Analysis of Shiraz Solar Thermal Power Plant Response Time

K. Azizian, M. Yaghoubi, I. Niknia, and P. Kanan

Abstract—**Shiraz pilot solar thermal power plant is the first Iranian solar power plant constructed near the city of Shiraz, Iran. The main purpose of constructing this pilot plant was to acquire the technology of developing parabolic trough solar thermal power plants for future energy production from solar energy. This plant consists of 48 parabolic trough collectors; each one has 25m long and 3.4 m wide. The plant consists of two cycles, oil heat absorbing cycle and steam production cycle. The plant performance and transition period to reach steady state condition or damping some disturbances as well as oil cycle heating and steam generation rate depends on several factors such as oil cycle response time. Response time is a parameter that can be used for efficient control of solar power plant. To study response time, field experimental measurements have been made during the years 2009 to 2010 based on the standard procedure and plant simulation. The experiments include: plant start up, evaluation of oil temperature increase in the field of collectors, solar radiation measurements, temperature and pressure changes in the heat exchangers, weather temperature changes and wind speed and the effect of above changes on the system response time are determined. Two modeling methods (based on the recommended standards) of finding response time are employed. Results show that response time of the oil cycle varies from 150 seconds to 400 seconds by measurements, while by modeling simulation it is about 400-500 seconds. Response time is strongly depends on the environmental conditions such as oil temperture, wind and ambient temperature and specially the oil mass flow rate.**

Index Terms—**Oil cycle, parabolic trough, response time, shiraz solar thermal power plant.**

I. Introduction

One of the most important problems for industrial and developing countries in the upcoming decades is the replacement of fossil fuel energy sources with renewable energy technologies. Environmental pollutions, increasing price rate of fossil fuels and their limited sources has led to the development of new design and concepts for their replacement with cheap and available environmental friendly energy sources. Among renewable energy sources, solar energy is one of the most important and available source of renewable energy all around the world and especially in Iran.

Energy consumption in Iran has been increased from 739 crude oil million barrels in 1996, 1002 crude oil million barrels in 2006 and 1115.1 million barrels in 2009, and it is predicted that it will be reach to much higher values of crude oil million barrels by 2020 [1]. Due to increase of energy demands, providing new energy resources is one of the most essential government policies. Environmental issues significantly have affected patterns of energy consumption in Iran. Any future efforts to limit carbon dioxide emissions in the line of Kyoto protocol, by using renewable energy sources in the country would be very valuable. From a number of feasibility studies, Shiraz the capital of Fars Province in the southern part of Iran at latitude 29° 36′ N and longitude 52° 32′ E with 1550 m elevation from sea level [2], enjoys 3354 hours of sunshine annually with average daily irradiation of 20 MJ/m^2 [3] can be one of the best palaces for Solar Thermal power plant.

In Iran several projects are defined to use this source of energy [4]. Among them, Shiraz Solar Thermal Power Plant (STPP), with capacity of 250 kW, is the first parabolic trough solar power plant constructed and tested successfully at Fars province in the south of Iran. In this plant 48 parabolic trough collectors, which are oriented in 8 independent loops (each loop contains 6 collectors) for concentrating and absorbing solar energy. After the basic design and simulations [5-6], construction, installation and start-up of this power plant have been done to produce superheated water vapor. For this plant different studies and simulations have been done to find the overall performance of the plant [7-11].

After several tests and evaluations of thermal performance of Shiraz solar power plant, it is decided to construct and install a new collector and increase the capacity of the plant from 250kW to 500 kW [12].

A view of collectors' field is shown in Fig. 1.

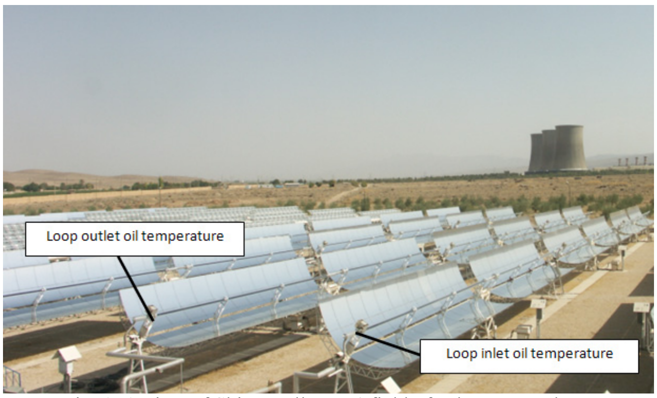

Fig. 1. A view of Shiraz collectors' field of solar power plant

II. Response Time

Measurement of response time for solar systems has been studied for some cases both theoretically and experimentally. In the researches carried out for obtaining the response time of solar thermal power plants, the main concentration has been on the selection of appropriate control procedure for

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obtaining high efficiency of the plant and appropriate reaction of the control equipment's of the plant to undesired disturbances. Some of the research done on this subject are control problem assessment and solving using MBPC (Model Based Predictive Control) concept in fuzzy control mechanism for solar power plant optimum controlling and developing a suitable control model for controlling the heat transfer fluid temperature in the collector field outlet, based on theoretical and practical methods and applying it an existing solar power plant.

Another subject studied by the NREL institute is the stabilization of various equipment of a parabolic trough solar power plant due to the changes in conditions such as sudden decrease of received radiation, stabilization of electricity generation of the power plant after start up and etc. Referring to [13], the response time for reaching a fixed outlet temperature from the collectors' field is 5.2 minutes and 8.3 minutes for the whole power plant based on modeling measurements. In this measurement main focus has been on the concept of inertia of the equipment and its effect on the controllability and reaching the steady state condition. Another research shows that CSPs (Concentrating Solar Power plants) have non-liner response time due to imposed environmental conditions [13].

Recently NREL has developed a detailed parabolic trough performance model within the SAM software tool. This model is capable of predicting solar field, sub-system, and component performance. A research has been done for comparing actual performance (for single collector field) and theoretical data (using modified SAM trough model) [14]. On the other hand test standards for parabolic trough collectors have been developed by both NREL, in conjunction with Kearney & Associates, and the ASME PTC-52 [15].

Recently a comparison between theoretical and experimental data has been done by Wagner and et al [14] based on capacity-based transient effects and also time response concept. No research has been done yet for measurement of response time based on ASME standard concept [16] and this is the first time that this method is used for Shiraz solar power plant. In fact the main concentration in the previous studies for Shiraz solar power plant has been simulation of the power plant, prediction of its performance in different conditions, performing various experiments on the equipments in order to compare between results and predictions and also some research on the plant troubleshooting. Based on these studies inertia concept (inertia of the equipments) has to be considered in the simulations. In fact the concept of response time discussed in this article was not considered in the primary design of the power plant but comparing the results of experiments with the simulations led the plant researchers to applying the concept and doing experiments in this regard. The most important result of these new studies is the improvement of control system of the power plant.

Response time for this plant is made as follows has a great effect on the plant performance if any of the following conditions happened:

1) Start-up of the plant and start of tracking and thermal oil temperature reaching the desired value for transferring to the steam cycle.
2) Collectors field out of service and the time of using heat capacity of the oil cycle for steam generation.
3) Trouble in tracking or any problem in the collector field.
4) Cloudy weather and low radiation leading to efficiency decrease of the collectors' field.
5) Changes in operational conditions due to some reasons such as weather conditions, problems in equipment performances, shocks such as sudden decrease or increase of oil flow and etc.

Apparently the more the response time, the more is the system resistance against changes. The less the response time, the lower is the system capacity and any of the above changes will have a great effect on the plant performance. Therefore the plant process control and consequently its higher efficiency would be highly dependent on the response time.

Collector field, Fig. 1 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 and the plant would not be able to generate electricity without an efficient collectors' field. Controlling the temperature of the collectors' field is a function of heat capacities of different components of the plant, control system and instrumentation of the plant. Before starting to investigate the response time of Shiraz solar power plant, the terms used in this article will be introduced as follows:

Transferred energy: is the rate of absorption of the energy received by heat transfer fluid, such as:

$$Q=\dot{m}Cp\,\Delta T \tag{1}$$

where Q is heat transfer rate, $\dot{m}$ is mass flow rate, C_p heat capacity and finally ΔT refers to difference between oil inlet and outlet temperatures. Response time is the required time for ΔT to reach 10% of its initial value provided that the collectors do not receive any radiation (collectors are shaded). In other world according to ASTM Standard definition, response time is the time required for ΔT to decline to 10% of its initial value after the collector is completely shaded from the sun's ray.

In the following section, approximate response times are calculated for the collector field by two methods. One method is the measurements for some loops of the collectors' field and the other method is based on a transient modeling and the results are compared and discussed briefly.

Before starting measurements and during the experiment, at certain intervals the followings should be checked [16]:

1) The oil inlet temperature to the collectors shall be kept at ±0.2 °C or 1٪ of temperature change between liquid inlet to/outlet from the field (whichever is higher).
2) The oil outlet temperature from the collectors shall be kept at ±0.2 °C or 1 ٪of temperature change between liquid inlet to/outlet from the field (whichever is higher).
3) Variation in product of mass flow and heat capacity ($\dot{m}$Cp) shall be less than 1%.
4) Variations of radiation received shall be less than 4%.
5) Variations in ambient temperature shall be less than 2°C.
6) Minimum received radiation 800 W/m^2 and the

difference between maximum and minimum received radiation shall be less than 200 W/m^2.

7) Wind speed shall be less than 4 m/s.

Response time is calculated by covering a series of collectors under radiation in the following method. These conditions are based on the standard conditions provided by ASME [16], with slight changes. First, the inlet temperature of working fluid is brought to ±10 ° C of ambient temperature or the maximum allowable working temperature (whichever is higher). Then the flow of working fluid is brought to the allowable value specified in experimental conditions and semi-steady conditions are provided for the system operation. In this condition, radiation is suddenly lowered form collectors. Inlet/outlet temperature of the collector field is checked accurately then and saved every minute. Response time is the required time for ΔT to reach 10% below its initial value in these conditions.

Response time of Shiraz solar power plant has been also calculated by numerical modeling. In order to model the response time, using the developed software for this research, a loop of collectors has been chosen from the software and modeled based on the conditions described for standard experiment conditions by using TRANSYS 16 Library and STEC components library source code. TRANSYS contains a number of components used for modeling different power plants. STEC is a TRANSYS model library for solar thermal electric components. Some of the more specific components used to model the current system such as evaporator and turbine are selected from STEC components library source code developed by Schwarzbözl [17]. The source codes of these components are imported in TRNEDIT which provides an editable environment for reprogramming. The computer code is modified to meet the specifications of the studied system and the rest of the required components are defined by programming in TRNEDIT environment [18].

A computer code is prepared to model the performances of such collectors for different working conditions. The code was developed in the TRNEDIT environment of TRNSYS software [19]. The code is developed for an evacuated tube of a parabolic trough concentrating collector based on (2):

$$\dot{Q}_u = A_c[F_R(\tau\alpha)_n I_t - F_R U_l \Delta T] \quad (2)$$

where $\dot{Q}_u$, A_c, F_R, $(\tau\alpha)_n$, I_t, U_l, ΔT refer to useful energy gain, collector area, collector heat removal factor, normal transmittance absorptance, incident solar radiation, collector overall loss factor from absorber to ambient and temperature difference respectively.

Due to the possibility of maintaining specified radiation intensity, ambient temperature and other standard conditions for computational modeling, are imposed to the model for subsequent calculations. Based on this concept, two independent models are considered for calculating the response time. In the first method the conditions are imported to the model based on ASME standards [15] and in the second method the real site conditions are considered for calculations in the specified modeling of the plant [18]. Also parallel with modeling, five independent experiments are carried on Shiraz solar power plant to measure the response time for various dates and environmental conditions.

III. Experiments

Shiraz Solar Power plant collectors' field consists of 8 separate loops each is equipped with temperature and flow measurement instruments. Temperature accuracy is about ±0.5 ˚C and for the flow meters it is about ±0.1 kg/s. For measurements the system starts with tracking the sun and collecting heat. The system followed the sun to warm the oil in the oil cycle and to reach an appropriate level of temperature as much as possible. In order to calculate the response time for the plant by experiment, 3 independent loops have been chosen. Loops 1, 2 &4 of Fig. 2 have been considered because of having accurate transmitters for checking temperature and oil flow rate and also due to better tracking conditions.

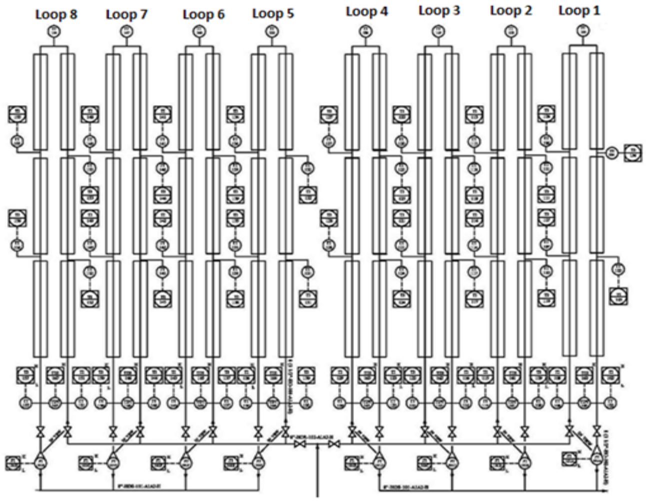

Fig. 2. A schematic of collectors loops of Shiraz solar power plant

A loop has been chosen instead of one collector because all collectors in Shiraz solar plant are not equipped with temperature and flow transmitters. Semi-steady conditions cannot be reached easily here due to the constant changes of weather conditions such as temperature and radiation and oil inlet/outlet temperature to the collectors' field. But as the oil temperature reaches its maximum value, oil inlet conditions to the collector field is fairly more stable and temperature variations are less, therefore maximum oil temperature is considered as the starting point of the experiment. For constant tracking in semi-steady conditions, experimental period have been chosen to have clear sky with no clouds. Since covering the collectors were impossible, stop tracking would stop direct radiation as well. In this case diffuse radiation reaches the collectors that would be considered as experimental error. The experiments are made with the above mentioned conditions for 5 different days and when the oil reaches its maximum temperature and tracking stopped the experiment started. Experimental conditions and results are shown in tables I and II. As shown in table I, the experiments are started when the collectors' inlet temperature reached to the values in third column (the times in the second column is in hour: minute format). It should be mentioned that the collectors' inlet temperature are equal values which are referred in table I (for the prescribed experiments the outlet temperature is not recorded).

IV. Modeling

Two types of modeling based on the boundary conditions have been considered. One is exactly based on the standard conditions and the other one is based on the conditions similar to the power plant operating condition. First the method of modeling: Conditions for the first method have been considered based on the ASME standard. In this condition, ambient temperature is 30°C and oil inlet temperature to the field is 35°C. Radiation of 800 W/m^2 is considered by the software and suddenly radiation is stopped after stabilizing the oil temperature outlet from the field. The time duration for the oil temperature difference at inlet and outlet to reach 10% of its initial value is reported.

TABLE I: Experimental Conditions for Response Time of Collector Field

	Collector Unfocusing Time (hour: minute)	Mass Flow (Kg/s)	Collector Field Inlet Temperature (°C)	Ambient Temperature (°C)	Average Wind Velocity (m/s)
First Test 2010/10/17	15:55	13.6	248	29	1
Second Test 2010/11/3	15:53	13.5	240	24	6
Third Test 2010/11/24	15:53	13.5	206	16	2
Fourth Test 2010/12/1	16:05	14.2	184	15	3.2
Fifth Test 2010/12/12	15:42	13.3	223	17	3.8

TABLE II: Response Times Measured from Experiments

	1st Test	2nd Test	3th Test	4th Test	5th Test
Loop1	219	125	138	244	390
Loop2	227	183	233	257	370
Loop4	174	122	203	270	330

This condition is similar to the 1st and 5th experiments (except for inlet temperature). A parametric research has been done on the oil flow and response time for different flow conditions. Results are shown in Fig. 3.

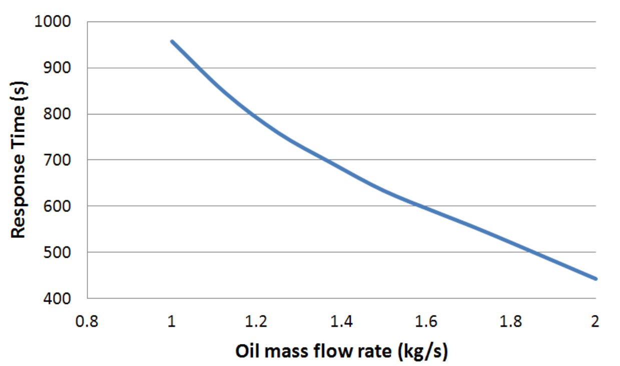

Fig. 3. Responsetime of collector field vs. flow for the first type of modeling

Results presented in Fig. 3 show that increasing flow in a loop leads to decrease of response time for the collector field. The main mechanism of heat loss from the plant components to the cold media (ambient) is convection heat transfer. Heat transfer coefficient increases by increasing fluid velocity (due to high mass flow rate), so when the fluid rate increases in every loop, heat transfer between loop components and ambient increases respectively, which leads to the rapid increase in the temperature fall of the components and consequently decrease of response time.

Response time is the required time for temperature difference between inlet and outlet fluid to reach 10% of its initial value. Above clarifications show that the energy reserved in the components is given to the fluid and it takes some time for the absorbed energy to transfer to the fluid and the surrounding ambient. The energy reserved already in the components is limited and will be transferred to the passing oil and ambient and they become colder. Regarding relation (1), and the fact that this energy is limited, the more the flow increases the less will be the difference between inlet/outlet temperatures of the system. Moreover, increasing the flow will lead to increasing heat transfer coefficient of hot oil with the components.

Typical modeling of time variation of cycle oil inlet and out temperature with respect to time after system shut down is illustrated in Fig.4. Comparing the results of modeling with experiment shows that for flow of 1.75 kg/s, results of modeling and experiment are different. In the modeling, the response time of 540 sec is determined, but for different experiments response time is between 125 sec to 370 sec for different days. The main reason for this difference is non-conformity of experimental conditions with standard modeling conditions. For example ambient conditions are changed during the experiment and scattered radiation to the field cannot be avoided. But more important is the method of measuring the time. In modeling, the inlet/outlet oil temperature to the field is quite steady before stopping the radiation. Fig. 4 clearly shows the steady inlet/outlet temperatures before stopping the radiation. But experiment will not provide such ideal conditions and additionally semi-steady conditions can't be reached in experiment, because ambient conditions are uncontrollable but in modeling semi-steady conditions can be reached with high accuracy.

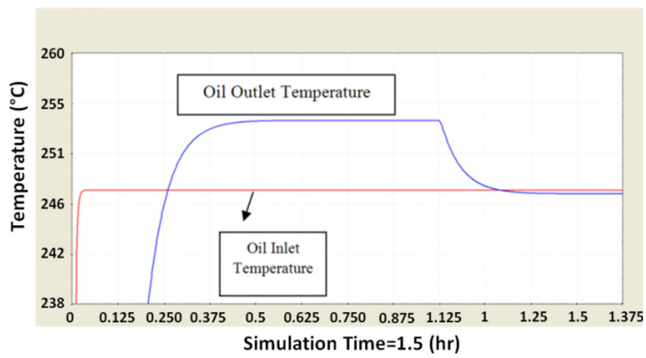

Fig. 4. Variations of inlet/outlet oil temperature of one experimental loop to check response time (modeling)

In the second method, conditions have been chosen near the experimental conditions, by means that experimental conditions of ambient temperature, radiation, wind speed and oil cycle temperature and flow rate have been carefully modeled. So the oil inlet temperature to the field is considered 248°C in line with the experiment and after reaching the maximum oil outlet temperature, radiation is stopped and response time for different flows are compared.

Results of the two scheme of modeling are shown in Fig. 5.

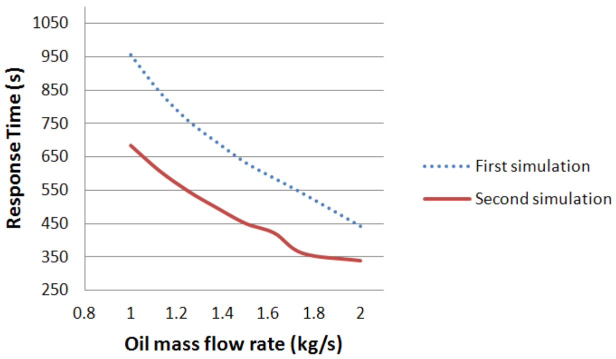

Fig. 5. Comparison of response time for two conditions of modeling

Fig. 5 shows that, in the second method the response time of the collector field is near the values obtained from experiments. This was expected because in the second method most of the parameters affecting experiment results are controlled and applied in the modeling. In the second modeling, the response time of 360 sec is obtained for the flow of 1.75kg/sec that is still more than the first experiment. For example, conditions of experiments 1, 2 & 5 of Table 1, are near each other compared to the other experiments but their response times vary between 125 to 390 seconds, which may be due to the cloudy condition, wind effect and experimental errors. The result of modeling is 360 seconds that seems to be in good range.

The important issue is the variation of inlet temperature to the field during experiment. In the modeling this temperature is properly controlled but during the experiment this temperature cannot be controlled easily. This could be another source of difference between results of modeling and experiment that cannot be easily removed.

Finally comparisons of experimental and theoretical results are shown in Fig. 6.

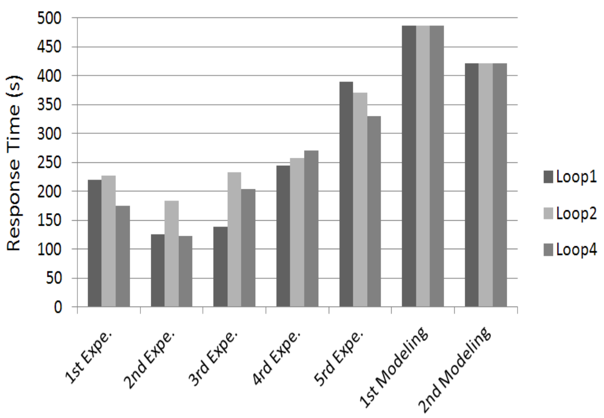

Fig. 6. Comparison of response time from modeling and experiments (according to Table I)

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