Experimental analysis of Shiraz solar thermal power plant performance during 2009-2011

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Among concentrated solar power (CSP) technologies, parabolic trough technology has been established worldwide due to current advances in technical and economical development of these systems. In this paper, durability and performance of current configuration of Shiraz Solar Power Plant (250 kW) is analyzed using the measurements of important parameters including the oil inlet/outlet temperature of the collector's field, thermal efficiency, direct radiation during 2009-2011 and system major deficiencies regarding installation and operating condition are discussed. In addition, effects of different factors on thermal efficiency of collector's field such as dust deposition and sun tracking are also studied.

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1. Introduction

Sun is an important source of energy in the world and it is a good substitute for fossil fuel energy for various applications such as solar thermal power plant. Several solar thermal power plants (STPP) are constructed and are in operation mainly in the USA and Spain [1]. Many research studies including both experimental and theoretical work are reported. In addition, a specific conference related to Solar Thermal Power Plant call SOLARPACES take places each year around the world.

As mentioned, some different experimental analyses have been done to study performance of STPP and effective parameters on them. Lippke [2] has studied a 30-MWe SEGS plant's behaviour and considered distinct factors affected its behavior. Since, accurate sun tracking is an essential factor for higher efficiency of STPP, Tora and Halwagi [3] studied this factor as well as others and showed that these parameters lead to unreliability of solar thermal power plants performance. They also investigated the combination of solar systems and fossil fuels for sustainable power outlet. In order to study other important factors, moreover, the seasonal effect of dust on transmittance of different materials is studied by El-Nashar [4]. Due to the importance of this factor (dust accommodation), recently, Nicknia et al. [5] studied the effect of dust formation on the performance of Shiraz parabolic trough solar collectors.

In addition, many numerical simulations of STPP have been done. An analytic method is used by Rolim et al. [6] to simulate solar power plant. They investigated nonlinearity heat loss of absorber tube of parabolic collectors. By using the TRNSYS simulation program a model for simulating parabolic trough collector is developed by Patnode [7]. Moreover, a computer model is developed by Price [8] to analyze the performance of a parabolic trough solar power plant, as well as the unit electricity cost and economic parameters. Due to importance of economic parameters, Baghernejad and Yaghoubi [9] performed an energy-thermo-economic analysis of an integrated solar combined cycle and found optimum condition to have the lowest electricity cost.

Beside these experimental and numerical studies, as a solar power plant does not work during the night due to a considerable reduction of solar radiation, some investigations have been done on combined systems such as hybrid solar-gas boiler system to solve this problem. A hybrid solar-geothermal system was proposed by Lentez and Almanza [10] to improve the steam flow rate. Niknia and Yaghoubi [11] investigated a combined solar thermal power plant and an auxiliary boiler in transient mode by using a developed code and experimental measurements.

The review of literature reveals that, however, different effective parameters on performance of solar power plants are studied; the effects of these parameters are not considered in a long duration and there are fewer analyses on durability and performance of a solar power plant. Therefore, in the current study attempt is made to analyze the performance of an installed solar power plant for three consecutive years and effect of various parameters on its thermal performance.

2. Nomenclature

I_{dir}	Direct radiation (W/m^2)
H	Thermal efficiency (%)
Q_s	Max energy that collectors can receive (kj)
Q_g	Energy gained by collectors (kj)
Cp	Heat capacity (kJ/kg ^{o}C)
ΔT	Temperature difference (^{o}C)
Q_l	Energy loss during the night(kj/hr)
M	Total mass of oil in the cycle (kg)

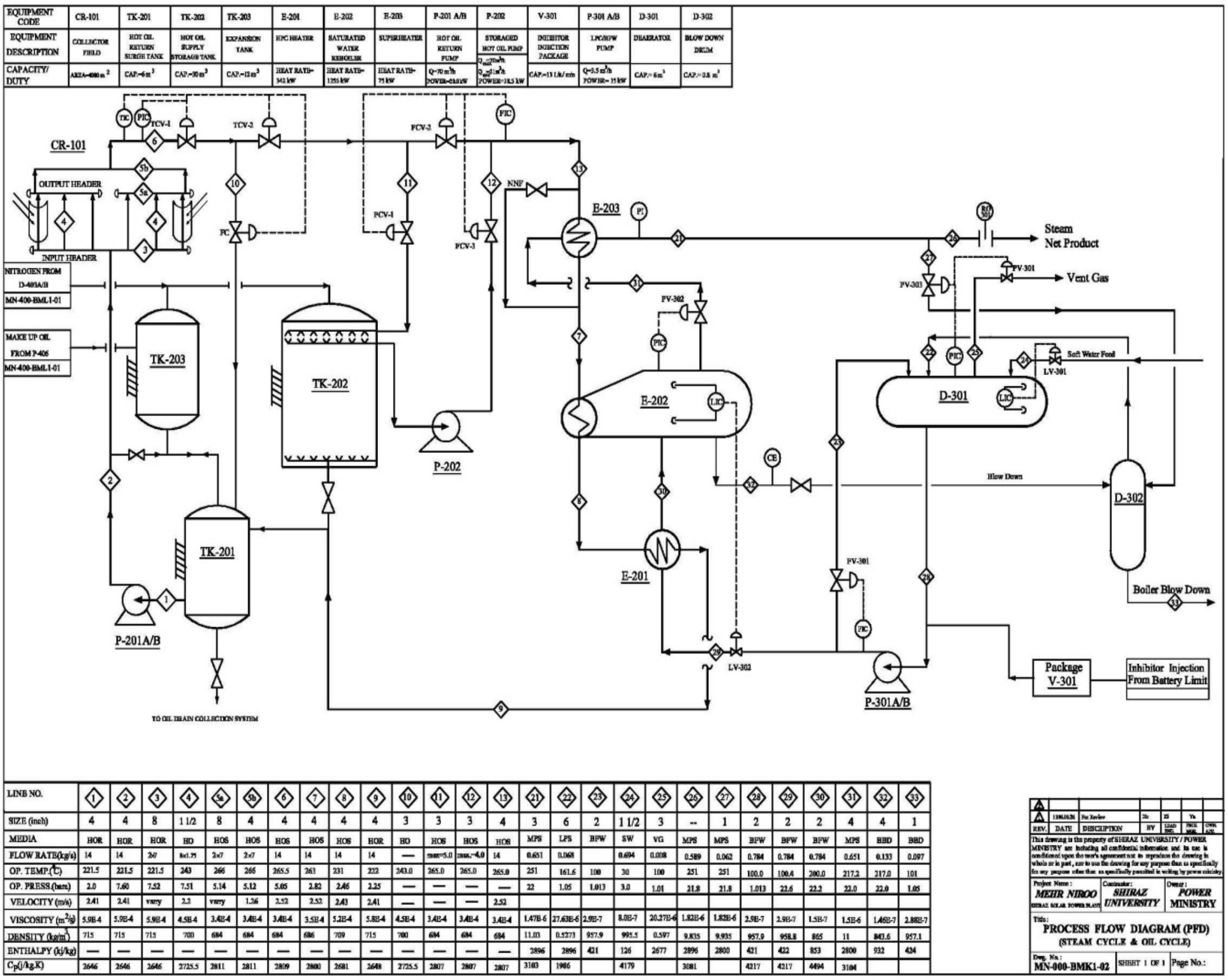


Fig. 1. Flow schematic of Shiraz solar power plant.

3. Shiraz solar thermal power plant (SSTPP)

Shiraz solar thermal power plant is located in Shiraz at south east of Iran with specifications of Table 1. Its collectors' field contains 48 parabolic collectors each 25 meters length and 3.4 meters wide containing 104 mirrors, Figs. 1 and 2 show flow schematic of Shiraz solar power plant and the collectors' field respectively. This power plant contains three heat exchangers and a deaerator. In the first heat exchanger (E-201), sub-cooled water is warmed up to saturated liquid state. In the second one (E-202) saturated vapour is produced from saturated liquid and finally in the third one (E-203), saturated vapour becomes superheated. Fig. 3 illustrated arrangement of the three installed heat exchangers as well as the steam production from the plant.

Table 1. Shiraz solar power plant's location.

Latitude	29.37 N
Longitude	52.61 E
Altitude	1510 m

Table 2. Specification of Shiraz solar power plant system.

Parameter	Size/kind	Parameter	Size/kind
Capacity	250kW	Electrical generation system	Under construction
Collectors	Parabolic trough	Inlet oil temperature	231 ^{o}C
Number of collectors	48	Outlet oil temperature	265 ^{o}C
Size of collectors	25×3.4 m^2	Oil flow rate	13.7 kg/s
Movement system	Hydraulic	Steam flow rate	0.673 kg/s
Structure	Truss	Steam temperature	250 ^{o}C
Fluid	Behran oil	Steam pressure	20 barg
Mirror reflectivity	90 %	-	-

Presently, the system can generate hot oil during the day and it may produce superheated steam with high pressure for research studies.

More specification of Shiraz solar power plant and parabolic through collectors are presented in Table 2 and Table 3 accordingly.

Table 3. Test conditions of data collections for each case.

Year	2009						2010						2011					
Season	Start time	Shut down time	Average ambient temp. (ºC)	Average wind velocity (m/s)	Mirrors condition (degree)*	Glass tube condition (degree)*	Start time	Shut down time	Average ambient temp. (ºC)	Average wind velocity (m/s)	Mirrors condition (degree)*	Glass tube condition (degree)*	Start time	Shut down time	Average ambient temp. (ºC)	Average wind velocity (m/s)	Mirrors condition (degree)*	Glass tube condition (degree)*
Spring	09:30	15:55	27.3	3.2	2	2	09:30	17:35	27.5	2	1	1	09:30	15:55	28	3.1	3	3
Summer	09:00	15:45	36.2	2.1	2	2	07:00	16:20	37.3	3.3	1	1	08:30	15:20	37	2.7	2	2

*1=surface is clean, 2= surface are not clean 3= surface is covered with dust

Passing hot oil through heat exchangers as shown in Fig. 1, superheated steam at 250˚C and 20 bar pressure is produced. Due to effects of various variables during heating process of oil, hot oil production will change during various days, seasons, and operating conditions [11]. The plant operation is started from 2008 and different parameters including oil temperature at various locations, mass flow rate of oil in the collector field, ambient air temperature, wind velocity, direct and global solar irradiation have been measured by using advanced equipments (Fig. 4 shows typical measuring instrument). Temperature, pressure and flow rate of produced steam are also measurable (however, they are not shown in this study). All components and parts of this power plant are explained in [12-13] extensively. In the following sections, attempt is made to illustrate the solar irradiation and hot oil production rate of the collector field in Figs. 5 and 6 for three consecutive years.

4. Shiraz solar power plant thermal analysis

This plant has been constructed with the purpose of acquiring the technology of developing parabolic trough solar plants for future energy generation. Shiraz solar power plant is designed to produce hot oil at 265 ˚C with 14 kg/s mass flow rate for the design conditions of Autumnal Equinox, September 21.

4.1 Temperature measurements

Collectors' field is the main component of any solar power plant. In fact, the optimum performance of a solar power plant is directly dependent on the optimum performance of collectors' field. The oil outlet temperature of the collectors' field is a function of heat capacities of different components of the plant, control system and instrumentation of the plant.

In order to study the oil cycle performance of Shiraz solar tthermal power plants, various parameters are recorded following the procedure explained in [13]. The recorded parameters include: oil temperature and thermal characteristics, ambient air temperature, wind velocity and direct solar radiation intensity during measurements. Table 3 presents typical measured data collected in mid-day of two seasons for the years 2009, 2010 and 2011, which is used in current study (unfortunately since, measurements in year 2009 was not continuous, the data for the mid day of two seasons in 2009 are not available. Therefore, it is tried to use the nearest available data, however it leads to some differences mentioned in the following.) Figs. 5 and 6 present temperature rise for inlet and outlet of the collector field, as well irradiance for three seasons of the years 2009-2011 in specific days (mid-day of each season).

Fig. 2. A picture of the collectors' field on tracking mode.

Fig. 3. A view of heat exchangers and steam generation of Shiraz solar power plant.

(a)

(b)

Fig. 4. Radiation measuring instruments; (a) Pyranometer; (b) Pyrheliometer

In order to discuss Figs 5 & 6, additional information is presented in Table 3 such as level of cleanliness of glass absorber tube and mirrors. Typical glass absorber tube and mirror condition are shown in Fig.7. During most of experiments, the most of mirrors and glass tubes did not have a suitable situation in term of cleanliness, which were mainly due to unfavourable cleaning schedule. Therefore, part of the radiations is diffused back to ambient without reaching the absorber tube. During each measurement dust accumulation are not recorded but effects of dust deposition are explained in section 4.2.

In Fig. 5 direct radiation for typical days of three seasons are illustrated. Strong differences between normal irradiance can be observed for the year 2009 in each season, which is due to unavailable data in the same day as 2010 and 2011. Maximum irradiance reached to 1000 W/m^2 during spring. There is no doubt that direct radiation depends strongly on the climate condition as well as seasonal period. Therefore, noticing these figures, one may conclude that spring has better clean sky irradiance.

Fig. 6 presents hot oil inlet and outlet temperatures from the collector field for the three years. The oil temperature is strongly related to the rate of direct normal solar radiation to the collector field. According to control plan, steam production is started when oil temperature is reached 250˚C. For this purpose, oil goes through the bypass line according to Fig.1 before its temperature reached to 250˚C. Once the oil temperature reaches to 250˚C, the bypass valve will partially be closed and oil will be directed to the heat exchangers. The distribution of flow rates (between the exchangers route and the bypass route) is adjusted in a manner that maintains a steady oil temperature. If the heat exchangers route is closed due to some technical considerations, the oil temperature increases again in the afternoon.

In spring, start-up time is almost similar for three years (9:30) but initial oil temperature is different. However, for some specific reasons steam production is started at different temperature in each year (2009 at 230˚C, 2010 at 250˚C, 2011 at 180˚C). For the year 2009 which has the highest starting point oil temperature reaches the operation temperature (Temperature for steam production) sooner than other years. In addition, for the year 2010 which mirrors have a good condition, the rate of increasing oil temperature is higher in comparison with other two years as shown in Table 4. It is worth noting that having a proper solar radiation in 2009 leads to a stable condition during steam generation. For example, in year 2010, oil temperature is higher than 2009 and steam generation continues only two hours (Between 16:00 - 18:00 PM), while in year 2009, steam generation last more than three hours (Between 13:00 -16:00 PM).

In summer, both start up time and initial oil temperature are different for the years. Therefore, each year has different trend, nevertheless, like spring, for year 2010 with higher initial oil temperature, steady state situation and consequently steam generation are achieved sooner than other years. Moreover, sooner start up time (almost 7:00 AM) in this year improves this stable and desirable trend. As a result, one may conclude that a suitable solar power plant should start operation as soon as possible and has a suitable storage system to have minimum heat loss during night.

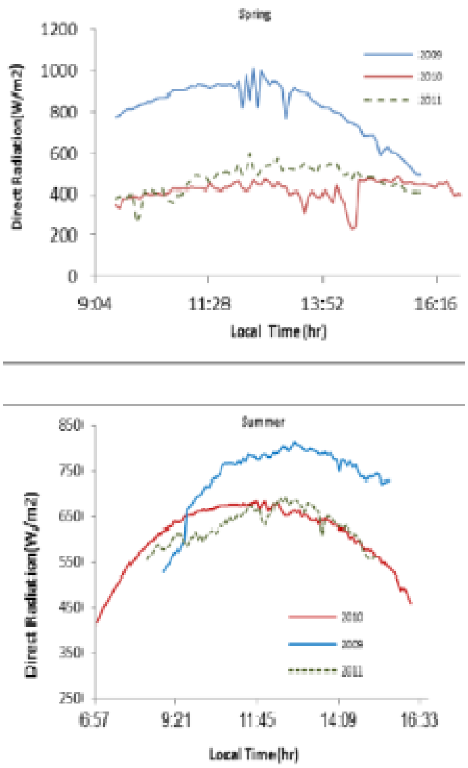


Fig. 5. Typical direct solar irradiances for different seasons.

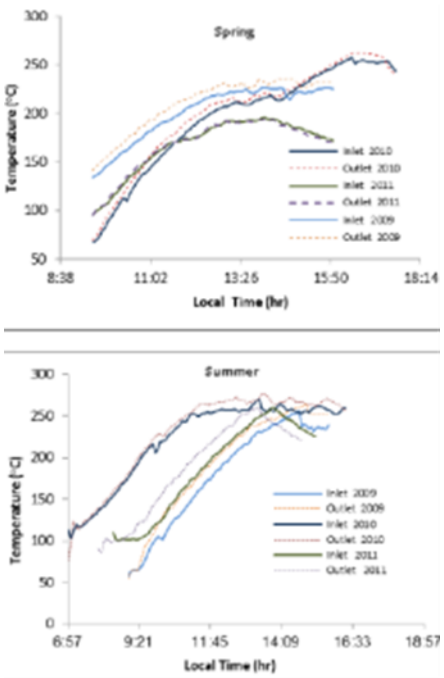


Fig. 6. Typical oil cycle Inlet/Outlet temperatures for different seasons.

Table 4. Collector field oil average temperature rise rate during typical day of each season for each years.

Year / Season	2009	2010	2011
Spring (^{o}C/min)	0.54	0.89	0.46
Summer (^{o}C/min)	0.66	0.73	0.60

Table 5. Typical thermal efficiencies of the collector field of solar power plant.

Year / Season	2009	2010	2011
Spring	9.33%	14.39%	4.1%
Summer	12.75%	20.19%	5.6%

To study performance of the STPP more extensively, , in Table 4, the average rate of temperature rise of the collector field during various seasons of the three years 2009, 2010 and 2011 are presented. There are various reasons for different performances, such as different climate condition, tracking condition, mirrors and absorber tube cleanliness, etc. According to Table 2 and 3, for the year 2010, the spring measurements illustrate high rate of temperature rise than other seasons because of good condition of mirrors, and for the year 2011, due to high dust accumulation (such as shown in Fig.7) and poor tracking condition, temperature rises are lower than the previous years.

Finally, in Table 5 thermal efficiency of the collector's field is compared for the three years. The efficiency is determined from:

$$\eta = (Q_g)/Q_S \quad (1)$$

where Q_g is energy gained by collectors and Q_S is maximum energy that collectors can receive.

In spring 2010, despite lower solar radiation (Fig.5), the thermal efficiency is higher, which may be due to their better tracking and cleanliness of the absorber tube and glass mirrors. Deposited dust on mirrors and receiver make a protective shield and reduce absorption considerably. In addition, comparing the three years of collector field efficiencies, one may attribute the lower efficiency in 2011due to cloudy sky, imperfect tracking performance of the collectors and more dusty of the glass mirrors and absorber tube as mentioned in Table 3. Generally, the performance is higher in summer than spring due to higher average solar radiation. It is worth mentioning that thermal efficiency of the collector's field is around 12.75% for a summer days in 2009 and around

20.19% for a corresponding summer day in 2010. The sharp difference is partially due to the solar radiation.

Table 6. Optical properties of absorber and cover glass tube.

Absorber		Cover glass tube	
Solar absorbance direct (AM1.5)	Average >= 96%	Solar transmittance (AM1.5)	Average >= 96%
Thermal emittance (at 380 ^0C)	Average <= 14%	Type of glass	Borosilicate glass
External diameter	70 mm ± 0.2 mm	External diameter	125 ± 2 mm
Wall thickness	4.060 mm ± 0.2 mm	Vacuum gas pressure	<= 10^{-3} supporter by a getter

4.2 Collector field defects

The designed performance of collector's field in different seasons were much higher than those presented in Table 5. The collectors loop is designed to have 8^{o}C temperature differences of outlet with inlet at steady state condition. But according to tables 4 and 5, the actual thermal performances of collector loops are much lower than those expected. In this section technical and operation deficiencies which caused such unexpected low performance are discussed.

There are various parameters which influence low thermal performances of collector field of the solar power plant. The main elements are sun tracking and dust accumulation. In the following section these effects and their analysis are presented and their relative reductions of the collector field performance are determined.

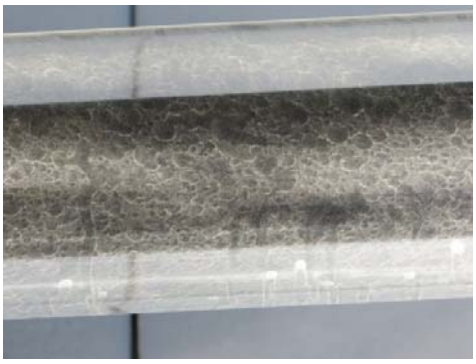
4.2.1 Sun tracking

Imperfect tracking is the most effective factor that influences the overall efficiency of the solar power plant. Thus, an investigation is performed to assess the operating system of tracking of each collector. The lower efficiencies presented in table 5 shows that, tracking is not efficient for the most days of the year. For instance, on average, half of the collectors have improper tracking performance in the spring 2010. This poor tracking performance has adversely affected the operation and efficiency of collector's field. Similarly, in summer 2010, more than half of the collectors have improper tracking condition. This means that the absorber tubes were not exactly in the focal points of parabola during the period that collectors follow the sun.

Sun tracking which, in turn, is affected by the accuracy of the instrument (transducer angle) that measures the sun (collector) angle [14]. The difference between the sun angle and collector angle influences the portion of reflected beams from the mirrors that are diverted the receiver tube. In Fig.8, only for 0.5 degree difference between sun angle and collector angles results in about 8% loss in the absorbed portion of reflected beams from reflecting surfaces. Such losses sharply rise for higher differences, which means that for 1.0 degree differences it is about 20%.

4.2.2 Dust accumulation

Due to local wind and weather conditions, dust accumulation take places on the glass tubes of collectors installed in Shiraz site (as illustrated in Fig 7-a and Fig. 7-b). Dust accumulation affects the optical properties of these components and consequently will reduce the amount of solar radiation absorbed by the collectors. (Table 6 depicts the optical properties for a clean collector of Shiraz Solar thermal power plant). Therefore, dust accumulation has adverse effects on overall performance of the entire system and should not be overlooked. In a comprehensive numerical study conducted by Niknia and Yaghoubi [9], these effects have been investigated. The amount of dust deposited on the collectors are measured and correlated to the overall performance declination of the system. Typical results of this study are presented in Fig. 8 which shows that only 0.75 mg/m^2 dust deposition can reduce the overall performance of a collector up to 40%.



(a)

(b)

Fig. 7. Typical condition of the mirrors and concentric glass tube with dust deposition; (a) cover glass tube; (b) mirror

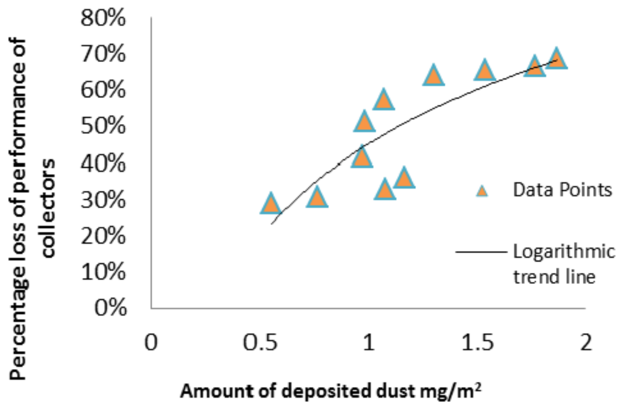


Fig. 8. Collector's overall loss of performance versus dust deposition, amount of dust (mg/m^2) [5].

5. Conclusions

In this paper, the operation of Shiraz solar thermal power plant for three years is investigated experimentally. Results show that:

1-Comparing thermal efficiency for spring and summer shows that the thermal efficiency of the collector's field is higher in summer due to higher solar radiation as expected. However, one may conclude that both dust deposition and climatic conditions can change the situation because of their high importance on thermal efficiency for different seasons of the studied years.

2- A suitable solar power plant should start operation as soon as possible to use solar radiation as much as possible and should have suitable storage system to minimize heat losses during night time.

3- The thermal efficiency of collector's field decreases considerable due to dust deposition over glass surfaces. The absorption of beam radiation decreases considerable due to dust accumulation.

4- Only 0.5 degrees differences between sun angle and collector tracking angle results of about 8% losses in the absorbed portion of reflected beam radiation. Such losses sharply rises for higher differences.

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