

SHIRAZ PILOT SOLAR THERMAL POWER PLANT DESIGN, CONSTRUCTION, INSTALLATION AND COMMISSIONING PROCEDURE

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ABSTRACT

Solar energy is a sustainable form of energy, which has attracted more attention during the recent years. There are numerous techniques for the effective conversion of the sun's energy to electricity. One of these techniques is solar thermal power plant with parabolic concentrators. Iran has a great deal amount of land located on the belt of the world's sunshine and is one of the countries which has a substantial amount of good solar irradiance. With tremendous renewable energy potential, environmental interest, as well as economic consideration of fossil fuel consumption and high emphasis of sustainable development, the Deputy Ministry of Energy of Iran defined, support and installed the first 250kW pilot solar of thermal power plant in Shiraz, Iran. All components of this plant are designed and constructed by local manufacturer, except the receiver tubes which are supplied by SCHOTT company. In this paper the power plant construction progress and system performance which is measured experimentally are presented. The power plant control is based on a control philosophy that is developed specially for this power plant. Results of field operation shows that high temperature of 265 °C for oil and high temperature and pressure of superheated steam (250 bar) can be supplied which are close to the design conditions. Such superheated steam can be used for electricity generation and other application of the relevant industries. The main achievement of this project are the development of large commercial parabolic trough collectors' design and manufacturing of oil and steam cycles, design of collectors' field, design, implementation of control system and producing superheated steam.

INTRODUCTION

Energy is essential to the economical progress, social development and improved quality of life all around the world. Much of the world's energy, however, is currently supplied mainly by fossil fuel and consumed in ways that could not be sustained if technology remains the same and if overall consumption increases substantially. To control atmospheric

emissions of greenhouse and other gases and substances, improvement should be made to increase efficiency in energy production, transmission, distribution and consumption in the world. Today because of population growth rate, world energy demand increased. Due to reduction of the present energy sources, finding new energy sources is one of the most strategic governments' policies. World energy usage has been increased from 100 Exsa Joules in 1960 to 485 Exsa Joules in 2004 and it is predicted to reach 700 Exsa Joules in 2020 [1]. Substituting of present energy sources with sustainable source is one of the priorities of humankind. It is predicted that the share of energy supplying of sustainable sources will increase from 50 Exsa Joules in 2000 to 135 Exsa Joules in 2020 [1]. Among many renewable sources, solar energy is one of the most important type of sustainable energy.

The sun offers on average radiation flux density of 343 W/m² of which about 70 percent are absorbed by the earth system. These remaining 237 W/m² reach to a large part the surface, namely 165 W/m². In comparison to mankind's energy flux density of about 0.03 W/m² the sun's offers at the surface is by a factor of more than 5000 higher [2]. One of the most popular usages of solar energy is for electricity generation. Among many ways, concentrated solar thermal power plants are one of the promising future renewable energy technologies. Currently 604 MWel are in operation, 761 MWel in construction, and 5.780 MWel in the planning phase [3]. Currently, concentrating solar power technologies are one of the most effective methods of generating electricity through renewable energy capabilities, particularly for countries with high irradiation. They provide an option for future clean energy production without adding to concentrations of atmospheric greenhouse gases or contributing to negative climate impacts. Of the four CSP technologies: parabolic troughs, central receiver systems, dish/Stirling systems and linear Fresnel reflectors, parabolic troughs are the system which has been used widely in commercial plants. Parabolic troughs are also the most technologically proven of all the solar energy production systems to date, primarily due to the development of nine American solar power plants built

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during the 1980's and 1990's by Luz International Limited and still in operation today. These sites are located in the Mojave Desert, California [4]. More recently a little more than 100 MW were added in Spain and USA and even more is expected that new projects around the world will help open an aggregate market [5].

Energy usage in Iran has been increased from 739 crude oil million barrels in 1996 to 1002 crude oil million barrels in 2006 and it is predicted that it will be reached to 1026 crude oil million barrels in 2020[6]. Due to increase of energy demand providing new energy resources is one of the most essential, government policies. Similar to the rest of the world, global environmental issues significantly affected patterns of energy use around the world, and in Iran. Any future efforts to limit carbon emissions in the line of Kyoto protocol, by using renewable energy sources in the country would be very valuable in this regard. From 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 has received the top rating among several sunny locations in the country as the most favourable site for a solar thermal power plant installation [7]. Shiraz enjoys 3354 hours of sunshine annually with average daily irradiation of 20 MJ/m². After lessons learned from the solar thermal power plants built during 90s this pilot design is proposed to produce 250 kW of electricity. It has been suggested by the Deputy Ministry of Energy of Iran to define, support and install the first pilot solar power plant in Shiraz, Iran [8]. The characteristics of plant are listed in Table 1 [9].

Table1 Characteristics of Shiraz Solar Power Plant

| Capacity | 250 kW | Electricity generation System | Turbine+ Generator |
|---------------------------|------------------------|----------------------------------------|--------------------|
| Collectors type | Parabolic trough | Collector field inlet oil temperature | 231°C |
| No. of collectors | 48 | Collector field outlet oil temperature | 265°C |
| Collectors' dimension | 25×3.4 m | Oil mass flow rate | 13.7 Kg/s |
| Collectors' driven System | Hydraulic | Steam mass flow rate | 0.673 Kg/s |
| Collectors' structure | Truss with torsion bar | Generated steam temperature | 250°C |
| Heat transfer fluid | Thermal oil | Generated steam pressure | 20 barg |

DESIGN AND CONSTRUCTION

After basic and detail design of power plants' parts, construction and installation of facilities begun. The most important activities that have been done during design and construction procedure are:

1-Design and manufacturing of solar collector including collector structure, mirrors shaping, collectors' driver system and also so many scientific simulation and tests like collectors moving, wind effects on collectors and etc[10-11].

2- Developing of control philosophy of collectors' field and oil cycle [12].

3- Design and manufacturing of oil cycle main parts like heat exchangers, expansion and storage tanks, piping and utility system [13].

4- Simulation and optimal assessment of oil and steam cycles based on basic design and optimal control of plant [12,14].

5- Design simulation and construction of steam cycle[15].

6- Thermoeconomic analysis of power plant[16]

A schematic of oil and steam cycle of Shiraz solar power plant is shown in Figure 1.

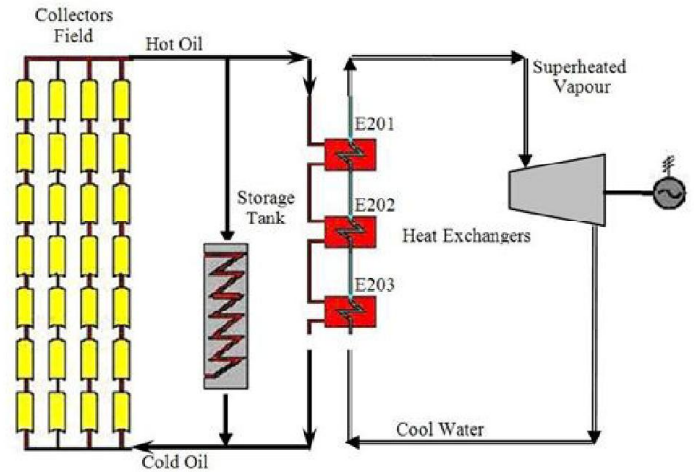


Figure 1 Schematic of oil and steam cycle



Figure 2 Laser beam testing for decreasing surface inequality errors

In addition of those activities some experiments and test have been done for improvement of plant facilities performance and decreasing the total errors of collectors parts (like mirrors slope error, mirrors surface inequality, receiver tube displacement and tracking error) with laser beams test on each shaped glass (before mirroring procedure) such as shown in Figure 2.

CONSTRUCTION

Based on the basic and detail designs, the power plant manufacturing and installation of oil cycle parts were begun. After performing civil activities, the first installed parts of the oil cycles were collectors' structures and continuously the rest part of the oil cycle like pipes, heat exchangers, tanks and utility system. The most complicated installation procedure were the mirrors and receiver tubes mounting. Due to high accuracy requirement of mirrors and receiver tubes locations (because of effective impacts on the collector optical efficiency) these were the last part with new installation procedure developed locally. In Figures 3-4 installation of power plant parts and a view of collectors' field are shown.



Figure 3 Installation of heat exchangers, valves, mirrors and absorber tube of Shiraz Solar Power Plant



Figure 4 A view of collectors' field

Figure 5 shows details of absorber support and flexible bracket which can rotate during expansion of absorber tube. In Figure 6 a collector from back side is shown. The torsion bar and specially designed mirror supporting frame and joints are visible.

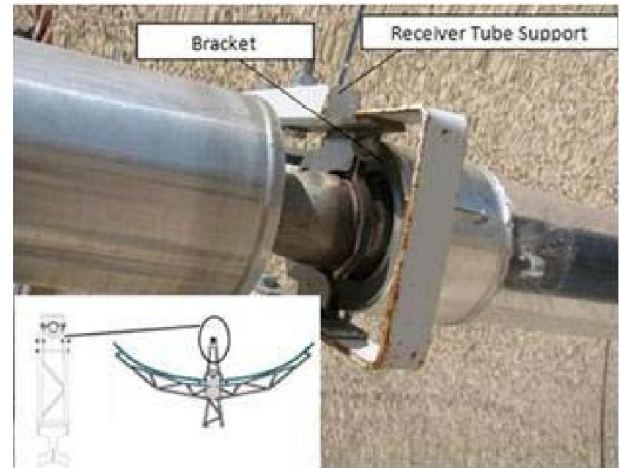


Figure 5 Absorber support and bracket



Figure 6 View of collector from back side

PRE-COMMISSIONING AND COMMISSIONING

After installation of all facilities of the oil cycle (including collectors, heat exchangers, pipes tanks, etc), due to high importance of collectors, it was decided to assess collectors' performance. Therefore a loop of collectors' field is isolated from the rest of collectors' field. A heat exchanger, a pump and an expansion tank are used to complete a closed, cycle. The final goal of this test was demonstration of optimal and effective operation of collectors which have been found successfully. A view of the tested loop with supplementary equipments is shown in Figure 7[8].



Figure 7 A view of tested loop

After successful evaluation of collectors' performance it was decided to commission the complete oil cycle. Pre-commissioning performed initially which includes oil flushing of all plant parts like pipes, heat exchangers, receiver tubes, and tanks etc, based on the power plant operation manual, and commissioning of oil cycle is started next. The commissioning of oil cycle was done based on the collectors and oil cycle control philosophy [12]. Within the philosophies, oil flows in a closed cycle up to warm up to 230°C then it will be directed to the heat exchangers, shown in Figure 1, for warming up them and steam generation. A storage tank also is provided for supplying hot oil (which is stored during noon when the received solar irradiation is at maximum levels), when solar irradiation going to decrease [12].

After commissioning of the plant it was decided to test and evaluate the plant performance and also detecting the defects of the system. During commissioning, Shiraz Solar power plant faced with several problems and defects like broking of collectors' mirrors, increasing of tracking error because of hydraulic driver systems and recently the bending of receiver tubes. As shown typically in Figure 8, receiver tube of collectors is thermally simulated. During tracking the absorber bends and it is no more in the focal point of mirror. Typical displacement of absorber tube with respect to the glass cover is shown in Figure 9 and Table 2. Table 2 shows typical displacement for three different collectors. It should be noted that from 48 collectors only three collectors are selected. For each collector 3 segments of absorber tubes' orientation are shown in this table. Each collector has two part, each part has 3 tube segment. Many efforts have been carried out for analyzing and solving this problem, by simulation of receiver tube, thermal stress analysis and field measurement and adjustment.

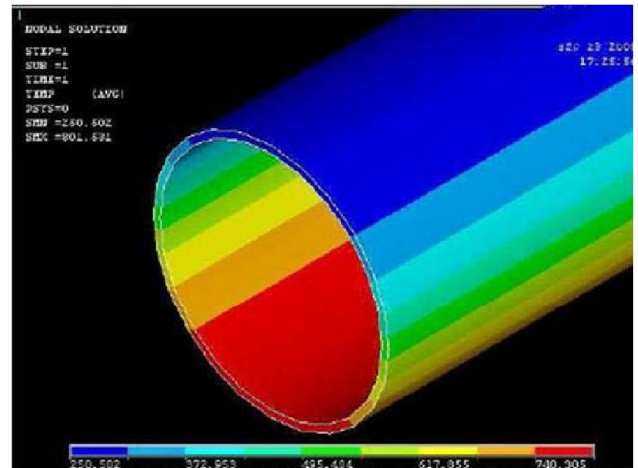


Figure 8 Thermal stress analysis of receiver tube



Figure 9 Closing of metal part of receiver tube to glass

Table 2 Local displacement of receiver tube of collectors with regard to glass cover

| Segment Number | | | |
|------------------|---------------------------|---------------------------|---------------------------|
| Collector Number | 1 | 3 | 5 |
| 3 | Up East ● West Down | Up East ● West Down | Up East ● West Down |
| 27 | Up East ● West Down | Up East ● West Down | Up East ● West Down |
| 45 | Up East ● West Down | Up East ● West Down | Up East ● West Down |

During many experimental observations it is found that the main reason of the receiver tube bending was non-uniform heat flux on the tube surface. The lower part of tube which receives the main part of solar reflected energy absorbs more heat than the upper part which causes that the upper part expands less than the lower part and finally it cause the absorber tube bending. Analysis demonstrated that the main reason of these phenomena is the low value of convection heat transfer coefficient between oil and inner wall of the receiver tube. Based on the oil cycle control philosophy oil flows in a closed cycle (which including collector fields) till warms up [12,17]. When solar irradiation is low for increasing warming rate, mass flow rate of oil should be decreased and consequently flow velocity and the Reynolds number will decrease. This reduction will led to decreasing of Nusselt number and convection heat transfer coefficient. In addition Re and Nu numbers decrease with oil temperature decreasing. Therefore convection heat transfer coefficient won't be adequate for increasing heat transfer between oil and receiver tube and hence the tube bending will occurs. Convection heat transfer coefficient variation versus temperature for various oil mass flow rate is shown in Figure 10. Convection coefficient of less than 500 w/m^2K during high solar radiation of 1000 w/m^2 may even bend the tube and contact between absorber tube and glass cover may occurs the broken down of glass protection.

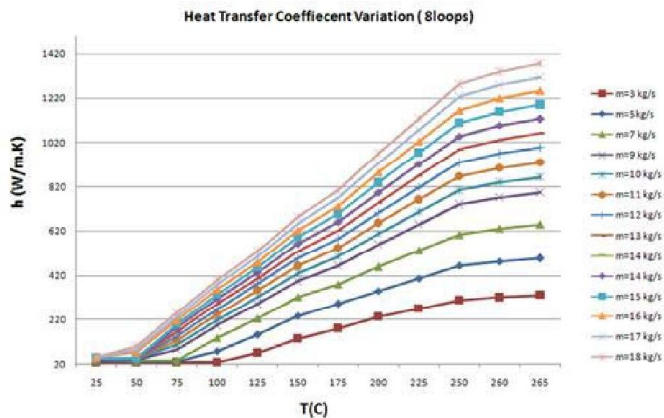


Figure 10 Convection heat transfer coefficient variation vs. oil temperature for various oil cycle flow rate

After commissioning the plant, regular data acquisition of the plant is performed. Fortunately gathered data in Figures 11-13 confirmed the design conditions of plant.

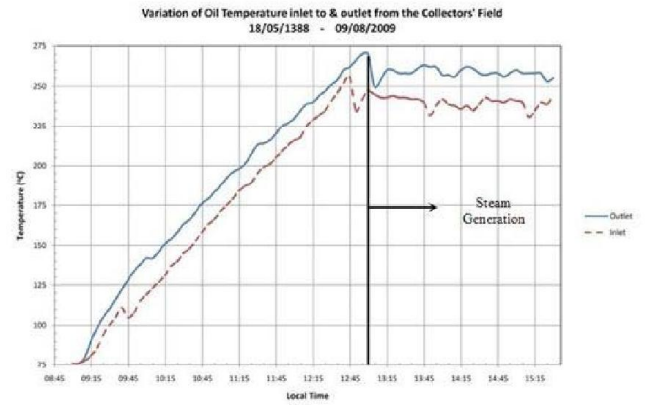


Figure 11 Variation of collector field inlet and outlet temperature with respect to time

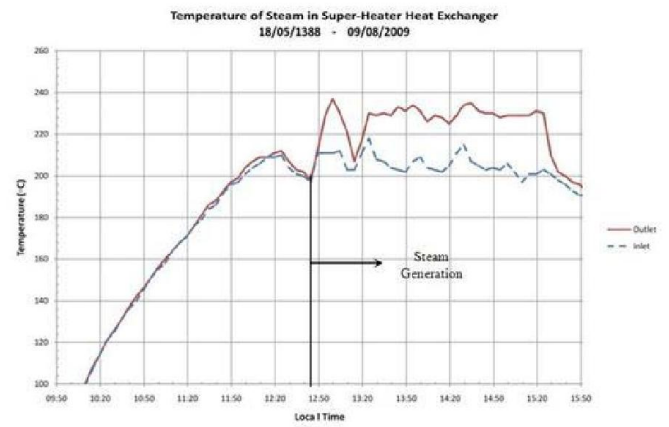


Figure 12 Variation of vapour temperature in superheater with respect to time (E-203)



Figure 13 Variation of outlet steam mass flow rate with respect to time

As shown in Figure 11 oil temperature rises to 272 °C and then decreased to about 265 °C because of steam generation started in the heat exchangers. It then remain constant (the fluctuations is result of non-linear performance of control valve). This problem is under consideration to be solved based on oil cycle control philosophy [12]. Figure 12 shows the generated steam temperature variation during a day. As shown in this Figure at the begging of the test the steam temperature in the inlet and outlet of heat exchanger is the same but around 12:50 o'clock of local time the outlet temperature begins to increase which is due to entering the hot oil into the heat exchangers (before 12:50 the superheater exchanger was isolated by a by pass path). Finally in Figure 13 variation of generated steam mass flow rate is shown. As seen in this Figure, mass flow rate of steam production fluctuates because of oil mass flow fluctuations.

In Figure 14 direct and horizontal global radiation for Shiraz on August 9th 2009 is shown and results presented in Figures 11-13 are based on such solar radiation intensity during the testing period.

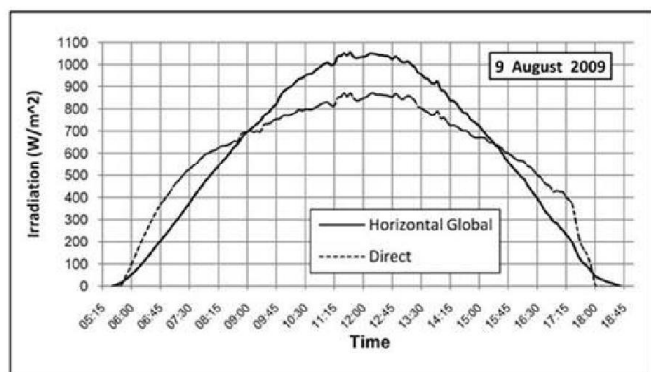


Figure 14 Direct and horizontal global solar radiation in Shiraz for 9th August 2009

CONCLUSION

Replacing fossil fuels sources with renewable sources is one of the governments' inevitable policies in future. Iran is one of the countries with high available renewable energy sources in Middle East and even in the world. Shiraz solar power plant is one of the pilot plant which has been constructed and successfully tested for accessing parabolic trough collectors technology. This kind of solar power plant system are under construction in several parts of the world in large commercial scales. According to the tests, the generated superheated vapour (250°C and 22 barg) which satisfied the design conditions can be used for several usages like electricity generation, distilled water production, cooling and ventilation purposes and etc. During the tests many system defects have been detected and some of them were solved but for more and complete achievements of solar parabolic trough collectors technology it needs to do more and different tests (which are under construction) and also more investments in using of solar energy for other applications.

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