Experimental investigation on performance of a light weight solar receiver of a parabolic dish concentrator

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Abstract. The need to extract maximum energy from renewable resources has become quite significant in day-to-day life. Solar energy is an essential source to meet the ever-increasing demand for energy today and the potential ways are to use efficient solar dish concentrators. In the present work, an external type solar receiver in the form of spiral tube is developed with mild steel material and tested with Scheffler type parabolic dish concentrator. The experimental performance analysis is performed in the real atmospheric conditions and the energy efficiency of the receiver in open loop circulation mode is studied for a whole day. Water is used as the heat transferring fluid with 2 LPM as the flow rate. The receiver showed an average thermal energy efficiency of 43.7% with a peak value of 47% during a sunny day with average beam radiation of 743 W/m² for a HTF flow rate of 2 LPM. The result shows that this receiver has potential to be used in the solar powered process heating application in the temperature range 30°C to 100°C.

Keywords: Solar dish concentrator, receiver, energy, efficiency, heat transfer fluid.

1. Introduction

Day-by-day the energy requirements all over the world are increasing at a rapid rate. Sunlight based energy which we get as warmth and light can be changed over to helpful form either through photovoltaic cells or concentrated sun based force (CSP). Concentrating sub based force gadgets concentrate energy from the sun’s beams to warm a recipient to very high temperatures. This warmth can be changed first into mechanical power by way of steam turbines or different motors and afterward into electrical power or it can be utilized for process heating applications. Solar parabolic dish concentrators are gaining popularity because of its high efficiency. Receiver of the solar parabolic dish concentrators is an important component, whose design has to be done very carefully inorder to maximize the efficiency of the collector system.

Pavlovic et al. [1] developed an external type spiral absorber with corrugated tubes for parabolic dish concentrator and its thermal performance was investigated with water. They have also developed a numerical thermal model for further investigation in various operating conditions and different heat transfer fluids. Patil et al. [2] used a water container of 20 liter capacity as a receiver for Scheffler parabolic dish reflector of area 8 m². An average power of 1.3 kW and efficiency of 21.61% was achieved by them in their experimental performance analysis”. Mawire and Simeon [3] investigated the
thermal performance of a cylindrical cavity receiver for an SK-14 domestic parabolic dish concentrator using energy and exergy analyses method for the purpose of teaching. The receiver exergy efficiencies and exergy rates were observed to be substantially smaller than receiver energy efficiencies and energy rates. Due to circular mode of operation, their maximum energy and exergy efficiencies were found to be around 45% and 10% respectively. Wang et al. [4] performed an experimental study under actual solar radiation conditions to investigate the performance of a coiled tube solar receiver for a 57m2 parabolic dish concentrator, with compressed air as heat transfer fluid. Energy and exergy analysis showed that, the maximum energy efficiency was around 82% and the maximum exergy efficiency was around 28% for an open loop system. Thirunavukkarasu et al [5] did experimental investigation on the spiral tube external type receiver in a closed loop mode. Average energy efficiency of 56% and exergy efficiency of 4% were obtained.

Azcue et al. [6] found that the greatest exergy loss of about 40% occurred in the heliostats. A lower ambient temperature is preferred. Pye et al. [7] observed that a better energy and economic performance can be obtained from the compound parabolic concentrator if the receiver temperature is in the range of 900 to 1200 K. Ho [8] made a review study on advances in central receiver. Technologies to increase the outlet temperature of the receiver was presented. Sanchez et al. [9] developed a new method to estimate the incident heat flux on central absorbers from deteriorated heliostats. Marin et al. [10] performed an analysis for a medium size solar central receiver plant. Conroy et al. [11] presented a number of thermal stress models for the receiver. Lim et al. [12] analytically assessed a novel hybrid solar tubular receiver and a combustor and obtained economic benefits. Ebert et al. [13] determined the efficiency of tubular solar receivers in central systems. Paret et al. [14] studied the effect of the incidence angles on the cylindrical receivers of solar power towers. Barreto et al. [15] observed that higher porosity improves the thermal and hydrodynamic performance of volumetric receiver. Bopche et al. [16] developed a modified cavity receiver with conical protrusions for the solar dish and observed a performance improvement. Collado et al. [17] proposed a new cylinder flux map based on the HFLCAL model. Herrmann et al. [18] proposed a heat transfer model to capture the dynamics of the volumetric absorber. Open volumetric receivers are capable of providing heat using ambient air as the working fluid over temperatures of 700°C.

The objective of the present work is to investigate the performance of external type spiral tubular receiver in the real time solar radiation conditions. The performance investigation has been done in the open loop mode of operation so that the result can be used to check its viability for process heating applications. The temperature range of study is 30°C to 100°C.

2. Experimentation

2.1 Description of the receiver

The receiver that has been used in this experiment is a 42 mm diameter spiral tube receiver. It is mild steel coated with black matte paint. The outer diameter of the tube is 1/2 ″ and the inner diameter is 3/8 ″. The tube is bent to form the flat spiral shape and welded with no gaps to increase harvesting of the incident concentrating radiation. The inlet water comes into the circumference of the receiver and the outlet water comes from the center from the back surface of the receiver. The back surface is insulated perfectly to reduce convection and radiation losses. The insulation that has been used on the back surface of the receivers is glass wool insulation which has very low thermal conductivity. The thermal conductivity of the insulation material is 0.04 W/mK and the thickness is 25mm. and the outer layer of the glass wool has been covered with aluminum foil to improve its function. The spiral receiver has been tilted 13 degrees to be parallel to the reflector surface, and the axis of the reflector has been normal to the surface of the plane receiver. The spot of the light on the focal point has been designed to be 40 mm which means that all the reflected radiation will be within the area of the receiver. Focus length is
constant through the experimental to ensure that all the radiation is reflected in the fixed receiver. The inlet and outlet for the receiver have two valves for installing the receiver in its position. Figure 1 shows the front and back surface of the receiver with the valve used on the outlet.

![Figure 1. The front and back view of the receiver.](image)

### 2.2. Experimental setup and procedure

The experiment setup is developed and installed at a location called Kattankulathur with 12.82° latitude and 80.04° longitude. Figure 2 shows the schematic of the developed setup. The heat transfer fluid from the feed water tank is circulated with the help of a quarter HP centrifugal pump. The flow rate is adjusted with the help of a gate valve provided in the pipe line, located after the pump. A rotameter is used to measure the flow rate of heat transfer fluid with an accuracy of ±2% and ranged from (0-500) LPH with 10 LPH steps. The temperature of the HTF at inlet and exit of the receiver is measured with the help of K type thermocouple. The receiver surface temperature is measured with the help of non-touch type infrared thermometer. The solar radiation data is recorded with the help of a pyranometer. Wind speed is recorded with the help of a cup type anemometer.

![Figure 2. HTF circulation layout of experimental setup](image)
The parabolic dish Scheffler type reflector has been made from solar grade mirrors which reflect the solar irradiation and acts as reflector surface with 16 m² area. For this experiment, the dish has a two-axis tracking system the first one is seasonal tracking (north and south axis) there is an adjustable lever fixed in the center of the dish. The second type of tracking which is done by a tracking system connecting with PLC which track for the other axis (east and west axis) which is done every 3 minutes to ensure that the all radiation incident on the reflector is reflected on to the receiver, this process called day tracking. The declination angle of the sun is varying for each day that varies from a day to a day, which influences the aperture area of the dish. The declination angle of the sun has been calculated for each day of the experiment and the aperture area of the reflector. The water enters the receiver at the periphery and goes out from the rear surface of the receiver from an outlet fixed to the centre of the receiver.

2.3 Energy analysis

Solar radiation power can be estimated as [5]:

\[ Q_S = I_b A_{ap} \]  

where \( A_{ap} \) is the Aperture area of the dish.

The dish power available is given by [5]:

\[ Q_D = \eta_{opt} Q_S \]  

where \( \eta_{opt} \) optical efficiency

Useful heat gain or Receiver power can be calculated from [5]:

\[ Q_R = \dot{m} C_p (T_{out} - T_{in}) \]  

The instantaneous thermal efficiency of the receiver is estimated by [5]:

\[ \eta_{th,I} = \frac{\dot{m} C_p (T_{out} - T_{in})}{\eta_{opt} A_{ap} I_b} \]  

Useful energy gain \( Q_u \) = Energy absorbed by the collector, \( Q_a \) – Heat losses to surroundings, \( Q_L \)

Absorbed energy, \( Q_a = Ac F_R \)

Energy Losses, \( Q_L = Ac F_R U_L (T_c - T_a) \)

Hence the useful energy gain can be rewritten as,

\[ Q_u = Ac F_R * (S - U_L (T_c - T_a)) \]  

where: \( Ac \) s the receiver area and FR is the heat removal factor

\[ F_R = \frac{m C_p}{Ac U_L} \left[ 1 - \exp \left( -\frac{Ak U_L}{m C_p} \right) \right] \]  

where

- \( S \) is absorbed solar radiation
- \( U_L \) is heat transfer loss coefficient
- \( T_c \) is the average temperature of the receiver surface and
- \( T_a \) is the ambient temperature

3. Results and Discussion

The experiments were conducted during the month of February 2021 with a mass flow rate of 2 LPM. The readings that have been collected are global radiation, diffuse radiation, direct radiation, inlet temperature, outlet temperature, surface temperature, and wind speed. Figure 3 depicts the variation of various radiation components during the experiment conducted. We can notice that the direct and global radiation increased initially to reach the peak at 12:15 PM after that they decreased towards the end of the experiment. In terms of diffuse radiation, it was approximately constant with slightly increasing because of sudden sky clouds. Beam radiation is obtained from deducting diffuse component from the global component of radiation. The average direct radiation recorded was 742 W/m².
Figure 3. Variation of global and diffuse radiation during the experiment

Figure 4 depicts the variation of inlet temperature, outlet temperature, and ambient temperature for the same duration of the experiment. The temperature readings have been measured with a K-type thermocouple connected to the data logger. The outlet temperature has been increased with the increase of the direct radiation, and it can be noticed that there is matching with the trend of direct radiation. The outlet temperature after the peak has decreased till the end of the experiment. Inlet and ambient temperatures have been increased continuously during the experiment. It can be noticed that the inlet temperature and ambient temperature have a similar trend. The reason for the increase in inlet temperature because of the increase in the surrounding temperature of the water feed tank. Figure 5 shows the wind speed recorded during the experiment. The speed of the wind for the flat receiver is the base stone in order to calculate losses and calculate the overall heat losses coefficient. The fluctuation of the wind speed can be noticed all over the experiment period. The readings were every 15 minutes.

Figure 4. Temperatures profiles
The surface temperature of receiver is also measured at regular intervals for the calculation of losses. The measurement is done at three different locations on the receiver surface and the average is considered for the loss calculations. The temperature of the absorber surface has increased till it reached peak and after that has undergone a decrease till the end of the experiment. Determine surface temperature will help to understand the losses and eventually the performance of the receiver.

After measuring all the parameters required for the calculation of the performance of the receiver, the useful heat gain, losses, and the thermal efficiency were evaluated. The temperature difference of the inlet and outlet temperature represents the useful heat gain and is represented in Figure 7. We can notice that the useful heat gain has increased and reached a peak and then has decreased till the end of the experiment. The useful heat gain has the same trend as that of the temperature difference of HTF across the receiver. The peak of the useful heat gain has matched the peak of the direct radiation. 2227 watts was the best useful heat gain that occurred at 12:30 PM, and the least useful heat gain was 1252 watts at 3:00 PM.
The main indicator of the performance of any receiver or even the performance of the overall system or set-up is thermal efficiency. The useful heat gain is playing a major role in terms of determining thermal efficiency. Thermal efficiency is the useful heat gain divided by the available energy on the aperture of the receiver. The thermal efficiency of the receiver has been calculated for the same period. Figure 8 depicts the variation of the thermal efficiency of the receiver during the test period. We can notice that unlike the trend of the useful energy, which started to reach the peak and then decreased, the trend in thermal efficiency is different because it depends on the available radiation on the aperture of the receiver too. There is some fluctuation in the efficiency but we can notice that the thermal efficiency is in its highest value in the peak unlike the other times especially at the end of the day because of the low value of the radiation. The average value of the thermal efficiency for the whole day has been estimated to be 43.7%.

4. Conclusions

An investigation on the thermal performance of a solar external type receiver for a 16 m² Scheffler type parabolic dish concentrator is done at actual radiation conditions. The experimental investigations in the open loop of testing are made at a mass flow rate of 0.5 LPM to 2 LPM with an increment of 0.5 LPM. The maximum outlet temperature of 64°C has been recorded during the experiment with 0.5 LPM. At increased flow rates, the outlet temperature actually showed a decreasing trend. The receiver showed an average thermal energy efficiency of 43.7% with a peak value of 47% during a sunny day with average beam radiation of 743 W/m² for a HTF flow rate of 2 LPM. Increasing the flow rate showed an increase in thermal efficiency and heat removal rate.
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