Design analysis for expansion of Shiraz solar power plant to 500 kW power generation capacity

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Abstract: Various projects have been developed to use solar energy and some of them are in the course of developing all around the world. In Iran a 250 kW pilot solar power plant is constructed using parabolic trough collectors from 2001 to 2006. Results of thermal tests of the plant leads to the generation of steam with 250 ^{o}C temperature and 2 MPa pressure. Based on several years of experiments (from 2006-2010) it is decided to expand the solar thermal power rate to produce 500 kW electricity by combining the present system with a larger size collector and an auxiliary boiler. This article, explains the thermal design of the new collector and then various design options for combination of the new collector to the present plant have been studied and the most practical method of producing 500 kW is selected applying first law of thermodynamics utilizing a hybrid system.

Keywords: *Solar power plant, Shiraz solar Thermal Power Plant (STPP), solar parabolic collector, plant expansion*

1. Introduction

One of the most important problems for industrial 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 them solar energy is one of the most important and available source of renewable energy all around the world and especially in Iran. The use of solar energy is daily growing in different fields such as generation of electricity [1]. In Iran several projects are defined to use this source of energy along with other countries of the world [2]. Among them, Shiraz solar Thermal Power Plant (STPP) is the first parabolic trough solar power plant constructed and tested successfully at Fars province at south of Iran. After the basic design and simulations [3-4], construction, installation and start-up of this power plant has been done to produce superheated vapor. For this plant different studies and simulations are made to find the overall performance of the plant [5-11]. Table 1 shows general specifications of the 250 kW STPP(Refer to [12] for more information on existing system operation).

After the successful` testing of this parabolic solar power plant (from2006-2010), it is decided to promote the system with advanced technologies and use an advanced parabolic trough collector for steam generation. This is made by beginning the constructing and installing a new parabolic trough collector with larger dimension and combining it with the existing system while increasing the power rate to 500 kW. The existing 250 kW Shiraz solar power plant, having been successfully tested for steam generation, uses old design, small parabolic trough collectors. Achieving the technology of parabolic trough collectors in the 250 kW power plant the following decisions were made:

1- Design and construction of a new collector, in the same dimensions as used in the new solar power plants of the world (such as Andasol plants).
2-Electicity generation

Table 1. Specification of 250kW Shiraz solar thermal power plant

Capacity	250 kW	Electricity generation System	Turbine+ Generator
Collectors Type	Parabolic Trough	Collector's Field Inlet Oil Temperature	231°C
No. of Collectors	48	Collectors Field Outlet Oil Temperature	265°C
Collector's Dimension	25×3.4 m^2	Oil Mass Flow Rate	13.7 Kg/s
Collectors' Driven System	Hydraulic	Steam Mass Flow Rate	0.673 Kg/s
Collector's Structure	Truss with Torsion Bar	Generated Steam Temperature	250°C
Heat Transfer Fluid	Thermal Oil	Generated Steam Pressure	2 MPa

These steps would lead to an increase in power plant capacity from 250 kW to 500 kW and at the same time design and construction of a new collector in length of 94 m and aperture width of 5.27 m. The main problem in the way of developing the power plant (except for the cost increase due to low capacity of turbo-generator system and high price of electricity generated) id the method of combining the new collector with the existing system. Due to the high operating temperature of the new collector compared to the existing system, optimal usage of the absorbed heat is the most important issue in the process of combining the two system of heating the old cycle primary fluid (oil) or its secondary fluid (superheated steam) or a combination of the two above. In addition to the above mentioned issue, the next step would be the selection of the appropriate turbo-generator considering the efficiency and price at the same time. Some explanations in this regard will follow. The most important equipment in the existing plant include the parabolic trough collectors field, heat storage and expansion tanks, three heat exchangers, deairetor and etc. To achieve the 500 kW power generation the equipment that shall be added to the system would be the new 100m collector, turbo-generator, storage and expansion tanks, fossil fuel boiler and condenser. In the following sections further explanation and results of thermodynamic analysis of the new design system are presented.

2. Design of new parabolic trough collector

After preliminary assessments [12] it was decided to construct and install a new collector and increase the capacity of the plant from 250kW to 500 kW. Based on these available technologies the design of the new collector of Shiraz solar power plant is made by following steps:

1-Thermal and thermodynamic design of collector
2-Design of structure and hydraulic system
3-Design of control and tracking system

2.1. Thermal design of Shiraz thermal solar power plant (STPP) with new collector

For thermal design and simulation of the new collector a program has been developed with Matlab software [13]. This program takes some primary data into account such as collector rim angle, optical properties of the mirror like its thickness and reflectance coefficient, errors in construction and installation of the collector, temperature of inlet and outlet of oil from the collector, temperature rise in the collector, date and day of design and its relevant data such as cloud factor, wind speed and ambient temperature, geographical location of the design point and length of the collector. Some other information for the receiver tube such as absorbtivity coefficient of the tube, transmisivity coefficient of the glass tube, thickness of the glass cover tube and its diameter would be considered as input data to this program. The input data screen of software is shown in Fig.1.

Fig. 1. Data input of developed collector design software

The output of this simulation program include the total optical error, concentrating ratio, direct radiation (based on Daneshyar model[5]) effective length , oil mass flow rate, optical and thermal efficiency, heat loss and heat absorbed in each m^2 of the receiver tube surface. The allowable total error for the design of collector is calculated based on [14].

Collector design is based on Rabl et al. [15] procedure. The details of calculation procedure are explained in [13]. The thermal design of the collector is made for September 23rd at in the noon time for Shiraz (with latitude of 29.53°). Solar radiation is modeled from [5] relations, wind speed is assumed to be 7 m/s and ambient temperature is considered 30^{o}C. Regarding the limitation of construction of collector structures hydraulic system and etc it is decided to construct a new collector parallel to the existing field of collectors, therefore the length of new collector is considered to be 100 m equal to the available space in the field. Results of calculation and specifications of the new collector of Shiraz solar power plant is presented in Table 2.

3. Combining the new collector with present system

The next step after designing the collector is to combine the collector to the present system showing in Fig 2. Regarding the differences between the oil used in the present collectors field (Behran thermal oil) and the new collector (VP1) and also the higher oil temperature of fluid in the new collector, combining the new collector to the present system need some considerations such as the transferring the absorbed heat in new collector to the secondary fluid (the oil in the present cycle or produced steam), selection of turbine type, new control philosophy, etc. Therefore it was decided to study the two important issues of the new cycle:

1- The way of using the absorbed heat (either transmitting the absorbed heat to the steam in order to superheat it or to heat the oil or a combination of these two).
2- Selecting the exhaust pressure of steam turbine.

Table 2. Specifications of the new collector of Shiraz solar power plant

Input Parameters			
Rim Angle(Degree):82	Length (m): 94	Absorber Tube Dia. (m): 0.07	Absorber Emmitance: 0.15
Absorber Absorbance: 0.94	Mirror Reflectance:0.90	Glass Transmittance: 0.9	σ- contour (mrad): 2.5
σ- specular (mrad): 2.5	σ- tracking (mrad): 3	σ- displacement (mrad): 3	T-ambient (K): 303
T-inlet (K): 567	T-rise (K): 19	Design Day: 23rd Sep.	Latitude Angle: 29.53
Output Parameters			
Avg. direct radiation (W/m2): 647.3	Avg. diffuse Radiation (W/m2): 84	Noon. Direct radiation (W/m2): 817.4	Noon diffuse Radiation (W/m2): 145.4
Concentrating ratio: 23.97	Mass flow rate (kg/s): 4.53	σ- total (mrad): 4.1	Mirror aperture width (m): 5.27

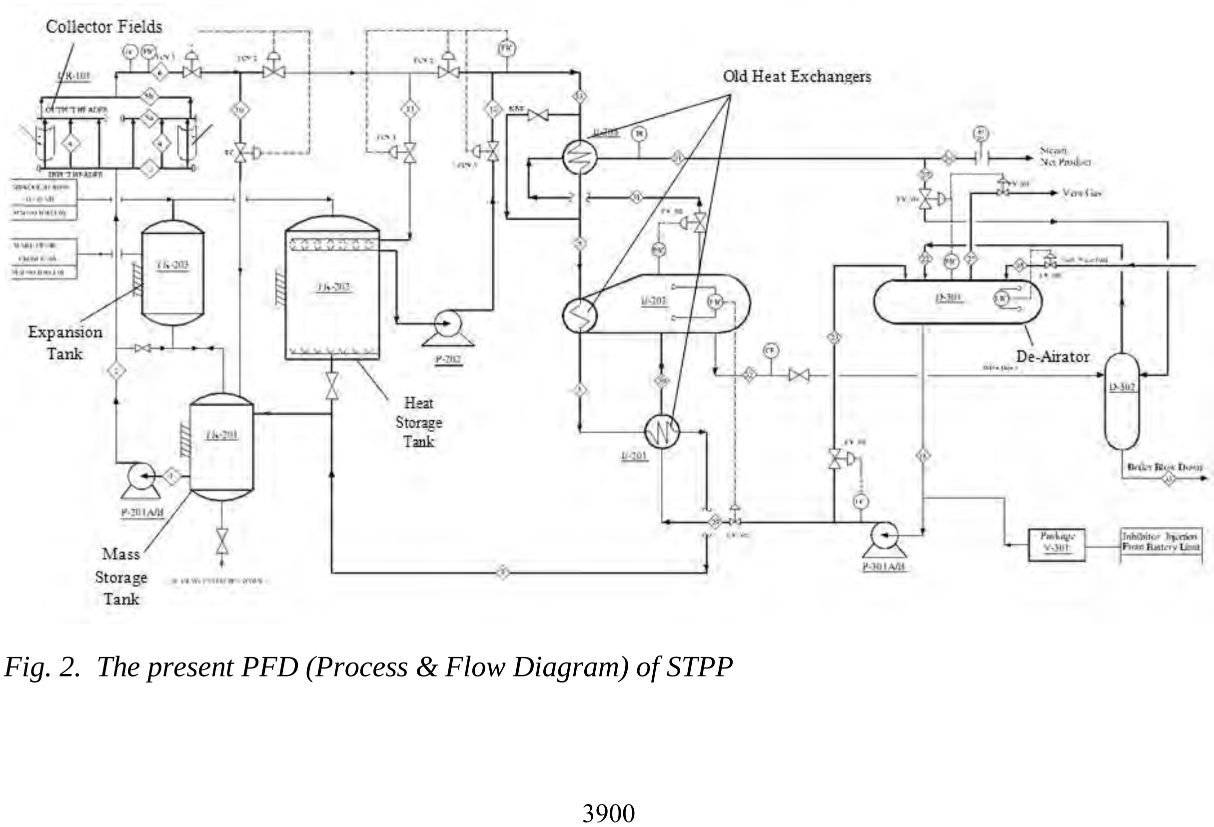

Fig. 2. The present PFD (Process & Flow Diagram) of STPP

Regarding the above objects, thermal design of the integration is made for two cases A and B. In case A, it is assumed that all the heat absorbed by the new collector would be transferred by an exchanger to heat generated steam in the present cycle and generated steam in the boiler, that leads to temperature rise of operating fluid in the new cycle. The heat absorbed will consequently lead to increasing steam temperature which leads to producing more electricity. In case B, the assumption is that a part of the heat absorbed in the new collector would be used to increase the temperature of superheated steam from the existing system and the rest of absorbed heat is used for heating up the outlet oil of existing collector field in order to increase the steam mass flow rate and consequently increasing the electricity generation. In this case 120 kW of the absorbed heat in the new collector is transferred to raise oil temperature and the rest (about 80 kW) will be used for superheating the generated superheated steam in the present cycle.

For each of the above cases 3 turbine outlet steam pressures of 100 kPa , 25kPa (using back pressure type turbine) and 10 kPa (using condensing type turbine) has been considered and the thermodynamic analysis for each case is carried out separately.

Considering the goal to produce 500 kW electricity power from the combination of the present plant and the new system, it is decided to add an auxiliary boiler to the system in order to compensate the superheat steam for generating 500 kW electricity and to provide possibility of using the power plant at night time. Fig. 3 shows results of thermodynamic analysis and condition for various cases studied. The estimated capacity for each equipment in each condition are provided in this table.

CASES		Farm Generated Steam			Boiler					Turbine					Condenser
		Temp (°C)	Press (kPa)	Flow rate (kg/h)	Working Capacity (kg/h)	Installed Capacity (kg/h)	Boiler load (%)	Press. (kPa)	Temp. (°C)	Considered Shaft Power (kW)	Inlet Press. (kPa)	Inlet Temp. (°C)	Exhaust Pressure (kPa)	estimated steam consumption (kg/h)	Duty (kW)
CASE A	100 kPa	250	2130	2399	3112	6000	52	2130	237	532	2100	294	100	5490	3429
	25 kPa	250	2130	2437	1951	5000	39	2130	215	532	2100	294	25	4095	2605
	10 kPa	250	2130	2486	1466	4500	33	2130	215	532	2100	294	10	3566	2286
CASE B	100 kPa	294	2130	2573	2912	6000	49	2130	294	532	2100	294	100	5467	3409
	25 kPa	294	2130	2573	1792	5000	36	2130	294	532	2100	294	25	4096	2605
	10k Pa	294	2130	2573	1336	4500	30	2130	294	532	2100	294	10	3558	2279

Fig.3. Results of calculators for the 6 primary plans cases

4. Selection of the appropriate plan

After considering the primary plans and the economical evaluation, one of the plans should be selected as the design plan. Each plan has some advantages and disadvantages. A list of the most important ones are summarized in Table 3.

The next step to choose a proper plan based on cost and other parameters. The most expensive equipments are condenser, turbine and boiler. Price quotations are gathered from local and international manufacturer for these three equipments. The relative cost with respect to case A of 100 kPa turbine outlet pressure is presented in Table 4.

Table 3. Results Advantage and disadvantages of case A and B

Case	Advantages	Disadvantages
A	Higher thermodynamic efficiency for exhaust pressure of 10 kpa Lower expenses due to use of a single heat exchanger Shutting down of present collectors there will be a possibility of using the heat absorbed by the new collector Boiler working at a lower temperature Lower boiler loss for lower exhaust pressures.	Dependency of electricity generation on the solar part Impossibility of complete heat absorption of the new collector in the system Impossibility of separating contribution of solar part & fossil fuel part power generation Un-available of the new collector, steam for turbine would not be at design condition Lower performance of one exchanger compared to two exchangers Impossibility of the new collector operation without boiler for produce power
B	Possibility of performance tests of new collector without boiler Equal importance of solar part and fossil fuel part Independency of solar and fossil fuel parts Possibility of electricity generation in case of an availablity of solar part Possibility of electricity generation with lower capacity in case that new collector is out of service Better performance of two exchangers compared to one exhanger Lower capacity of boiler in the exhaust pressure of 25 Kpa	Two heat exchangers needed Complicated control system With shutting down of present collectors field the new collector can be used to heat the oil in collectors field

Table 4. The relative cost of the new cycle for various cases

Case	Boiler	Turbine	Condenser	Total
A (Pout=100 kPa)	1	1	1	1
A (Pout=25 kPa)	0.8704	2.5129	2.0218	1.8140
A (Pout=10 kPa)	0.8055	2.5086	0.5523	1.4142
B (Pout=100 kPa)	1	1	1	1
B (Pout=25 kPa)	0.8704	2.5129	2.0218	1.8140
B (Pout=10 kPa)	0.8055	2.5086	0.5523	1.4142

One of the most important issue to be addressed before selection of a proper case is the type of condenser needed for the 3 exhaust pressures of the steam turbine. According to the estimations and calculations for turbine with 100 kPa and 25 kPa exhaust pressure the condenser needed could be air cooled type condenser, whereas for 10 kPa exhaust pressure, the condenser should be water cooled type. In case of using water cooled type condenser water a significant amounts of will be vaporized in the cooling tower.

According to Table 5, for the 3 items (turbine condenser and boiler) for each case A and B the final cost. A direct function of turbine price and consequently the boiler and condenser. Therefore it is observed that for both cases A and B for the different exhaust steam pressure the final cost is equal but regarding Fig. 3 the load of boiler in case of 10 kPa exhaust pressure is less than the case of 25 kPa exhaust pressure. In the same manner less than 100 kPa steam exhaust pressure, which would lead to lower fuel consumption and less fuel cost in the long term. But it must be mentioned that the weakness of 10 kPa exhaust pressure in comparison to the two other exhaust pressures is the requirement of water to cool the exhaust steam from turbine. Calculations show that the consumption of water in the power plant with capacity of 500 kW would be approximately 6.8 m^3/hr. Due to the great limitations of water in the present plant location and for most part of Iran the case B with an exhaust steam pressure of 25 kPa has been selected as the final plan. This is due to relatively higher efficiency, lower water consumption and lower risk with air cooled condenser in spite of higher final cost. Fig. 4 shows the PFD (Process Flow Diagram) of the selected plan.

5. Conclusion

For Expansion of STPP the case B with exhaust turbine of 25 kPa is selected based on following advantages:

1-The selected power plant configuration has lower water consumption, which is critical for the arid region of Iran. This will be more economical to install large plant in the semi-arid region of Iran with no available water sources.
2-In the selected configuration, lower fossil fuel needed for generating 500 kW electricity energy (because of lower boiler load).
3-Solar and fossil part of the plant can operate and be assessed separately.
4-Performance of new designed collector can be measured during normal operation of the plant or individually.

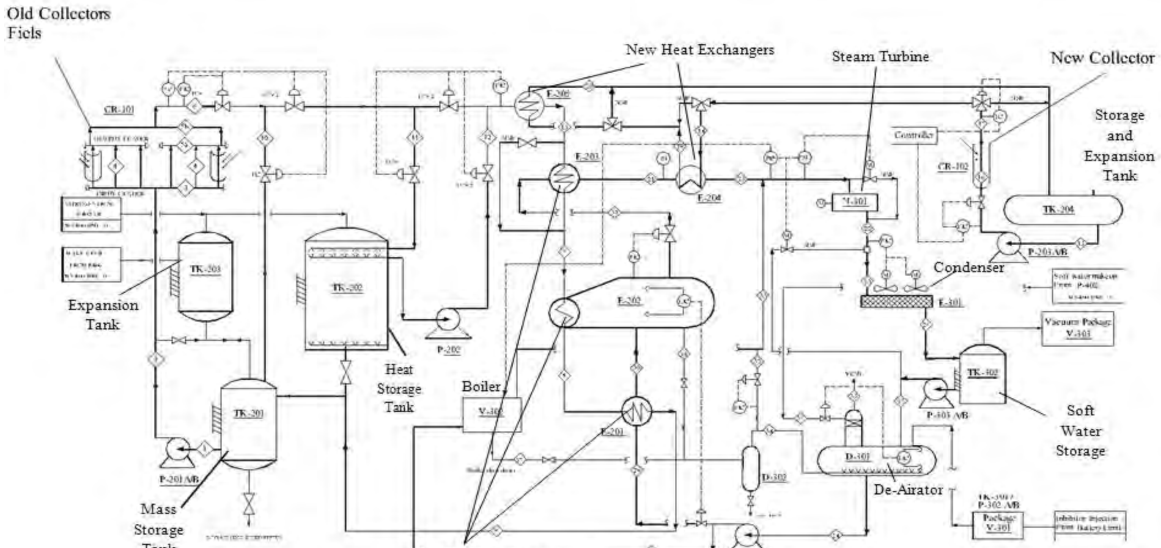

Fig. 3. PFD of the integrated 500 kW Shiraz parabolic trough solar power plant

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