Geothermal Steam Production by Solar Energy

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Keywords

Ahuachapán geothermal field, geothermal facilities, steam fraction, concentrating solar power, solar parabolic trough, heat gain, heat transfer fluid, heat exchanger

ABSTRACT

A concentrating solar power (CSP) prototype is testing close to AH-6 geothermal well in Ahuachapán geothermal field, El Salvador. The prototype consists of two small parallel parabolic trough concentrators (PTC) and thermal oil as heat transfer fluid (HTF). Heat gain from PTC could be a booster for current geothermal power during picks of demanding. The possibility of increasing steam fraction of two phase mixing geothermal fluid, separated geothermal water and heating condensed steam are the main objective of the testing. A theoretical increment of 5 kg/s of steam (equivalent to 2 MWe) from separated water, at under current bore field conditions and facilities, needs 40 kg/s of HTF heated from 170 to 270°C through a PTC field of 40 trough arrows of 200m long and 4 m wide (land size 250m X 500m) with a similar design and local materials for the testing prototype.

El Salvador is located inside the zone of higher solar irradiation of Central America. Solar light ranges from 8 to 11 hours. Direct solar irradiance has been recorded between 314 and 722 W/m^2. Direct normal solar energy flux has been observed between 2.9 and 6.0 KWh/m^2/day that correspond to 90% both cloudy and sunny days, respectively. During a 90% clear day and PTC operation from 8:00 to 13:30 local hours, HTF temperature changed from 158 to 243 °C. An entire oil mass of 688 Kg gained 41.3 KWh of useful heat for a thermal power average of 7.4 KW. For these operating conditions, solar to thermal efficiency results small, only 10.5%. It should be acceptable since the current PTC prototype presents high optical and heat losses due to mainly reflector materials used and heat absorber pipe design. Improvement of those elements and/or application of accurate technology should produce efficiency as higher as 50-60%.

Introduction

Oil crisis, hydrocarbon resources depletion, air pollution and global warming concerns are some of the main reasons to define a vision of energy technology for the future generations. Industrialized nations have notable advances in hydrogen technology, solar power generators, wind power, small hydraulic power plants, oceanic wave energy and biomass. Those countries have defined a long term researching program to develop alternative technologies for energy utilization (1).

Since 2006 LaGeo is studying technological information about alternative energies that have been projected to be part in the near future model of worldwide renewable energy facilities. LaGeo should become familiar with such kinds of technologies and being prepared to keep a competitive position in the energetic regional market by the year 2015. LaGeo has established a program to study CSP to increase useful heat steam and so rising up current geothermal power. Additional benefits are the opportunity of applying for CO_2 reduction bonus and a recently taxes law approved by the El Salvador´s Congress.

This article presents information related to a concentrating solar power (CSP) testing at AH-6 geothermal well in the Ahuachapán geothermal field. Parabolic trough concentrators (PTC) have been selected to test CSP because it is the most experimented and commercial developed since 1980´s. Testing performance, started late March 2007, is developing into two states:

State I. Thermal Characterization of the Parabolic Trough Prototype

From 8 a.m. to 4 p.m. a mechanical solar tracking system rotates both troughs from east to west regarding a north-south single axis. Reflective surface and heat absorber pipe are of stainless and carbon steel, respectively. During the first two months of testing, the absorber carbon steel tube exposes directly to the environment and heat losses (convection and radiation) are so high. Later, to avoid steel degradation and reduce heat losses, glass vacuum tubes will envelope the absorber elements, which are being coated by a black selective chemical formula. At this state, 688 Kg of a thermal synthetic oil or heat transfer fluid (HTF) pump through the troughs at 1.5 l/s flow rate and hot oil discharges into an expansion vessel insulated with fiberglass to reduce heat losses. After some hours of operation the entire mass of oil has increased its enthalpy and so gained useful heat. The results of the first part of this stage are described in this article.

State II. Boosting Geothermal Power by PTC Heat Gain

Ahuachapán geothermal plant, 95 MW installed capacity, locates at the western part of El Salvador, Central America (Figure 2). The reservoir temperature in the main exploitation area is 225°C. For mostly of the wells, mixing fluids at well head conditions are 6-8 bar, 158-160°C and 15-20% of mass steam fraction. Mass flow production averages 45 and 10 kg/s of water and steam, respectively. Ahuachapán geothermal field is a double flash system. First fluid separation is in the range 6-8 bar medium pressure (MP) and steam factor consumption is 2.5 Kg/s/MWe. Liquid separated flashes into a boiler system at 1.5 bar low pressure (LP) and 8.8% separation efficiency. Consumption factor for LP steam is 4.2 Kg/s/MWe. Current gross and net generations are 79 MWe and 73 MWe. Approximately 550 kg/s of water leaving the flashers are pumping and reinjecting into a neighbor field (Chipilapa) located 5 km of the reservoir to avoid cooling effects and sustain a pressure above 18 bar. Besides, 50 kg/s of waste water (condensed steam from cooling tower) is pumping and reinjected into Chipilapa area.

For this researching state the energy conversion flow is planned to be: 1) Solar to thermal energy, 2) Storaged heat in the HTF, 3) Geothermal steam fraction increment by a heat exchanger (HE) and 4) Electrical power increment. A set of possible scenarios to use the heat gained by the HTF are:

1. Heating two-phase mixing geothermal fluids from a production well. Steam quality increases through a HE installed before the mixing fluids enter into a cyclonic separator. A preliminary conceptual design indicates a restriction to the circulation of the two-phase flow and consequently the reduction of the productive characteristics of the well. In addition HE will require large size because of the steam initial volume in the mixing fluid. This option needs more analysis and is not considered in this document.
2. Heating water in a separator. Vaporize and so increase steam fraction from a separated liquid inside the same cyclonic separator is easy because the fluid is under saturated conditions. The HE is supposed to be one of the so-called vertical types as is shown in Figure 1. The vertical loop allows water moves down into equipment filling up the HE, taking heat from de HTF and producing additional MP steam.
3. Heating separated water before flasher system. HE heats the saturated water, increases steam fraction at the exit of the HE and more LP steam will be available into the flasher system.

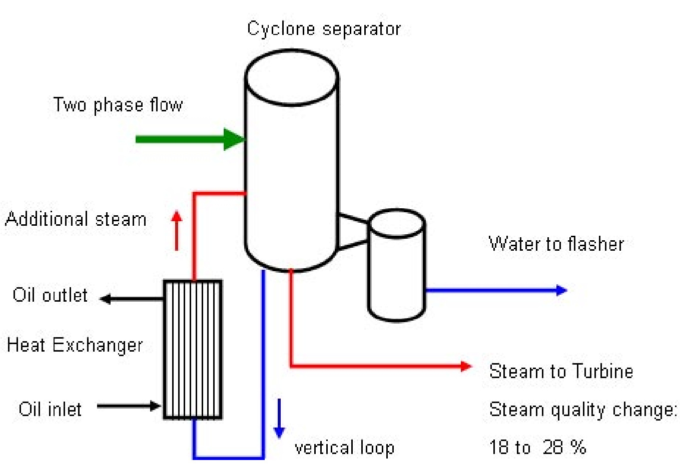

Figure 1. Heat Exchanger for heating water into a cyclonic separator.

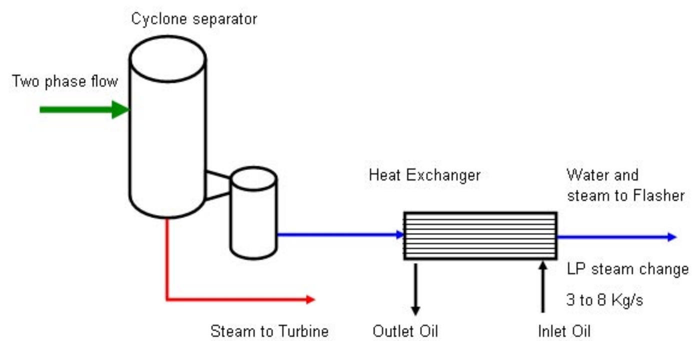

Figure 2. Heat Exchanger for heating separated water before flasher system.

4. Heating condensed steam from cooling towers to flashers. Waste water from cooling tower passes through the HE, where saturated water is produced and sent to the flashing system to obtain additional LP steam.

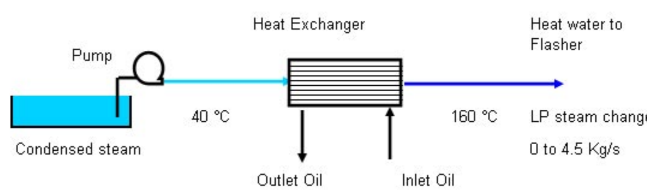

Figure 3. Heat Exchanger for heating condensate steam before flasher system.

HE is being designed to be of the shell-tube type, where geothermal fluid will flow into pipes for cleaning possible chemical precipitation (silica scaling), while HTF will flow through the shell. For the case of heating saturated water in the cyclonic separator, the HW will be vertical and non counter flow to maintain filled the shell. For heating the separated water toward the Flasher or the condensed steam, the HE has been selected to be horizontal and counter flow type.

Table 1 summarizes theoretical calculations to increase 5 Kg/s for the above 2 and 3 options and 50 kg/s for the 4 scenario. The estimations are based on mass – energy balance principles and heat transfer basic concepts. The calculations considerer resizing and improvements of the current PTC prototype, which will allow to heat 40 or 90 kg/s of HTF from 170-270 °C temperature during 6-7 hours of operation. Heating water in the cyclonic separator allows increasing steam quality from 18 to 28%. Although heating either separated water or condensate steam does not change the initial steam quality, LP steam increases into de flasher system, which could be available for power generation purposes. An energy balance, shows in Table 2, indicates two different HTF mass flows that should be circulated to gain heat into the solar field. HTF mass flow and its thermal requirements are so high because of the low well head pressure of the geothermal wells (6 to 8 bar) and vaporization latent heat greater than 2000 KJ/kg. This is not the case for current solar plants, where the steam is at condition of 100 bar and energetic requirements are smaller than 65% for those of geothermal power plants.

Table I. Theoretical calculations to add 5 kg/s of geothermal steam by a HE using solar energy.

Heat Exchanger Option		Initial condition of geothermal fluid before heating			
		Steam MP kg/s	Water kg/s	Total Mass kg/s	Initial steam quality
2	Heating water into Separator (P=6 bar)	9	40	49	18.4
3	Heating separated water to Flasher (P=6 bar)	9	40	49	18.4
4	Heating condensate steam (from 40 to 160°C)	0	50	50	0

Heat Exchanger Option		Finally condition of geothermal fluid after heating					
		Steam MP additional kg/s	Steam LP additional kg/s	Total steam MP kg/s	Total steam LP kg/s	wastewater kg/s	Final steam quality
2	Heating water into Sepatator (P=6 bar)	5	0	14	3.08	31.92	28.6
3	Heating separated water to Flasher (P=6 bar)	0	5	9	8.08	31.92	18.4
4	Heating condensate steam (from 40 to 160°C)	0	0	0	4.40	45.60	0

Notes: MP= Medium Pressure, LP= Low pressure, Geothermal fluid temperature is about 160 °C

Table II. Energy Balance and HTF mass flow in the solar field

Heat Exchanger Option		Energy balance into Heat Exchanger					
		Geothermal fluid			HTF in Solar Field		
		Additional kg/s water / steam	Enthalpy KJ/kg	Heat load KW	Enthalpy KJ/kg	Heat loss KW	mass Oil kg/s
2	Heating water into Sepatator (P=6 bar)	5	2087	10435	262	10435	39.8
3	Heating separated water to Flasher (P=6 bar)	5	2087	10435	262	10435	39.8
4	Heating condensate steam (from 40 to 160°C)	50	501	25050	262	25050	95.6

Notes: the HTF (Oil) will be heating from 170 °C to 270 °C in the Solar Field, Geothermal fluid temperature is about 160 °C

Solar Irradiation

SNET (The Salvadorian Institution for Territorial Studies) has summarized solar data recorded by other national agencies since about 30 years ago (2). The information consists of climatic parameters gathering by meteorological stations. Daily annual average of global radiation can be observed in Figure 4. El Salvador has approximately 8 hours/day of solar light and 19 MJ/m^2/day (5.3 KWh/m^{2}day) average of global solar energy. Solar data for Ahuachapán and Berlin geothermal areas as well La Unión near future develop area are indicated in three frames of that map. Global irradiation reaching Ahuachapán is slightly higher than that one into Berlin zone. Irradiation data of La Unión province are the highest for the entire El Salvador. A comparison makes between SNET data and solar energy assessment maps provided by UCA (2) and SWERA cooperation results in a high correlation. Two different historic sources of information reveal an annual average global solar energy higher than 5 KWh/m^2/day.

From May to October 2006 (rainy season) a Davis climate monitoring station was installed on the platform of the AH-6 geothermal well (13.9174 N, 89.8145 W and 785 msnm) to collect climate parameters and particularly global solar data. In figures 5 and 6 can be observed a maximum global insolation of 500-700 W/m^2, daylight of almost 12 hours and global solar energy over 4.7 KWh/m^2/day. Variations were caused by climate conditions mainly due to clouds and shadows projected by some small buildings and eucalypt plantations located around the solar receiver. The global solar energy, obtained along 6 months of sampling, is 88% of the average computed by SNET and 78% of the global radiation reported by UCA and SWERA. The Davis station was uninstalled when civil works for supporting PTC took place there.

From middle March 2007 the original Davis Station and an additional one were installed to collect global, diffuse and reflected solar data. Thus,

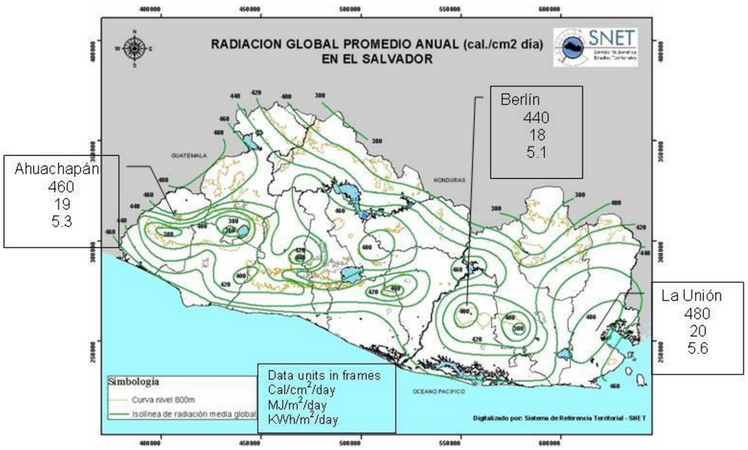

Figure 4. Global Annual Irradiation (SNET).

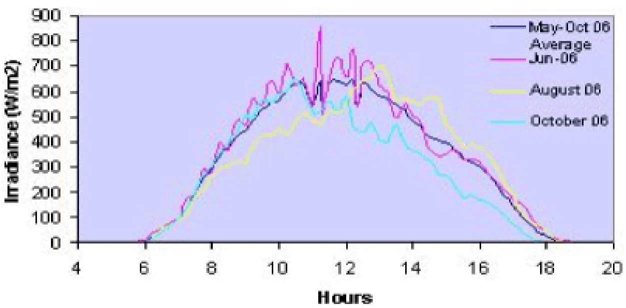

Figure 5. Global Solar irradiation into AH-6 geothermal well.

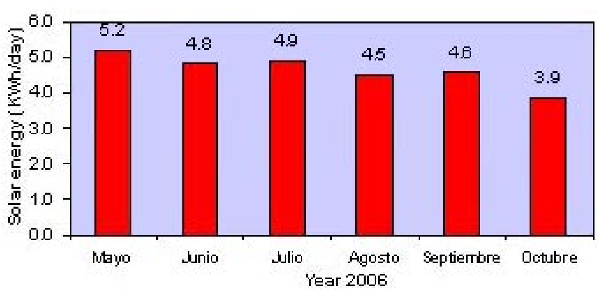

Figure 6. Global Solar Energy into AH-6 geothermal well.

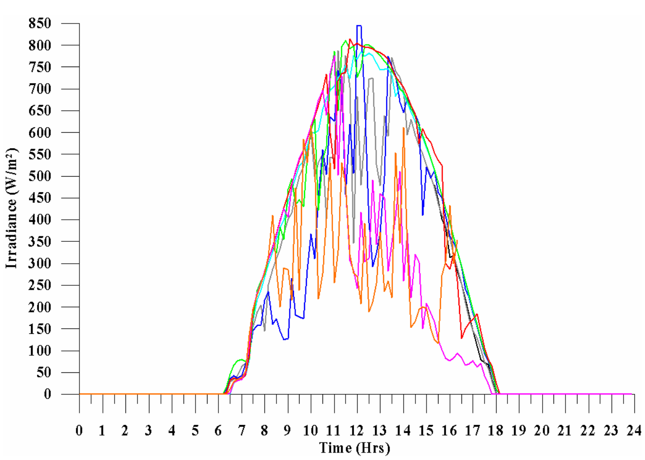

Figure 7. Direct normal irradiation into AH-6 geothermal well.

both direct solar irradiance and energy could be calculated. Figure 7 deploys direct normal irradiation for some days under opposite cloudy conditions. For nearly 11.5 hours of solar day, average of direct irradiance and energy were 394 W/m^2/day and 4.6 KWh/m^2/day. A range between 2.9 and 5.5 KWh/m^2/day of direct solar energy could be accepted for a later PTC feasibility analysis at AH-6 geothermal well.

Concentrating Solar Power

Publications about CSP technology is provided by different web sites (6). The plants consist of two or three parts:

a) Solar field, which collects solar energy to convert it into useful heat.

b) Power block, which by a Rankine cycle converts useful heat into electricity.

c) Hybrid power plants. Some systems use heat storage to operate during cloudy periods, evenings and peak demanding. Others can be combined with other resources such as natural gas and the resulting hybrid power plants provide a higher load factor. These attributes can make CSP technology an attractive renewable energy option to make a hybrid system with geothermal areas located on zones of high solar energy and favorable climate conditions

Power generated by CSP devices use only direct-beam sunlight. Diffuse solar irradiation caused by clouds, dust and air pollution is not appropriated by CSP. Concentrating systems use lenses or mirrors and solar tracking systems to focus a large area of direct sunlight into a small area capable of producing high temperature fluid.

CSP vary in the way they track the sun and focus light. There are three main kinds systems of concentrating solar power: Troughs, dish/engines and power towers. Parabolic trough technology is actually the more proven solar thermal electric technology (i.e. California and Almería). For 2008 Nevada will commissioned 64 MW by using improved technology of the CSP in Mojave. Early solar power tower one (10 MW at Mojave, 1982-1988) utilized steam as the heat transfer fluid. Current designs, including Solar Two (Mojave) and Three (Spain), utilize molten nitrate salt because of its superior heat transfer and energy storage capabilities. The first commercial 11 MW power tower (PS10 in Spain) started operations late 2006. Dish systems can achieve much higher temperatures and display the highest solar to electric efficiency among CSP technologies due to its highest factor concentration.

Figure 8 shows a representative process of the parabolic trough solar power plants today in operation. The solar field consists of large and horizontal parabolic trough solar collectors. The solar field is modular in nature and is composed of many parallel rows of solar collectors aligned on a N-S horizontal axis. Each solar collector has a linear parabolic shaped reflector that focuses the solar irradiation on a 2D linear receiver located at the focus of the parabola. The collectors track the sun from east to west during the day to ensure that the sun is continuously focused on the linear receiver. A heat transfer fluid (HTF) is heated as it circulates into the receiver and returns to a series of heat exchangers at the power block where the fluid is used to generate high pressure superheated steam. The superheated steam feeds a steam turbine generator to produce electricity. Steam from the turbine is condensed and returned to the heat exchangers to be transformed back into steam. Cooled HTF is recirculated through the solar field. If sufficient solar energy is available the plant can operates at full rated power. During summer, plants typically can operate for 10 to 12 hours a day at full rated electric output. Nowadays, they have a backup fossil fired capability that can be used to supplement the solar output during periods of low solar radiation or night periods. In Figure 8, an optional natural gas boiler located in parallel with the solar heat exchangers provides this capability.

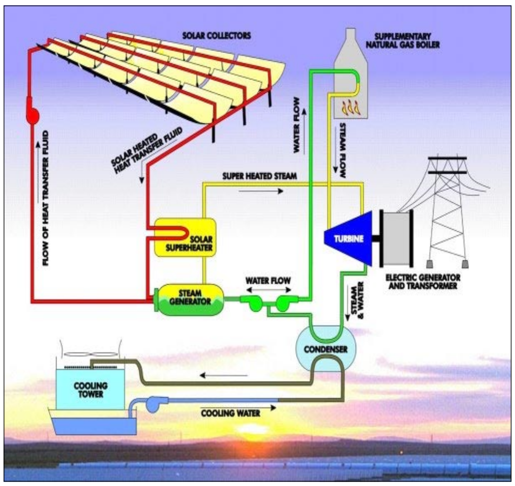

Figure 8. Concentrating Solar Power Plants (NREL).

Parabolic Trough Layout

Figure 9 and Photo 1 illustrate the layout of the PTC prototype installed close to well head of the AH-6 geothermal well. It consists of four units or modular parabolic troughs dispose in a serial parallel arrangement. Each unit is 4m wide or aperture and 10m length. Every absorber tube is also 10 m length and they are constrained to be no more than 1.6 inches (4.1cm) external diameter to keep a solar concentration ratio (horizontal reflector area / absorber area) of almost 31. The absorber pipe internal diameter is 1.25 inches (3.2 cm). Axes of the parallel troughs are 11 m distance each other to avoid shadows projection from each other. Focal 2D line or absorber tube is positioned 1m above the vertex of the parabolic reflector and 4m from the ground level. These parabolic troughs are oriented N-S and horizontally leveled.

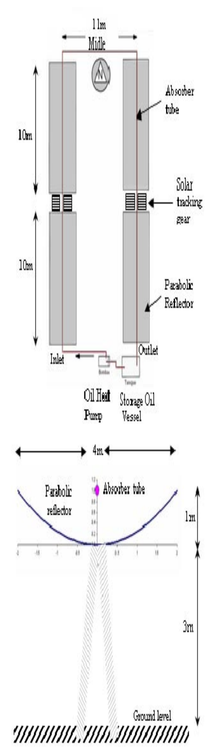

Figure 9. Layout of Parabolic Trough Concentrator prototype.

Photo 1. PTC and AH-6 geothermal well facilities.

Each serial trough follows the direct solar radiation by means of an independent mechanical solar tracking of 115-120° arc lengths. This consists of a reducing speed gear box drives by a step motor in a relation of 1 to 10388. The step motor responds to a computer code, which every 30 seconds reads the angular positions of the sun, causing the troughs rotate 7.2 minutes arc lengths. The reflector material makes of stainless steel have a reflectivity around 64%. Optical properties of the absorber tube carbon steel are unknown. Considering the PTC construction procedure, the reflectivity of the stainless steel and uncertainties in the solar tracking system optical losses are estimated to be 42%.

A total mass of 688 Kg of Therminol 55 thermal synthetic oil is pumped at 1.5 l/s into a closed loop consisting of a glassy insulated tank, absorber tubes and external coupling tubes between troughs. The external coupling tubes of carbon steel are glassy insulated to reduce heat losses. The 688 Kg of oil working fluid can be heated up from approximately 8 a.m. to 16 p.m. local time taking into consideration that optimal operation temperature of the therminol 55 is from -25 to 290 °C (7). The hot oil is storage in the insulated vessel until a next day of operation. Temperature and gauge pressure readings are taken in the inlet, middle, outlet and vessel points labeled in Figure 9. Under unfavorable climate conditions the PTC is turned off.

Thermal Characterization of the PTC Prototype

Initial testing of the PTC prototype was carried out during 7 days from March 26 to April 11 of 2007. Effective area and optical losses of the PTC as well the climate conditions, operation temperature and the main results are summarized in Table 1.

The most favorable direct solar days occurred in April 10 and 11 since cloudy time period was less than 10% of the total period of operation. Climate recorded data allowed to calculate averages for wind velocity, air temperature, atmospheric pressure and relative humidity in 8 Km/h, 27°C, 936 mbar and 50%, respectively. Direct solar energy flux and average irradiance are calculated from the climate recorded data for only the corresponding periods of operation. Solar energy and power are

Table III. Operation conditions and results of PTC testing.

Date / 2007	26/03	27/03	29/03	02/04	03/04	10/04	11/04
Operation period	11:30 14:30	10:10 12:10	08:10 10:45	09:50 15:15	09:00 13:00	11:00 16:00	08:00 13:37
Cloudy time period (%)	24	48	28	40	40	9	3
Operation time (hrs)	3.00	2.00	2.58	5.42	4.00	5.00	5.62
Area CSP (m^2)	160	160	160	160	160	160	160
Optical losses CSP (%)	42%	42%	42%	42%	42%	42%	42%
Solar Energy flux (KWh/m^2)	2.6	1.5	1.3	3.0	2.6	3.7	4.1
Solar Energy (KWh)	416	240	208	480	416	592	656
Effective energy (KWh)	241	139	121	278	241	343	380
Average Irradiance (W/m^2)	680	700	450	538	630	737	722
Solar Power (KW)	109	112	72	86	101	118	116
Effective Power (KW)	63	65	42	50	58	68	67
Oil mass (Kg)	688	688	688	688	688	688	688
Initial temperature (°C)	40	136	51	60	122	50	158
Final temperature (°C)	178	190	160	154	189	172	243
Initial entalphy (KJ/Kg)	107.9	314	130.1	148.6	281.6	128	366.3
Final entalphy (KJ/Kg)	415.5	445.7	371.2	356.7	443.2	400.6	582.4
Heat gain (KWh)	58.8	25.2	46.1	39.8	30.9	52.1	41.3
Thermal power (KW)	19.6	12.6	17.8	7.3	7.7	10.4	7.4
Solar-thermal Effic (%)	24.4%	18.1%	38.2%	14.3%	12.8%	15.2%	10.9%

obtained over the total area of the PTC. Effective energy and power result from considering the indicated optical losses.

For March 26 pressure and oil mass flow of pumping were assigned to 35 psi and 1.5 l/s. Figure 10 indicates that for March 26 oil initial temperature was 40°C for all the points of measuring. As the oil heated up, oil viscosity reduced and so was pumping pressure. In April 11, oil initial temperature was 158 °C, pumping pressure 5 psi and outlet pressure at the absorber pipe was zero. Expansion tank was settled to atmospheric pressure to release evaporated oil gases.

Temporal variation of oil temperature at points of measuring for March 26 is show in Figure 10. Inlet, middle and outlet oil temperatures ranks from lower to higher temperature unless the external surface of the absorber tube cools down due to the occurrence of unfavorable climate conditions. When heat losses from absorber tube start to increase, oil outlet temperature goes down and tends to be the oil temperatures in both the inlet and middle points. Convection and radiation heat losses should increase when temperature differences between the external surface of the absorber element and the surrounding environment are higher than those at initial conditions. Oil temperature in the tank remains below the oil outlet temperature until equilibrium temperature is obtained. This balance is broken because of heat loss rate differences. When the oil outlet temperature decreases, oil temperature in tank continues increasing as a result of its thermal insolation. It is important to notice that oil temperature increment rate is smaller with higher temperatures. Figure 11, presenting temperature behavior for March 27, reveals that when the initial oil temperature in the tank is higher than outlet oil temperature, it firstly cools down because it is mixing with cooler oil kept in the absorber tube during the night before. After a new equilibrium is obtained, oil temperature in the tank behaves like the description for March 26.

Enthalpies as a function of the oil tank temperatures were calculated according to the thermodynamical properties of the heat transfer fluid therminol 55 issued by Solutia (7). In correspondence to the operation period, the enthalpy results presented in Figure 12 can be classified into two groups. Operation period for the first group is from 8:00 to 13:00 hours belonging to 27/03, 29/03, 03/04 and 11/04. The second group settled to the range 10:00 to 16.00 hours includes 26/03, 02/04 and 10/04. For each group the solar thermal efficiency is high only if the initial oil enthalpy (o temperature) is small. In some intervals of operation a slow rate of enthalpy changes also occur, which probably is a result of heat losses increment from the absorber tube. In table 1 are found the heat gain and solar

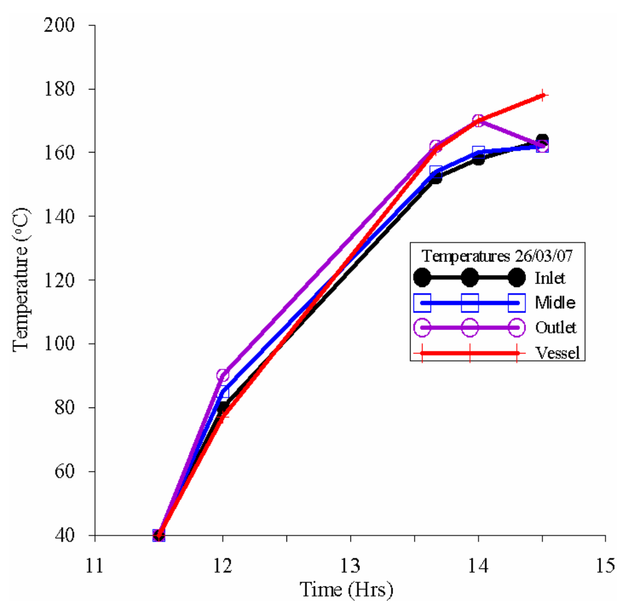

Figure 10. PTC temperatures in March 26/03/07.

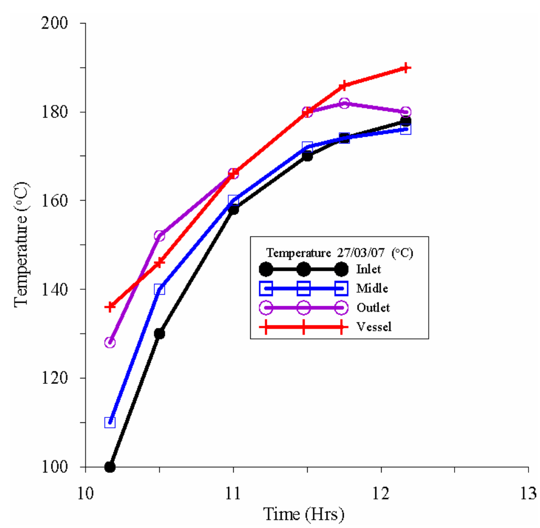

Figure 11. PTC temperatures in March 27/03/07.

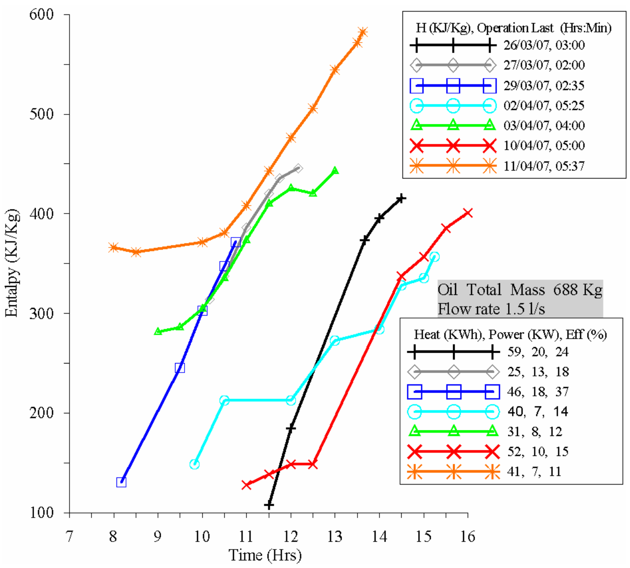

Figure 12. Enthalpies of oil heat transfer for 7 day of PTC testing.

thermal efficiency for each day of testing. For oil temperature operation between 125 and 190°C the efficiency is about 15%. This decreases to 11% for temperature between 160 and 250 °C. The lower the oil operation temperature range the higher the solar thermal efficiency.

For the last condition and according to Forristal (8) wind case models, convection thermal power losses could result in 23 KW if absorber tube temperature was 200°C, wind velocity 5.6 Km/h and 30°C air temperature. If heat losses by radiation were considered, heat gain should be at least 4 times higher than the collected 41 KWh by the current PTC. Evidently to increase efficiency the reflectivity, absorber tube design and accuracy of the solar tracking system of the PTC prototype need improvements. If so, enough useful heat could be provided to test the planned heat exchangers for boosting current geothermal facilities.

Conclusions

Direct annual average irradiation and solar energy in Ahuachapán are over 400 W/m^2, 4.5 KWh/m^2/day and solar light is about 10 hours/day/year. Cloudy or rainy days constrain the direct solar energy and so the heat gains by the PTC.

For a HTF flow rate of 1.5 kg/s into the PTC a maximum temperature of 243°C was observed, recording 11% of solar thermal efficiency. The best operation period is between 9a.m. and 3 p.m. Efficiency can reach up to 50-60% if optical and heat losses are reduced by improvement reflective materials, heat absorber design and solar tracking accuracy.

It should notice that the maximum temperature (243°C) obtained in the HTF is higher than the Ahuachapán geothermal reservoir (225°C). CSP and geothermal power located on sunny zones can combine to increase power with the same mass extraction. This combination can held on the definition of clean energy and can apply for CO_2 reduction bonus. Generation with CSP technology does not result in greenhouse gas emissions.

A theoretical increment of 5 kg/s of steam (equivalent to 2 MWe) from separated water, at under current bore field conditions and facilities, needs 40 kg/s of HTF heated from 170 to 270°C through a PTC field of 40 trough arrows of 200m long and 4 m wide (land size 250m X 500m) with a similar design and local materials for the testing prototype.

The low operation pressure in geothermal fields demands a large solar energy to produce steam, which impact the solar field size and so capital investments. PTC current technologies cost about $3000/KWe. A combination of CSP and geothermal power facilities could present costs lower than those for hybrid solar-fossil plants. CO_2 reduction bonus, fiscal incentives, use of efficiency technology to storage and heat transfer is advantage to invest in a geothermal solar hybrid system.

Acknowledgments

We would like to recognize to LaGeo´s Managers and Board of Directors the advanced decision to develop local researching about energy alternatives, especially solar power generation and hydrogen technology. This researching is taking place due to the synergy and support of many colleagues of all the management units. Special thanks to all the technical and administrative staff who contribute with ideas and logistic support.

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