Solar Thermal Steam Generation System at Domestic Level

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Abstract— In recent years, power demand has been drastically increased whereas conventional energy resources are decreasing day by day. Most of the existing power generating stations in the world are based on fossil fuels, resulting in huge amount of CO₂ emissions that have harmful impacts on environment. In this work, a heater powered steam generation system is designed and optimized. A Linear Fresnel Reflector (LFR) and receiver may be used to collect heat from sun. The heat energy received from Concentrated Solar Power (CSP) may be utilized for steam generation using heat exchanger. Therma-B oil, having high heat transfer coefficient, is used as Heat Transfer Fluid (HTF). In this work, different design parameters such as, the rate of oil flow, steam pressure and temperature, oil temperature, water flow and rate of steam generation are optimized on experimental basis. The designed steam generation system provides enough steam that can run a 1 KVA steam generator for power production. This provides green electricity at domestic level to cope with energy crisis, using sustainable energy source.

Index Terms— CSP receiver, Linear Fresnel reflector, Heat exchanger, Heat storage, Heat transfer fluid, Renewable energy sources, Solar powered steam generation system, sustainable energy

1 INTRODUCTION

Energy demand is continuously increasing in the recent decades that reflects an alarming future for the world [1]. On the other hand, fossil fuel reserves are drastically decreasing while they are major energy sources for electricity production throughout the world. Fossil fuel based power generation results in CO₂ emission which pose a potential risk to the environment. The awareness of climate change and sustainable energy production has been increased since last decade [2]. For that reason, it is essential to find satisfactory alternatives and comprehensive strategies for a shift to other energy sources that deliver least environmental impact.

Sun is the permanent source of energy in direct (solar radiations) and indirect forms (wind, biogass, etc.). Numerous studies have been carried out in countries, such as Slovenia [4], India [5], Bangladesh [6], Ghana [7], Nepal [8], Malaysia [9] and Nigeria [10], where it was assessed that renewable energy sources are viable sustainable energy alternative to cope with problems like energy crisis and Green House Gass (GHG) emissions [11].

Sun gives 100,000 TW solar power on earth surface in one hour which is sufficient to meet world energy demand for one year. Solar energy can be directly harnessed by Photovoltaic (PV) and CSP plants. CSP is a low cost and CO₂ free technology that makes it a potential candidate to be a global green energy technology as compared with PV [12]. There are four main CSP systems reported in literature and are named as, 1) parabolic trough, 2) centreal receiver or solar tower, 3) parabolic dish, and 4) LFR. Direct solar radiation based solar thermal plants are non-dispatchable sources of energy. Heat storage system is necessary to make it dispatchable. CSP receivers must have good optical performance with ability of absorbing as much heat as possible [13] and heat storage system must have high heat storage density having good heat transfer rate [14]. Compact heat exchanger is used to exchange heat between HTF and water for steam generation.

In this research, LFR based aluminum duct type CSP receiver was designed to collect solar radiation from sun. LFR reflects the incoming solar radiations from sun and focuses on aluminum receiver. HTF collects the heat through receiver and stores in heat storage tank. A heat exchanger was designed to generate steam from hot oil.

This research focuses on following contributions;

- Optimization of different parameters such as oil temperature, steam pressure and temperature for steam generation.
- Designing a steam generation system which can run 1 KVA steam generator for electricity production.
- Designing a solar powered heat storage system which can be used for cooking meal, water heating purposes.
This research work is organized into four sections. Section 1 provides a brief introduction about renewable energy sources, CO₂ emission and CSP systems. Section 2 describe the methodology of system design for CSP receiver, heat storage tank, heat exchanger and steam generation system. Experimental results and discussion for parameter optimization are presented in section 3 followed by conclusion in section 4. Section 5 indicates the future work on the designed system.

2 SYSTEM DESIGN

The detailed schematic diagram of the designed solar thermal steam generation system is given in Fig. 2. It consists of a CSP receiver, heat storage tank and a heat exchanger. Engine oil pumps are used to feed water to heat exchanger and for oil circulation. Temperature sensors are used to measure temperature of oil and steam. Data logger is used to record temperature data from all sensors. CSP receiver, heat storage tank and heat exchanger are discussed below.

2.1 CSP Receiver

The CSP receiver consists of an optical concentrator and a receiver. Optical concentrator uses LFR to reflect direct radiations from sun at different appropriate angles [15]. The angle of each mirror is manually adjusted such that the solar radiations are focused at the same line on receiver as shown in Fig. 3. The reflected radiations from sun are then focused on aluminum duct type receiver. The mirrors are placed horizontal on the ground. The design parameters of the LFR mirrors are given in Table 1.

The receiver uses a longitudinal aluminum duct as shown in Fig. 3. The three sides of the aluminum duct are covered with glass wool for insulation and ceramic wool for high temperature resistance, while bottom side is covered with 8 mm thick tempered crystal glass to trap infrared radiations and to provide insulation to the aluminum duct from bottom side.

Heat losses in CSP receiver can be calculated as:

\[
Q_R = \frac{KA\Delta t}{L}
\]

Where, \(Q_R\) = Heat transfer, \(K\) = Thermal conductivity, \(A\) = Cross sectional area, \(\Delta t\) = Temperature difference and \(L\) = Thickness of insulation, which are given in Table 1.

2.2 Heat Storage Tank

A cylindrical steel tank of 14 inch diameter and 13 inch height, is used for heat storage. The tank is filled with Shell Thermia-B oil as HTF that has low viscosity and high boiling temperature. Thermia-B oil can withstand temperatures as high as 340°C before boiling. The storage tank has been insulated from all sides with multiple layers of ceramic wool (thermal conductivity 0.12 k-W/ m.K) and glass wool (ther-
mal conductivity 0.04 k W/m·K) [16]. The ceramic wool layers have been used to withstand high temperatures in the closed vicinity of the storage tank. Fig. 4 shows a heat storage tank covered with fiber tape.

### 2.3 Heat Exchanger and Steam Generation

The aluminum duct is enclosed with a heat exchanger as shown in Fig. 3. Heat exchanger takes hot oil from heat storage tank and cold oil is pumped to CSP receiver via heat exchanger tubes. Two holes were placed at one side of the heat exchanger with connector for oil in and out. The cold water pumped to heat exchanger is converted into steam by exchanging the heat of hot oil from heat exchanger. The water flows in opposite direction of hot oil flow. A nozzle has been placed on the top of the heat exchanger to increase the pressure of steam. The design parameters of heat exchanger are given in Table 2.

Heat exchanger is insulated with three layers of fiber wool to reduce heat losses. Heat losses in heat exchanger can be calculated as follows;

\[
Q_{HE} = \frac{2 \times Pl \times Km \times \Delta t}{l} \times \ln \left( \frac{D_o}{D_i} \right)
\]

Where, \( Q_{HE} \) = loss due to surrounding, \( l \) = length of shell in meter, \( \Delta t \) = change in temperature, \( D_o \) = outer shell diameter, \( D_i \) = internal temperature of shell, \( Km \) = thermal conductivity of shell.

### 3 RESULTS AND DISCUSSION

Five experiments were performed on the solar thermal steam generation system for the purpose of finding best parameters. For the purpose of experiment only half liter water is taken as input to the heat exchanger for steam generation. The time taken to convert water into steam is observed for each experiment at different values of temperature and pressure.

First experiment was performed at 2 bar steam pressure.
The average value of steam temperature is found to be 138°C. Fig. 6 shows that temperature of oil is decreasing gradually with time due to low steam pressure. Steam temperature is also decreasing because rate of steam generation is high. At 2 bar steam pressure, half liter water is converted into steam in 4 minutes and 40 seconds. After conversion of water into steam, initial oil temperature decreases from 246°C to 229°C. Average difference of entrance and exit temperature of heat exchanger comes out to be 25°C in 275s. This shows that oil temperature rapidly decreases at low steam pressure making the system inappropriate for storing heat for long run.

In third experiment, the steam pressure is now further increased to 3 bar with 147°C as an average value of steam temperature. Fig. 8 represents that oil temperature is decreasing normally because the steam pressure is now increased enough. It can be clearly seen that the temperature of steam is almost constant with a very slight deviation after some time. It takes 6 minutes and 30 seconds to convert half liter of water into steam in this experiment. The initial oil temperature was 207°C which decreases to 197°C. The average difference of entrance and exit temperature of heat exchanger comes out to be 18°C.

Experiment four was performed at 5 bar steam pressure while the average value of steam temperature is 172°C. Fig. 9 shows that oil temperature is decreasing very slowly because the pressure of steam is high. In this graph, steam temperature, and in and out temperatures of heat exchanger remains almost constant. From Fig. 9, the heat exchanger in and out temperature also remains constant during this time. At 5 bar pressure, half liter water is converted into steam in 6 minute and 45 seconds.
Experiment 5 was performed at very high steam pressure of about 6 bar. In this experiment, the average value of steam temperature is 177°C. Fig. 10 shows that temperature of oil is decreasing very slowly because the pressure of steam is high. In this graph, an increasing trend is observed for steam temperature at the beginning and becomes almost constant after a minute. At 6 bar pressure steam generation of half liter water is converted into steam in 7 minute and 25 seconds. The initial temperature of oil is 285°C, which decreases to 280°C after conversion of water into steam. Average difference of entrance and exit temperature of heat exchanger comes out to be 15°C.

Fig. 11. Effect of pressure on rate of steam generation

In this graph, an increasing trend is observed for steam temperature at the beginning and becomes almost constant after a minute. At 6 bar pressure steam generation of half liter water is converted into steam in 7 minute and 25 seconds. The initial temperature of oil is 285°C, which decreases to 280°C after conversion of water into steam. Average difference of entrance and exit temperature of heat exchanger comes out to be 15°C.

Fig. 12. Effect of pressure on difference in HE in and out temperature

Fig. 13. Effect of pressure on half liter water to steam conversion time

4 Conclusion

The results presented in this work highlight the impact of different factors effecting the steam generation system. These parameters include oil temperature in the receiver, water pressure, oil flow, steam temperature, rate of steam generation, oil temperature in and out of heat exchanger. It has been observed that the steam generated at 5 bar pressure above 170°C system gives best performance of solar thermal steam generation system. At this steam temperature and pressure, 4.5 liter of water is converted into steam in one hour. This system provides enough steam to run 1 KVA turbine for power generation. The steam generation system is also suitable for cooking meals, space and water heating applications.

5 Future Work

The design of solar powered steam generation system can extended to:
- Design a 1 KVA steam turbine for power generation at domestic level.
- Design cooking appliances such as pressure cookers.
- Design a water heating applications at domestic level.

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References


