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Estimation of Steam Production in a Receiver Under Solar Concentrating Radiation

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Abstract

Solar energy is a substitute for fossil fuels mainly for power generation. A method of solar concentration of medium and high range of temperatures has been adopted for different electrical applications. In this perspective we try to evaluate the performance of a parabolic dish concentrator type on the production of steam. For this, we simulated the evolution of the production of steam in a cylinder containing a receiver coil. The receiver is based on the focal point of the concentrator. Finally, we test the time evolution of the mass, temperature and pressure for steam at the receiver output. The prototype was realized with simple and available means making it very convenient and economical.

Keywords: Receiver, Coil, Steam, Prototype

1 Introduction

Solar parabolic dish collector is an attractive method to concentrate direct beam radiation which converts it to thermal energy in a useful form for electrical power generation [1]. Solar thermal power plants with concentration technologies are important candidates for providing the bulk solar electricity needed within the next few decades. Four concentrating solar power technologies are developed: parabolic trough collectors (PTC), linear Fresnel reflector systems (LF), power towers or central receiver systems (CRS) and dish engine systems (DE) [2].

The receiver is part of the parabolic dish; it can be used to produce steam to generate electricity in the range of kilowatts. The parabolic concave mirror concentrates sunlight; the mirror has two axes allowing it to follow the sun with a high degree of accuracy to achieve high yields (see Fig. 1). In the foyer is a receptor that is heated to average 550 °C. The heat absorbed by a receiver as a coil of copper containing a working fluid (water), which converts heat into mechanical energy by a turbine. This turbine drives a generator to produce electricity. If enough sunlight is not available, the heat of combustion of fossil fuels or bio-fuels can also driving the system producing electricity. The efficiency of the turbine can reach 20% and that of the receiver can be more than that of the turbine. The production of steam and hot air is used as a heating receiver (boiler) the use of hydrocarbon resources such as Diesel, LPG, or coal, wood, electricity, agricultural waste, etc. It is noted that the natural resources of fossil fuels cited above are depleting fast and the use of wood for fuel leads to deforestation which leads to serious ecological imbalance. The prices of sources of oil are increasing rapidly and the combustion of these fuels leads to the generation of CO_2, which is the main cause of global warming. Days are not far away, when restrictions are imposed by the strict international standards on the production of CO treatment as CO_2 is very costly in capital investment and operating costs. Therefore, solar energy is the best way to avoid all these problems. The solar heating system of production can be easily configured to the existing system with the rapid evolution of fashion without any major change in the pattern of production methods or current. In this system, the steam can be produced from 2 to 16 bars of pressure, the oil can be heated even above 350 °C or air can be heated directly above 750 °C or indirect air heating can be achieved by using oil heated to a temperature of 250 °C. Concentrating solar collectors of different geometric shapes, sizes and orientation are in use today. They are generally either one- or two-axis tracking or non tracking. A new class of collectors using fixed reflectors and tracking absorbers, known as stationary reflector/tracking absorbers (SRTA) has also been designed. The SRTA employs a fixed spherical reflector and tracks the sun with an absorber. Water is used as the heat transfer fluid, and an output temperature of 80 °C above ambient can be obtained [3]. In the actual operation of solar concentrators, the thermal energy is used for medium and high temperature applications maximum up to 400°C with either steam generation or sensible heating of working fluid [4]. In all the above mentioned testing procedures, the heat gain of the dish solar concentrator absorbed by the working fluid contributes to increase the temperature of the latter.

2 Experimental study

The experiments have been done at university of Constantine site (Laboratory of Energy Physics) (Latitude 36°10 North, Longitude 6°22 east , Altitude 694 m) on summer season with clear sky conditions. Liu Jordan model is a good estimator of beam radiation for this period of the year illustrated in figure 1. Two comparative experimental studies are made between cylindrical receiver and coil receiver to compare the evolution of steam production in these two receivers. The first experiment is made on July 26th 2011 and the second experiment on August 16th 2011 for the same period for both, from 11h to 14h. Figure 1 represents the evolution of solar radiation received by the reflector parabolic. As shown in this figure the solar beam radiation can reach in the experiment conditions in average 800 W/m^2 between 11h and 14h.

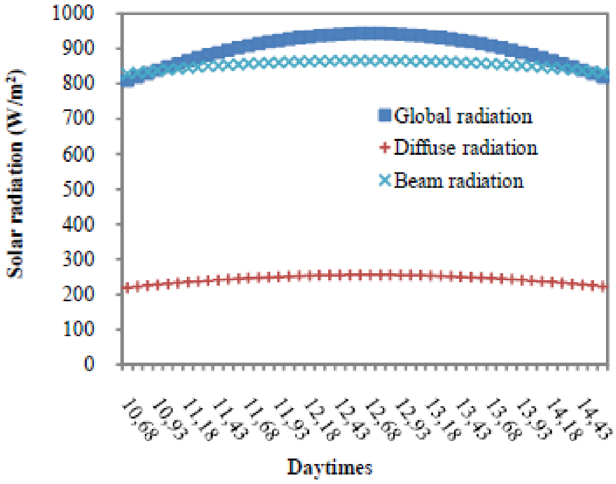

Figure 1: Variation of solar radiation during the experience on 26th July 2011 by Liu Jordan model [7].

In this present work, a parabolic solar concentrator has been experimentally studied. The experimental devise consists of a dish of 1.95 m opening diameter. Its interior surface is covered with about 1,100 squares of mirror of 5cm sides in average, and equipped with a cylindrical receiver in its focal position as shown in figure 1. The orientation of the parabola is ensured by two mechanical axes and experimental measurement of steam production is ensured by the two different receivers. In the first case of the experiment as shown in figure 3,

Figure 2: Picture of the concentrator with cylinder mounted as receiver

we determine the time evolution of the receiver surface and water temperature, one thermocouple was installed in the bottom of the cylindrical receiver which contains six liters of water and the volume of the cylindrical receiver is 13.6 liters, the time evolution of the pressure of the steam by a manometer and the quantity of the condensate steam by a condenser steam and condensate measurement.

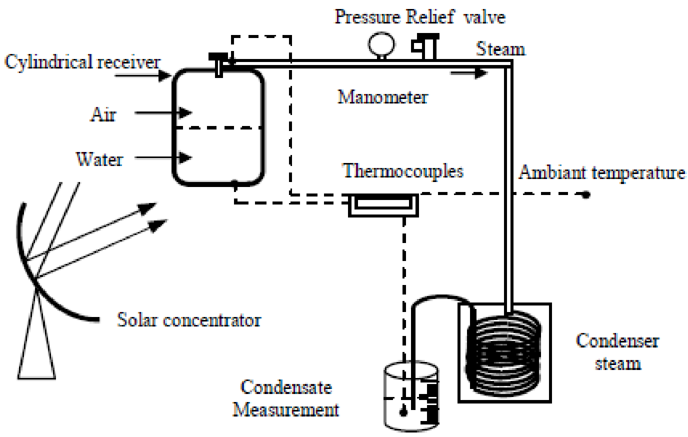

Figure 3: Schematic of a solar concentrator with cylindrical receiver

The installation is also equipped with pressure relief valve to insure security. Other thermocouples are installed to measure ambient and steam temperature. The test starts at 11h20 local time, with focusing of reflected radiation on the receiver. The reflected radiations are focused on the cylindrical receiver base. Initially, heat is absorbed by the bottom of the cylindrical receiver, once thermal equilibrium is reached between the receiver and lateral surfaces, heat is absorbed by water for sensible heating and then for phase change. The phase change of water generates steam and increases pressure inside the cylindrical receiver.

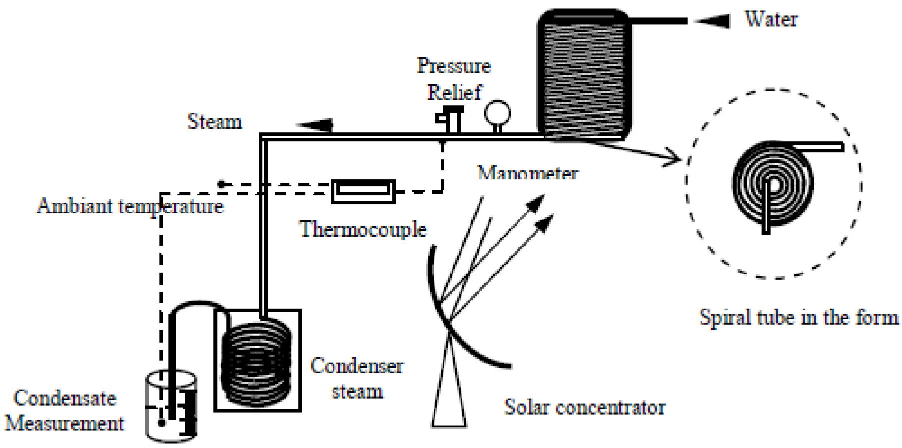

Figure 4: Schematic of a solar concentrator with coil receiver

Once the pressure exceeds 10 bars the pressure relief valve operates to vent the steam. The venting of steam releases the mass of steam (from the feed water). This steam is condensed by passing through the steam condensing arrangement and the condensate is measured to estimate the steam generated during the test. The second experiment we change the first receiver by coil receiver made of copper, containing a working fluid (water). Four thermocouples are used to measure inlet and outlet coil receiver, ambient and steam temperature.

3 Theoretical model

The power concentration that arrives to the flat bottom surface of the receiver can be estimated by using the following equation:

$$\dot{Q}_c = \alpha_{abs}\rho\Gamma A_a I_b \tag{1}$$

Where A_a is the dish mirror area and I_b is the solar beam radiation at the time of the experiment, α_{abs} and ρ is the absorbtivity of the absorber and average reflectivity of the mirrors in the dish respectively, where Γ is a fraction of the radiation reflected on the absorbing surface.

$$\dot{Q}_l = UA_{abs}(T_{abs} - T_{amb}) + GA_{abs}\varepsilon_{abs}\sigma(T_{abs}^4 - T_{amb}^4) \tag{2}$$

Heat losses are modeled using a geometrical correlation factor *G* for the radiative portion and a heat transfer factor *U* for the convective portion that have been determined experimentally. In equation (3) the Subscript *abs* refers to the combined receiver and fluid control volume, as it is assumed that the receiver tube will be at the same average temperature as the fluid.

$$\dot{Q}_{abs} = \dot{m}c_{pw}(T_{out} - T_{int}) \tag{3}$$

Where $\dot{m}$ is the mass flow rate, and T_{int} and T_{out} are water inlet and outlet temperatures, respectively. The above assumption about negligible losses will be revised in the following by making a detailed thermal analysis of the receiver. The outlet temperature is calculated from the inlet fluid temperature and the average control volume temperature:

$$T_{abs} = 2T_{out} - T_{int} \tag{4}$$

The surface Temperature of the receiver T_{abs} is obtained from solving the equation (5), when replacing the expressions of the energy gain and the energy loss which is based on the first Law of thermodynamics.

$$m_{abs}\left(c_{abs} - c_{pw}\right)\frac{dT_{abs}}{dt} = \alpha_{abs}\rho\Gamma A_a I_b - UA_{abs}(T_{abs} - T_{amb}) - GA_{abs}\varepsilon_{abs}\sigma(T_{abs}^4 - T_{amb}^4) \tag{5}$$

We use a mean ambient temperature of the surface receiver at time zero as the initial condition. The solution of this equation gives us the instantaneous temperature *Tabs* of the receiver surface and water. Due to the fourth order form of the last equation the resulting differential equation is nonlinear and must be solved by numerical methods. We applied the Rung-Kutta method to the fourth order [7,8]. For this purpose we wrote a corresponding program in FORTRAN to solve it. The overall thermal efficiency is defined as the ratio of the change in thermal energy of the fluid and the dish solar radiation captured by the receiver. The calculation is expressed in the following equation:

$$\eta = \frac{\dot{Q}_{abs}}{\dot{Q}_c} \tag{6}$$

4 Results and discussion

At 11h20, we started the measurements of the thermal test of our concentrator by tracking the concentrator such as the collector aperture plane is perpendicular to the incident solar radiation. The temperature increases to reach 170°C and nearly 9.80 bars in the receiver pressure (at 12h30), this pressure can be exceeded more than 10bars. After 12h30 the receiver is defocused, it is allowed to cool down till the receiver pressure reaches the atmospheric pressure. The test is started by tracking the concentrator such that collector aperture plane is perpendicular to incident solar radiation.

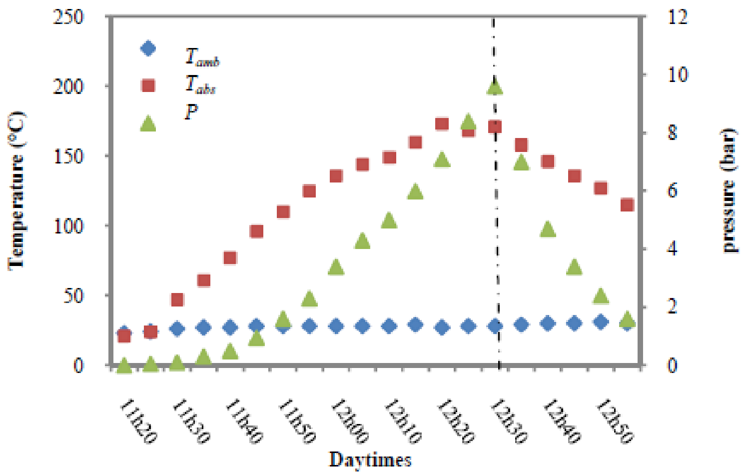

Figure 5: Variation of temperature and pressure with time during the performance test on 26th July 2011.

The output values of the temperature as function of time are then compared to experimental data using equivalent initial conditions. For this purpose we choose the data of the test for comparison. In Figure 5 the estimation and experimental measured temperature are illustrated, good agreement of both data is observed.

The thermal efficiency of dish is the ratio of useful heat recovered to the total heat received on the aperture area of the concentrator as presented in Figure 7. Thermal efficiencies may be around 40% and increase in receiver temperature of 145 °C (at 12h00). Qualitatively, the estimated efficiency fit the experimental efficiency results, by varying the parameters U. The thermal efficiency of dish is the ratio of useful heat recovered to the total heat received on the aperture area of the concentrator as presented in Fig. 6.

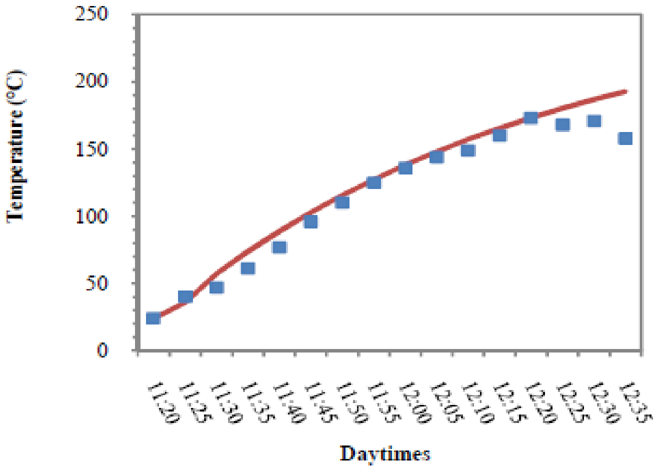

Figure 6: Experimental temperature versus estimated temperature
(—— : Estimated, ■ : Experimental).

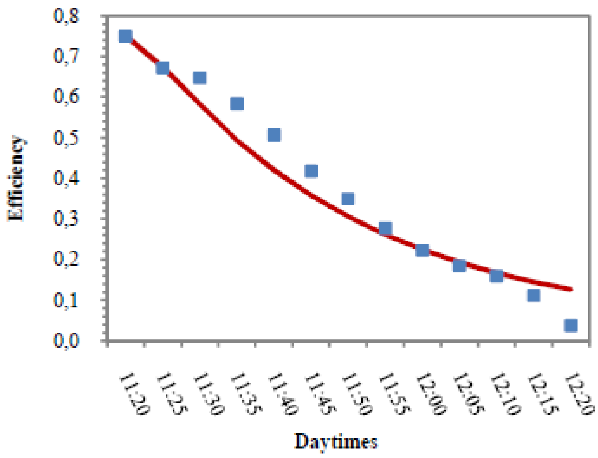

Figure 7: Experimental efficiency versus estimated temperature
(—— : Estimated, ■ : Experimental).

Thermal efficiencies may be around 40% and increase in receiver temperature of 145 °C (at 12h00). Qualitatively, the estimated efficiency fit the experimental efficiency results, by varying the parameters U. The thermal exchange surface of the absorber (coil receiver) is more important than that of the first experiment. When this surface is larger than that of the first experiment, the heating speed of the water is faster. The figure 7 below shows the result of the second experiment. At 12h45, the inlet temperature of the water equals the ambient temperature. We notice an increase of the outlet temperature of the coil receiver and an increase of the steam temperature which stagnates at around 100°C at 13h03, but the outlet temperature continues to rise exceeding 180°C until 13h40 the end of the experiment. Steam is blown off to ambient air after passing through the coil receiver, which affects pressure drop over the coil receiver length, in comparison to a receiver connected to a steam generating system.

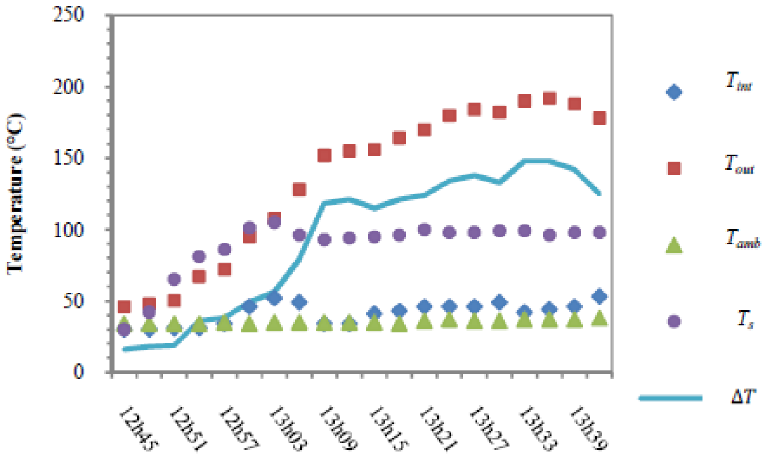

Figure 8: Variation of temperatures for coil receiver with time during the performance test on 16th August 2011

We conclude that the receiver coil is better in the production of condensed steam; the collection for the first receiver is about 1.2 liters in 30 minutes whereas the collection is 3.6 liters for the second receiver.

Table 1: Parameters used for the experiments and results

Particular	Unite	Value
A_a	m^2	2.98
A_{tube}	m^2	0.57
Average solar beam radiation	W/m^2	750
$\dot{Q}_l$ (cylindrical receiver)	W	250
$\dot{Q}_l$ (coil receiver)	W	350
Steam condensing for cylindrical receiver	Litre/30min	1.2
Steam condensing for coil receiver	Litre/30min	3.6

5 Conclusion

The aim of this work is to characterize the thermal performance of the solar concentrator system which is based on the collection of the heat concentrated by a parabolic mirror absorbed by a working fluid (water). The thermal efficiencies may be around 40% and increase in receiver temperature of 145 °C (at 12h00). The flow and temperature of the steam measurements are critical during the experiments which are based on heat receiver. This test procedure will be useful in characterize any concentration of point focus solar different operating temperatures and to evaluate the real performance in an application In most Thermal performance tests where water is used as a working fluid, tests are performed below 100°C and the curve is extrapolated for superior performance in temperature. For testing at temperatures above 100°C with water under pressure hot water loop is required. The proposed procedure uses the feature of phase change water at constant temperature to measure thermal performance. The phase change leads to the decrease of the steam and it is easy to measure the produced amount of the steam in relation with an increase of receiver temperature. This procedure can be used for all types of solar concentrators with modifications in the simulation of the energy balance. The proposed test procedure is used to estimate the thermal efficiency of a solar concentrator focus point 3 m2. This test procedure based on the latent heat can also be used to characterize a group of solar focus concentrator systems generating steam.

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