reduce fuel consumption and greenhouse gases emission. A closed type Parabolic Trough Solar Collector (PTSC) is designed, constructed, instrumented, and tested. Its thermal characteristics are reported under Iraq climate conditions for the period extended from June, to September 2017. The collector heat gain, efficiency, absorber temperature and heat exchanger effectiveness (considered as feed water heater) were presented for absorber side flow rates of (0.15, 0.2, 0.3, 0.4, 0.5) lpm of water or oil), and shell side water flow rates of (0.4, 0.5, 0.6lpm). Results show that the maximum obtained thermal efficiency of parabolic trough solar collector was 83.33% for oil working fluid. The maximum obtained oil outlet temperature was 106 °C at solar noon for (0.15) lpm. Theoretical results showed that the fuel save mode needs collector area of (32842 m²), while that needed for power boosting is (102569 m²) for the same thermal cycle efficiency. The fuel save mode reported a reduction in greenhouse emission.

Keywords: Power plant, Solar aided power generation, Regenerative steam cycle, Parabolic trough solar collector.

دراسة لمحطة قدرة بخارية شمسية هجينة: حالة مدروسة للعراق

الخلاصة:

في هذا العمل تم دراسة دمج الطاقة الشمسية بالمحطة الحرارية في الزبيدية من خلال تسخين ماء التغذية بالطاقة الشمسية لتقليل صرف الوقود التقليدي وانبعثات الغازات الدفينة. تم تصميم و بناء وتجهيز مجمع قطع مكافئ شمسي ذو دورة مغلقة باجهزة القياس وتم فحصه عمليا. المواصفات الحرارية لهذا المجمع تم تحديدها للظروف الجوية العراقية و للفترة الممتدة من حزيران ولغاية ايلول 2017. عرضت الحرارة المستحصلة، الكفاءة الحرارية، درجة حرارة السطح الماص و فعالية المبادل الحراري (والذي مثل مسخن ماء التغذية) لمعدل جريان الماء او الزيت الحراري داخل الانبوب الماص (0.15، 0.2، 0.3، 0.4، و 0.5) لتر/دقيقة، و لمعدل جريان الماء داخل القشرة (0.4، 0.5، 0.6 لتر/دقيقة). بينت النتائج ان القيمة العظمى للكفاءة الحرارية للمجمع المكافئ كانت 83.33% عندما كان الزيت هو مائع التدوير. اعظم درجة حرارة كانت 106 درجة مئوية للزيت الخارج من الانبوب الماص عند الظهر الشمسي ولمعدل تدوير 0.15 لتر/دقيقة. بينت النتائج النظرية انه لحالة الاقتصاد بالوقود فان مساحة 32842م² من المجمعات الشمسية تغطي هذا الهدف، بينما للوصول الى اعظم قدرة منتجة فان مساحة المجمعات المطلوبة هي 102569 م² ولنفس كفاءة المحطة الحرارية. ان العمل على تقليص الوقود سنخفض من انبعثات الغازات الدفينة.

1. Introduction:

The consumed fossil fuel in power plants causes many serious negative effects on the environment like global warming, ozone layer destruction and air pollution. Solar energy is clean, free, non-depleting source with zero greenhouse gas emissions. Iraq receives annual solar radiation approximately for 4000 hours with daily incident (4.5 to 5.4) kWh/m² (NASA 2008). Technically Iraqi power needs is distributed between (65-70%) for heating and cooling equipment, and 30% for lighting and other electrical sets. So there is a need for efficient solar thermal system to convert solar energy to thermal energy by (60-70%).

In a typical parabolic trough collector's power plant, hybridization is the combination of thermal energy obtained from parabolic trough collectors with that obtained from another conventional fuel. [1] Studied the techno-economic feasibility of a parabolic trough concentrator solar thermal power plant. [2] Studied the efficiency of solar aided power generation with different solar replacements of extraction steam. The results show that the solar to electricity efficiency of solar aided power generation are higher than those of a solar alone power plant with the same temperature level of solar input. Also, the low temperature

heat resource is very hard to be used for power generation in other types of solar power plants. [3] investigated the energy and economic advantages of developed solar aided model. The thermal solar aided (in the temperature ranged from 250 to 901) was coupled with 200 and 300MW typical, 1000MW ultra-supercritical and 600MW, 600MW subcritical and 600MW supercritical fuel power plant. The solar aided is used to replace the steam extraction in fuel saving and power boosting modes.

The reported solar aided power generation is appropriate to be adopted in supercritical and subcritical plants compared with ultra-supercritical plants. The solar energy contributed (up to 20%) significantly for boosting electricity. [4] proposed and analyzed a novel integrated solar combined cycle with direct steam power plant. To increase solar share in the global output power, they used two stage solar inputs.

The results show that utilizing solar energy to supply latent heat for vaporization of feed water is better than that used for sensible heating purposes. Also the efficiency of solar to electricity for two stages was 30% higher than that for one stage of integrated solar combined cycle. [5] studied the thermal performance of the integrated solar/North Benghazi united. Cycle under Libyan climate conditions. Parabolic trough solar is used as solar thermal system with direct steam generation. The proposed solar assisted plant was analyzed as power boosting and fuel saving modes for the same area of solar field. The obtained results show that the yearly the natural gas consumption saving with approximate 3001.56 tons and CO₂ emission is 7972.25 tons for fuel saving mode. For power boosting mode, the yearly solar to. Electricity is 93.33 GW-h.

The benefit per cost ratios for power boosting modes is 1.30 and for fuel savings is 1.74 for the same area of solar field. So, the fuel saving mode is found more beneficial. [6] Investigated heating of feed water by solar energy in power plant units of Isfahan. The reported net increase in power plant efficiency was 18.3%, when all high-pressure feed water heaters are replaced by solar farm. [7] Studied thermodynamic performance of hybrid solar/coal plant. They derived an expression of solar-to-power efficiency of hybrid solar and coal fired power plant. This correlation indicates three affecting parameters on solar system with 330 MW coal-fired power plant thermal performance, these are: turbine load, solar radiation and incident angle. Results showed that the net solar-to-electricity efficiency has peak value at a given turbine load. While it keeps constant with increasing incident angle then decreases. [8] developed a model of solar

field and power block to evaluate solar to electrical efficiency and solar energy efficiency. The influences of operation condition and structure layouts on the solar hybrid coal-fired power plant performance are disclosed. It is reported that the solar radiation has slight influence when receiver temperature is 290 °C and the concentration ratio is higher than 60.

Flow rate in the range from 0.5 m/s to 4 m/s has inconsiderable effect on the performance of solar receiver. [9] established a correlation to describe the effect of collector efficiency, turbine efficiency and upgraded energy level of solar heat on plant thermodynamics. Results show that the moderate-temperature solar and coal-fired power plant hybridization can provide a promising direction for efficient utilization of low-grade solar heat. [10] simulated proposed kalina cycle system 11 (KCS11) assisted with indirect solar heating system, parabolic trough solar collectors with oil heating fluid is used to superheat Ammonia -water binary mixture (75% mass fraction). the KCS11 is integrated with (500MW) subcritical coal fired steam power plant to assist power generation, the evaporation of (Ammonia -water) mixture is accomplished by waste heat recovery of coal fired flue gases in the kalina cycle, this process reduces the temperature of flue gases by (10k), a thermodynamic modeling algorithm is adopted to analyses the proposed system at different environmental conditions. Results show that the power generated from kalina (KCS11) cycle is increased from 389.51KW to 515.37 KW by integrating solar energy. The cycle efficiency is increased from 5.946% to 6.988%, there by annual CO_2 emission can be reduced daily by 1008.28 ton. [11] proposed integrating solar-assisted pressure-temperature swing adsorption (PTSA) into an 800MW electrical coal-fired power plant, to avoid energy consumption by turbine steam extraction. They found lower gas mission than that of the referenced power plant.

In regenerative Rankine cycle, steam is extracted to heat feed water from 40°C (condenser outlet) to 300°C (boiler inlet) to increase the overall plant thermal efficiency while the power generated by turbine is reduced due to bled steam mass. By replacing part or all the extracted steam by solar thermal energy for heating feed water gives a good solution to increase the generated capacity with the same or lower consumption of fuel. Up to the author knowledge, this work is unprecedented for Iraq climate conditions. The objective of this work is to evaluate theoretically and experimentally the hydrothermal characteristics of solar thermal system used for Al-Zubaydia thermal power plant in Kut –Iraq feed water heating. Depending on the performance of this solar thermal unit, area of solar heating units will be proposed.

2. Thermal analysis:

2.1 Solar collector

The collector useful heat gain (W) is evaluated as:

$$Q_u = A_{ap} F_R \left[I \cdot \tau \alpha - \frac{U_L (T_{in} - T_{amb})}{C_r} \right] \quad (1)$$

where

A_{ap} : aperture area (m^2).

F_R : heat removal factor.

I : incident solar radiation taken as an average value as (750 W/m^2).

$\tau \alpha$: optical transmittance absorptance product (0.84) [12].

T_{in} : inlet temperature of the working fluid (K).

T_{amb} : ambient Temperature (K).

U_L : heat loss coefficient ($\text{W/m}^2 \cdot \text{K}$).

C_r : the concentration ratio. It is calculated as:

$$C_r = \frac{\text{Aperture area } (A_{ap})}{\text{surface area of the absorber } (A_{abs})} \quad (2)$$

U_L is collector heat loss coefficient ($\text{W/m}^2 \cdot \text{K}$). It is calculated by [12]:

$$U_L = \left[\frac{A_{abs}}{(h_w + h_{r,g-amb}) A_g} + \frac{1}{h_{r,abs-g}} \right]^{-1} \quad (3)$$

in which,

A_{abs} : absorber surface area (m^2).

h_w : convective heat transfer coefficient due to wind speed V_w ($\text{W/m}^2 \cdot \text{K}$).

$h_{r,g-amb}$: heat transfer coefficient due to radiation between glass cover and ambient ($\text{W/m}^2 \cdot \text{K}$)

$h_{r,abs-g}$: heat transfer coefficient due to radiation between the absorber and glass cover ($\text{W/m}^2 \cdot \text{K}$)

all the variables presented in eq. 3 are calculated as cited by [13]

The value of correction factor or heat removal factor (F_R) is ($0 < F_R < 1$), it can be interpreted as the ratio of the actual useful heat to that which would be collected if the entire absorbed surface is at the fluid inlet temperature, and it can be evaluated as:

$$F_R = \frac{\dot{m}_f C_p}{A_{ap} U_L} \left[1 - e^{\left(-\frac{A_{ap} U_L F'}{\dot{m}_f C_p} \right)} \right] \quad (4)$$

The collector efficiency factor (F') can be calculated as [13]:

$$F' = \frac{U_o}{U_L} \quad (5)$$

The solar collector thermal efficiency (η_{th}) depends upon the operating conditions namely: (solar radiation flux, inlet fluid temperature, as well as the ambient temperature) and on the concentrator design. It is evaluated as:

$$\eta_{th} = \frac{Q_u}{I \cdot A_{ap}} \quad (6)$$

2.2 Heat Exchanger

Shell and U tube heat exchanger is designed and instrumented in this study, its thermal analysis involves the determination of the heat transfer coefficient of shell side and tube side.

2.2.1 Heat Transfer in tube side

The internal heat transfer coefficient h_t in tube side is calculated as:

$$h_t = \frac{Nu_t k_{f,t}}{d_i} \quad (7)$$

For laminar flow in circular pipes ($Re < 2100$), The Nusselt number was calculated by using [14]:

$$Nu_t = 4 \cdot 36 \quad (8)$$

The Reynolds and Prandtl numbers of the tube side flow can be determined by:

$$Re = \frac{\dot{m}_t d_i}{A_t \mu_t} \quad (9)$$

$$Pr = \frac{Cp_t \mu_t}{K_{f,t}} \quad (10)$$

The tube side flow area pass is calculated by:

$$A_t = \frac{\pi}{4} d_i^2 * \text{number of tubes} \quad (11)$$

2.2.2 The overall and shell side heat transfer coefficient

The shell side heat transfer coefficient can be calculated as:

$$h_o = \frac{q}{A_t (T_{av,h} - T_{av,c})} \quad (12)$$

Heat transfer from U tube to the shell side is calculated as:

$$q = q_{tube} = (\dot{m}c_p)_h (T_{h,i} - T_{h,o}) \quad (13)$$

or

$$q = q_{shell} = (\dot{m}c_p)_c(T_{c,o} - T_{c,i}) \quad (14)$$

The overall heat transfer coefficient of the heat exchangers is evaluated as:

$$U = \left[\frac{1}{A_o h_o} + \frac{\ln(d_o/d_i)}{k A_i} + \frac{1}{A_i h_i} \right]^{-1} \quad (15)$$

The effectiveness of the heat exchanger is calculated as [14]:

$$\varepsilon = \frac{1 - \exp[-(NTU)(1 - C_{ratio})]}{1 - C_{ratio} \exp[-(NTU)(1 - C_{ratio})]} \quad (16)$$

where:

NTU is Number of Transfer Units, it is calculated as:

$$NTU = \frac{U A_t}{C_{min}} \quad (17)$$

C_{ratio} is the ratio between the minimum (C_{min}) to maximum (C_{max}) heat capacity, such that:

$$C_{ratio} = \frac{C_{min}}{C_{max}} \quad (18)$$

The heat capacity of hot fluid (C_h) and cold fluid (C_c) can be determined as:

$$C_h = \dot{m}_h C_{p,h} \quad (19)$$

$$C_c = \dot{m}_c C_{p,c} \quad (20)$$

If $C_h > C_c$, then $C_{min} = C_c$ and $C_{max} = C_h$. If $C_c > C_h$, then $C_{min} = C_h$ and $C_{max} = C_c$.

2.3 Power plant theory

Al-Zubaydia thermal power plant consists of one reheater and eight feed water heaters. One of these is an open type called (deaerator) as shown in Figure (1). The unaltered unit originally generates (330.77 MW) which is considered as a reference case in this work. The thermal efficiency of the steam plant is (45.45%) which is calculated by:

$$\eta = \frac{\text{Output power}}{\text{Input power}} \quad (21)$$

where the output power (W_{Tur}) is calculated as:

$$\begin{aligned} W_{Tur} = & \dot{m}_1(h_1 - h_2) + (\dot{m}_1 - \dot{m}_2)(h_3 - h_2) + \dot{m}_4(h_4 - h_5) + (\dot{m}_4 - \dot{m}_5)(h_5 - h_6) + \dot{m}_7(h_6 - h_7) + \dot{m}_7(h_7 - h_8) + \\ & (\dot{m}_7 - \dot{m}_8)(h_8 - h_9) + (\dot{m}_7 - \dot{m}_8 - \dot{m}_9)(h_9 - h_{10}) + (\dot{m}_7 - \dot{m}_8 - \dot{m}_9 - \dot{m}_{10})(h_{10} - h_{11}) + (\dot{m}_7 - \dot{m}_8 - \dot{m}_9 - \dot{m}_{10} - \dot{m}_{11})(h_{11} - \\ & h_{12}) \end{aligned} \quad (22)$$

while the input power is (Q_{Boiler})

$$Q_{Boiler} = \dot{m}_{32}(h_1 - h_{32}) + \dot{m}_4(h_4 - h_2) \quad (23)$$

The considered enthalpies of the plant are given in Table (1).

To calculate the advantage or the efficiency of the solar energy utilization, the solar percentage (P_{solar}) is defined as:

$$P_{solar} = \frac{Q_{solar}}{Q_{boiler} + Q_{solar}} \cdot 100\% \quad (24)$$

Where:

$$Q_{solar} = I * A_{ap} \quad (25)$$

and solar to power efficiency (η_{se}) is defined as:

$$\eta_{se} = \frac{W_{sol-hyp}}{I * A_{ap}} \cdot 100\% \quad (26)$$

where $W_{sol-hyp}$ is defined as the difference in the output works between the hybrid power plant (W_{hyb}) (after replaced the extracted steam energy by solar energy) and only steam power plant (W_{Tur}). It can be calculated as:

$$W_{sol-hyp} = \Delta E_{solar} + Q_{solar}(A_{steam} - A_{solar}) \quad (27)$$

Where: ΔE_{solar} is the exergy of collector solar heat and determined as:

$$\Delta E_{solar} = I * A_{ap} * \eta_{th} * \eta_{carnot} \quad (28)$$

in which, η_{carnot} is the Carnot efficiency corresponding to the receiver temperature.

η_{th} is the thermal efficiency of collector

A_{steam} and A_{solar} are the energy level of bled steam and solar heat, respectively. The energy level be calculated as:

$$A = 1 - T_0 * \frac{\Delta S}{\Delta H} \quad (29)$$

where ΔS denotes the entropy change in the process, ΔH represents the enthalpy change in the process, and T_0 is ambient temperature.

3. Experimental Setup:

The experimental system consists of a parabolic trough solar collector, heat exchanger (feed water heater), down comer, supply tank (oil and water tanks), water pumps, oil pump and connecting pipes as shown in the Figure (2). This system is tested under the climatic conditions of Baghdad/Iraq from June to September 2017 (lat. 33.33°) and (long. 44.42°). The parabolic trough solar collector consists of reflective surface (matrix of mirror straight tapes as shown in Figure (3a), copper tube (absorber) which is located along the reflector focus, flat glass which covered the reflector from the top and two axis tracking system. The design parameters of the parabolic trough are given in Table (2). A counter flow heat exchanger is used for the experimental test. A novel heat exchanger is used in this work; the cross-sectional area of its shell is elliptical with (210mm and 100mm) major and minor diameters and (600mm) length. The copper tube is formed as S shape coil shown in Figure (3b) with (14mm) diameter and (2000mm) length.

Eighteen K-type thermocouples are located at inlet and outlet of each heat exchanger and absorber, also at absorber surface, glass cover and reflective surface as illustrated in Figure (2). All these thermocouples are connected to channels of the digital thermometers inserted with SD card data logger model BTM-4208SD. Two flow meters are employed to measure water flow rates. Z-4002 float type flow meter ranged from (0.1 to 0.9 lpm) is utilized to measure water flow rate in shell side of heat exchanger. The other is ranged from (0.1 to 1 lpm) used for tube side. Two Borden gages are utilized to measure the inlet and outlet pressure of circulating fluid (water and oil).

4. Results and Discussion:

4.1 Ambient conditions and temperature variation of solar collector

Figure (4) presents that solar radiation on (13th June, 30th July, 30th August and 11th September, 2017) rises to reach its maximum value at noon, and then ceased to vanish at sunset. The maximum solar radiation was (996W/m²) at (12:00 pm) on 30th July and decreases after that. The ambient temperature follows the solar radiation as illustrated in Figure (5), it rises from (34.8 °C) at (9:00 Am) to maximum value (49.4 °C) at (13:00 Pm) on 13th August and then decreases.

4.2 Heat removal factor of solar collector

Figure (6) shows that the heat removal factor increases slowly with the increasing of mass flow rate. Heat removal factor for the solar collector with circulating water is higher than that when oil was the thermal circulating fluid. This is due to the differences in thermo physical properties between them as given in Table (3).

4.3 Heat Exchanger

Figure (7) shows the variation of the heat exchanger effectiveness with shell mass flow rate for 0.15 lpm of water or oil in the tube side. It can be seen that the effectiveness increases with the increase in shell mass flow rate due to the increase in shell side Reynolds's number that results an increase in overall heat transfer coefficient. Heat exchanger effectiveness when oil flows inside the tube is higher than that reported when water flows inside the tube, due to higher values of thermal conductivity and specific heat for oil as illustrated in Figure (8). The maximum obtained effectiveness is (80.1%) for (0.15) oil mass flow rate in tube side and water flow rate of (0.6 lpm) in shell side.

4.4 Al-Zubaydia thermal power plant

The given data from the Al-Zubaydia thermal power plant (theoretical model) are analyzed as a power boosting mode and a fuel saving mode for the same increase in the cycle thermal efficiency. It is found that the work of the turbine is 338.6MW, work of the pump is 7.85 MW, work net is 330.8MW, the heat added in the boiler is 727.7MW and thermal efficiency is 45.45%. Three Cases were studied namely:

- **CASE I)** Six closed feed water heaters are replaced by solar thermal energy.
- **CASE II)** The feed water heaters of LP Turbine (feed water heaters number 8, 7, 6, and 5 as presented in Figure (1)) are replaced by solar thermal energy.
- **CASE III)** The feed water heater of IP Turbine (feed water heater number 3 as presented in Figure (1)) is replaced by solar thermal energy.

For each case two sub cases are investigated, these are **A** refers to power boosting and **B** refers to fuel saving. Per results given in Table (4) (preprocessing of the field data under Iraq climatic conditions), the maximum cycle efficiency reached is (47.85%) and solar share of

electrical energy is (17.5 MW) for power boosting. This required collector area of (193,9 m²) for power boosting and (42,82 m²) for fuel saving.

4.5 Comparison of this work with published data

The reported average efficiency of parabolic trough solar collector with reflector of (1.8 x 2.8m) dimensions was 61% by [15] when synthetic oil in evacuated receiver was used. The experimental tests are carried out under Baghdad climate conditions (33.3° N, 44.4° E). The heat loss coefficient of the evacuated receiver was 7.6 W/°C.m². The present work reported an average collector thermal efficiency of 78% and 85% for water and thermal oil as receiver working fluid respectively. The heat loss coefficients were 7.4 W/°C.m², and 8.5 W/°C.m² for water and thermal oil respectively. These results are well agreed with Mutlak.

[16] Analyzed the solar aided steam power system for power boosting mode. They simulate parabolic trough solar field. They viewed that this type of power cycle can achieve higher cycle efficiency compared with lignite fired power cycle for fuel save mode with maximum solar field of (120000 m²). In this work, Al-Zubaydia thermal power plant needs collector area of (32842 m²), since higher values of incident solar radiation and ambient temperature are recorded for Iraq compared with Greece.

5. Conclusions:

According to the previous discussion of the obtained results, it can be concluded that the maximum thermal efficiency of parabolic trough solar collector PTSC is (80.3%) and (83.33%) for water and oil working fluid respectively. The maximum outlet temperature of the absorber tube was (106 °C) for solar radiation of (973 W/m²) and ambient temperature (47.5 °C) for oil working fluid. Oil is suitable for obtaining higher temperature and higher efficiency. The suitable mass flow rate adopted in this work is (0.15 lpm) accompanied with high thermal efficiency and high outlet fluid temperature. The maximum effectiveness of the heat exchanger is (80.1%) for oil flows in the tube side and (79.65%) for water flows tube side. Oil flows in the tube side of heat exchanger is suitable for obtaining high effectiveness of (80.1%).with optimum mass flow rate of (0.15 lpm) in the tube and (0.6 lpm) in the shell side of heat exchanger. For the case study (Al-Zubaydia thermal power plant) the solar energy is capable to assist this plant to increase its thermal efficiency by (5.3%, 4% and 0.6%) by replace all

feed water heaters, replace low pressure feed water heaters , replace intermediate pressure feed water heaters.

The results for Al-Zubaydia thermal power plant show that the fuel save mode has higher benefit than power boosting for the same increase in cycle efficiency, because the first requires less the collector area less (32,842 m²) than the second (102,569 m²) and the fuel save mode reduces greenhouse gas emission.

Table (1) Selected thermodynamics properties of the steam cycle
[Al-Zubaydia thermal power plant]

State Number	Mass flow rate (kJ/s)	Enthalpy (kJ/kg)	State Number	Mass flow rate (kJ/s)	Enthalpy (kJ/kg)
1	279.26	3397.47	8	11.84	2972.6
2	253.3	3035.48	9	7.99	2759.6
3	20.6	3148.2	10	7.19	2632.32
4	232.4	3538.3	11	6.79	2563.14
5	10.078	3352.1	12	179.7	2376.7
6	12.44	3161.3	32	279.26	1208.6
7	213.34	3159.6			

Table (2) Reflector Specifications

Specification	Description	Specification	Description
Appearance	Parabolic trough	Mode of tracking	Two – axis
Length	2 m	Concentration ratio	26.3
Aperture width	1.05 m	Thickness of glass cover	3 mm
Depth of parabolic	0.27 m	Focal point	0.253 m
Aperture area	2.1 m ²	Diameter of absorber	0.0127 m
Rim angle	92.2°		

Table (3) Thermo physical properties of water and oil

Circulated fluid	ρ (kg/m ³)	C_p (J/kg.°C)	k (W/m.°C)	μ (Pa. s)
Water	1000	4186	0.589	0.0006532
Oil	880	1900	0.21	0.0793

Table (4) Theoretical results of Al-Zubaydia thermal power plant

Variable	CASE I		CASE II		CASE III	
	A	B	A	B	A	B
Output power generated (MW)	356.101	338.6	351.839	338.6	340.562	338.622
Increase of cycle eff. (based on referenced case)	5.39%	5.39%	4%	4%	0.601%	0.601%
Added generation capacity (MW) (based on referenced case)	17.479	-----	13.217	-----	1.94	-----
Power increase	5.101%	-----	3.903%	-----	0.57%	-----
Required collector area (m ²)	193,869	42,819	102,569	32,842	41,100	4,966
solar to power efficiency	10.6%	-----	15.15%	-----	5.55%	-----

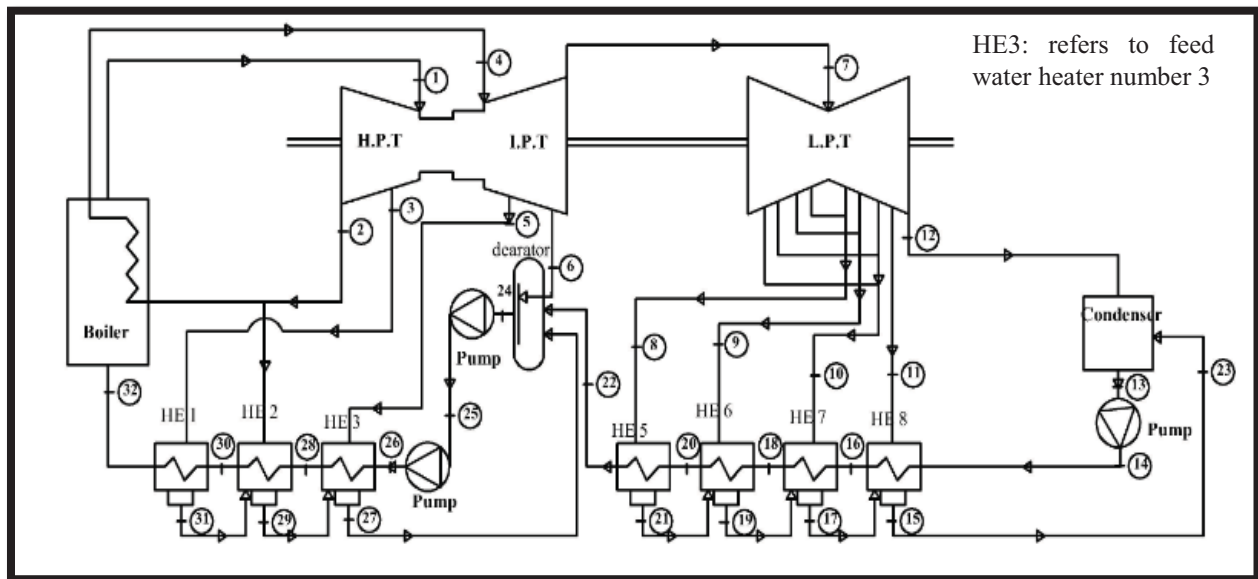


Fig. (1) Steam cycle structure diagram for Al-Zubaydia power plant.

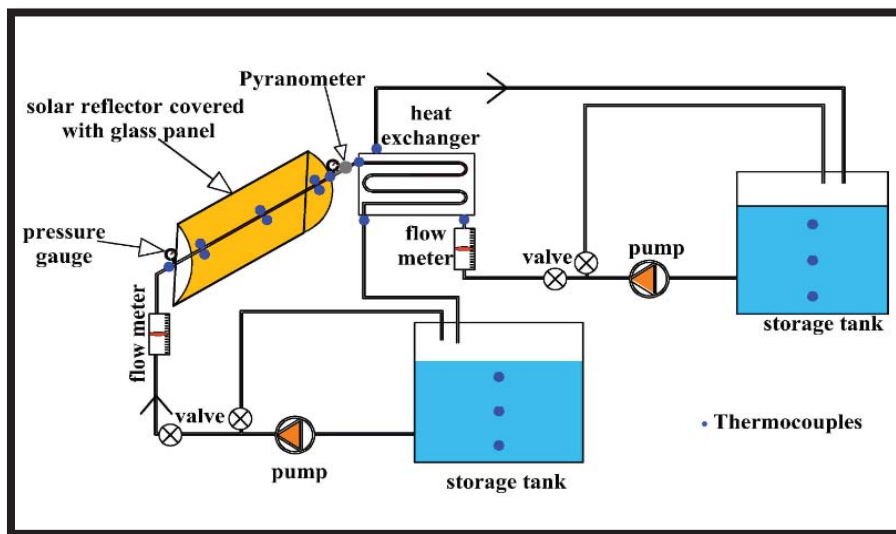


Fig. (2) The experimental setup.

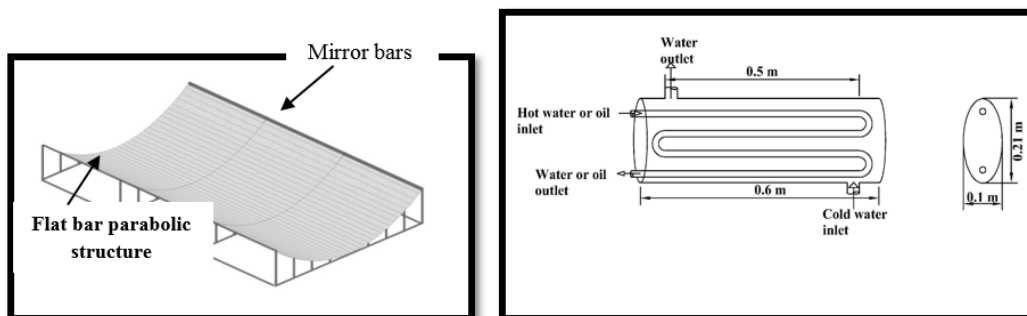


Fig.(3). a) Parabolic Reflector. b). Heat exchanger.

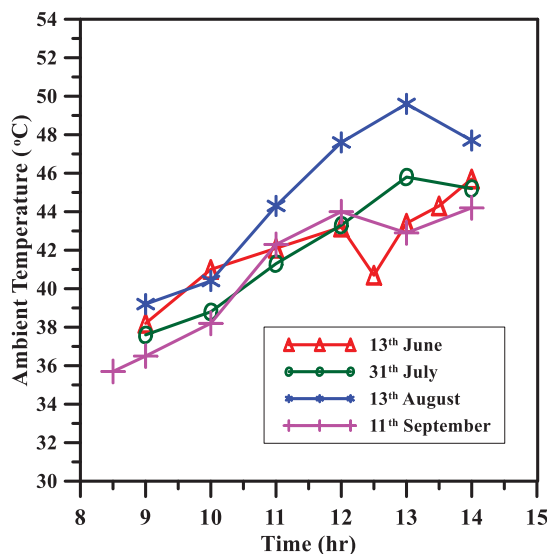
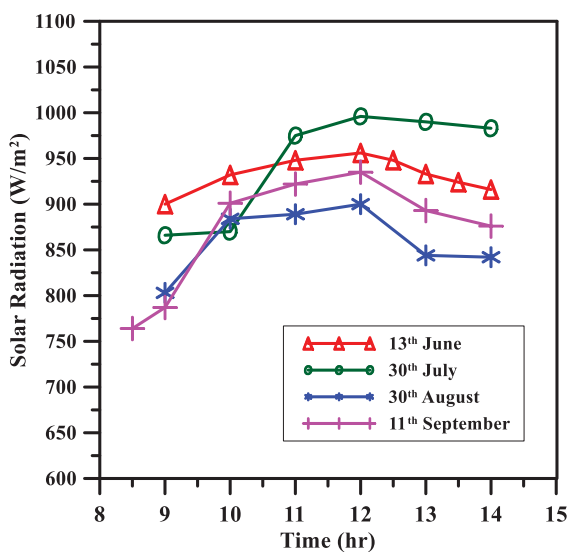


Fig. (4) Hourly variation of solar radiation Fig. (5) History of ambient temperature

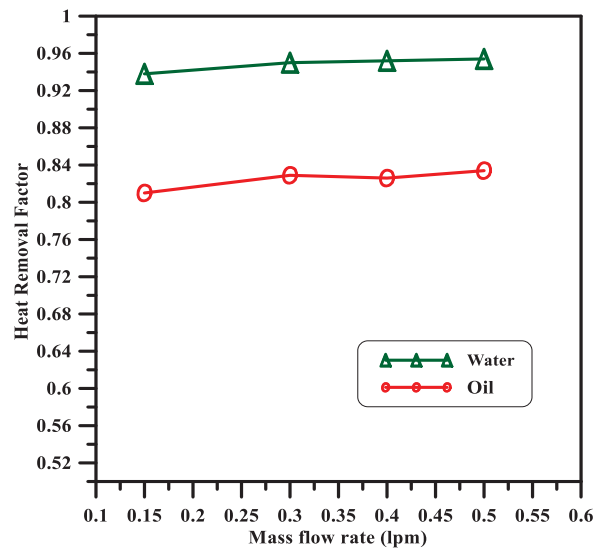


Fig. (6) Variation of collector heat removal factor with mass flow rate.

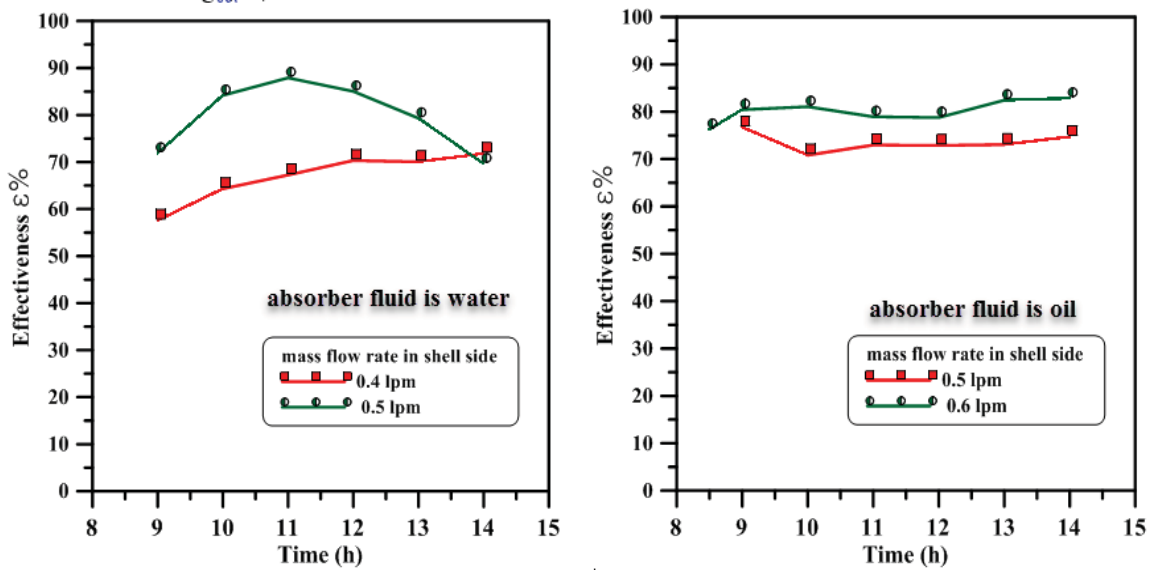


Fig. (7) Heat exchanger effectiveness variation with shell mass flow rate. (0.15 lpm flow rate in the tube side)

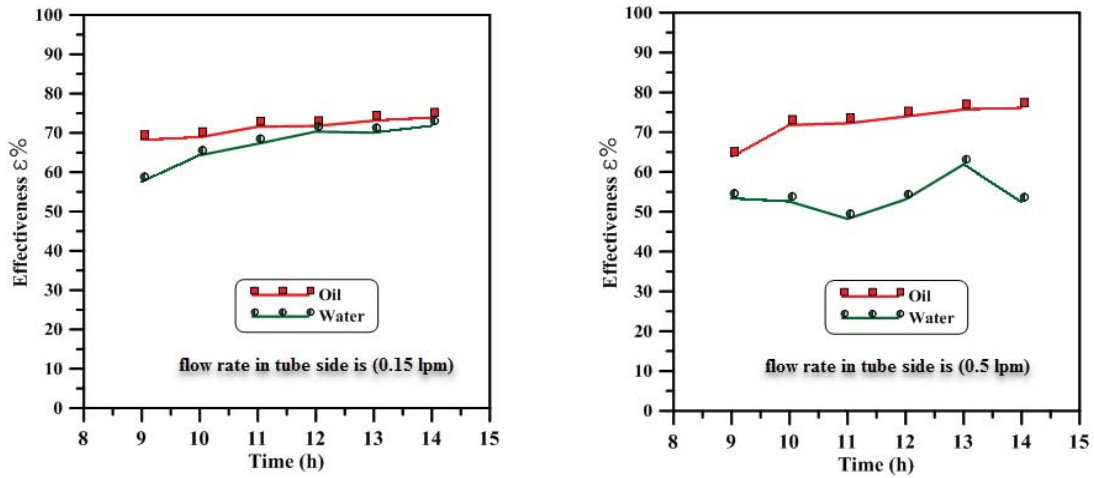


Fig. (8) Variation of heat exchanger effectiveness with tube side flow rates for the adopted collector two working fluids. (0.4 lpm water flow rate in shell side)

Nomenclature:

Symb.	Description	Symb.	Description	Subscripts	
A_a	aperture area (m^2)	T	temperature ($^{\circ}C$)	Symb.	Description
A_r	receiver area (m^2)	U_L	heat loss coefficient(W/m^2K)	Abs	absorber
C_p	specific heat at constant pressure ($kJ/kg. K$)	W	Work (kJ)	ap	aperture
C_r	geometric concentration ratio	Greek Symbols		amb	ambient
D	diameter (m)	η_{se}	solar to power efficiency	av	average
F'	collector efficiency factor	η_{th}	thermal efficiency	b	beam radiation
F_R	heat removal factor	T	transmittance	c	cold
h	enthalpy (kJ/s)	ϵ	emissivity	f	fluid
$h_{r,g-amb}$	radiation heat transfer coefficient between glass and ambient ($W/m^2 .K$)	α	absorptance	i	Inlet
I	solar radiation (W/m^2)	μ	dynamic viscosity $kg/m. s$	g	glass
k	thermal conductivity ($W/m K$)	ρ	mass density kg/m^3	h	hot
\dot{m}	mass flow rate (kg)			o	outlet
Q_u	useful heat gain (W)			s	shell
t	time (s)			t	tube
S	entropy			Tur.	turbine
Abbreviation					
HE	Heat exchanger	NTU	Number of transfer units	PTSC	Parabolic trough solar collector
NIR	Near Infrared	PV	Photovoltaic	UV	UltraViolet

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