

Effect of Once-through and Recirculated Fluid Flow on Thermal Performance of Parabolic Dish Solar Receiver

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Abstract

Objectives: The effect of mass flow rate of heat transfer fluid (HTF) during once-through (OTF) and recirculation (RF) operations, through its solar receiver was analyzed in a parabolic dish (PD) collector. **Methods/Statistical Analysis:** Inlet temperature of HTF and mass flow rate are the most important operating parameters in solar concentrating collectors along with local solar irradiance. The solar receiver was tested on sunny days (solar beam radiation intensity in the range of 500 - 700 W/m²) in February and March 2016 at Chennai, India (Latitude: 13°N, Longitude: 80°E) with HTF mass flow rates of 25, 50, 75, 100 and 125 kg/h. **Findings:** The instantaneous temperature gain by the HTF was observed to be around 100°C for the OTF with 25 kg/h due to effective heat absorption than that of 40.5°C for the RF due to more heat loss. The instantaneous energy efficiency during the RF mode is around three times more than the efficiency of OTF mode. Exergy efficiency of OTF is 3.28% more than the RF due to lower exergy destruction. **Application/Improvements:** The once-through flow has an advantage over recirculation by the way of less thermal stress effect on the receiver and piping.

Keywords: Exergy Efficiency, Once-through Flow, Parabolic Dish, Recirculation, Solar Receiver

1. Introduction

Researchers have been working for several decades on efficient technologies to collect, store and utilize solar energy. The paraboloidal reflectors are well suited for applications like preheating of furnace oil for boiler or captive power generation, preheating of biodiesel for engines, LPG vaporization before burner, pre-treatment of metals, cooking and laundry applications in the temperature range of 100 – 150°C. The water or thermic oil or air can be used as HTF. Preheating of fuel using solar collectors reduces the viscosity of fuel oils. A storage tank of 20 litres capacity was kept at the focal point of 8 m² Scheffler reflector and investigated by ¹ for the temperature sensitive process industry with the average thermal efficiency of 21.61% to reach 98°C of water. Elliptical heat pipe solar collector and flat plate collector performance were analyzed ²⁻⁴. ⁵ compared the energetic and exergetic efficiencies of the box type solar cooker, animal feed solar cooker and PD solar cooker. ⁶ carried

out charging experiments on three solar thermal oils. The more effective oil was found with the highest density and specific heat capacity for solar cooking. In ⁷ formed correlations to determine the natural convection heat loss from the V-trough solar concentrator for the Rayleigh number range of 1×10^8 to 2×10^8 through experimental study. In ⁸ demonstrated a cylindrical cavity receiver with an optical efficiency of 52%, with the heat loss factor of the receiver at 4.6 W/K. In ⁹ found that an increase in the HTF inlet temperature of PDC leads to a significant increase in collector exergy efficiency, but causes a reduction in the collector energy efficiency. Energy conservation was described by ^{10,11}. Modelling of tracking of solar cell was done by ¹². ¹³ enhanced the efficiency of solar cell by cooling.

Based on literature, the HTF inlet temperature and mass flow rates are determined to be the important operating parameters affecting the thermal performance of solar receivers. However, comparison of OTF and RF for a PDC has not been reported thus far in any literature

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for the working fluid remains liquid without phase change. The energy and exergetic analyses of the receiver for OTF and RF with different mass flow rates in a 16 m² Scheffler PDC are discussed in this paper. The preheating of furnace oil in the range of 60 – 110°C before entering to a boiler, furnace/oven and a considerable thermal performance variations are reported for the OTF and RF modes of operation.

2. Experimental Work

The paraboloidal dish concentrator was fabricated with hardened steel in an elliptical frame of minor and major axis as 3.8 m and 5.3 m respectively by Thermax Ltd, Pune, India. The same paraboloidal dish was described by^{14,15}. The cylindrical tank type receiver was fabricated with mild steel plate of 5 mm thickness. The external diameter and width of the receiver were 406 mm and 80 mm respectively. The actual concentration ratio varied from 80-100. The fixed focal length of the receiver was 2.5 m. The water flow direction is upwards through rectangular fins, inside the receiver.

The receiver is kept inclined 13.5° towards the South as per Chennai latitude as the optimal position for the seasonal movement of the Sun. The schematic layout of the PDC experimental test set up is illustrated in Figure 1.

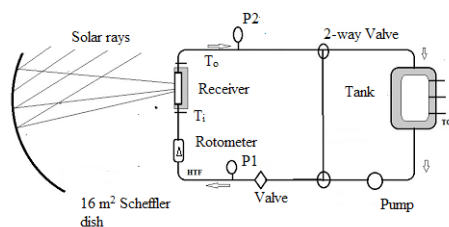


Figure 1. Schematic of the PDC setup.

The outdoor tests were conducted in February and March 2015. The solar radiation intensity (Kipp and Zonen pyranometer with shaded ring, $\pm 3\%$ accuracy), wind speed (Cup type anemometer, range 0.3 to 30 m/s, accuracy $\pm 1\%$), HTF flow rate (Glass rotometer, range 0 to 150 kg/h, accuracy $\pm 1\%$), HTF temperature and ambient temperature (K-type thermocouples, accuracy $\pm 1\%$) were measured by above mentioned quality instruments during the test periods.

The operating parameters of HTF flow rate, inlet and outlet temperature of HTF, HTF temperature in

storage tank and receiver surface temperature at multiple predetermined points are measured from the experimental setup. Cold-start operation was considered in all the cases. Mass flow rate of HTF varied in increments, 75, 100 and 125 kg/h for both OTF and RF cases. The instantaneous energy and exergy efficiency of the receiver for OTF and RF modes were compared to specify the effective mass flow rate for specific preheating application by PDC.

3. Thermal Analysis

The energy analysis focuses mainly on the heat gain from the overall input energy to the system. The incident solar energy entering the PDC is dependent on the solar beam radiation (I_b) and aperture area of the concentrator (A_c); it is expressed as Eq. (1),

$$Q_i = A_c I_b \quad (1)$$

Heat absorbed by the HTF in the receiver is dependent on liquid specific heat (C_p), mass flow rate (\dot{m}) and entry and exit temperature of fluid (T_i and T_o). The useful heat gain by the HTF (Q_u) is given by¹⁶,

$$Q_u = \dot{m} C_p (T_o - T_i) \quad (2)$$

The Nusselt correlation for the natural convective heat loss from Rayleigh number (Ra) (Incropera and DeWitt, 2002) from the dish receiver is expressed in Eq. (3),

$$Nu_{free} = 0.68 + \frac{0.67 Ra^{1/4}}{[1 + (0.492/Pr)^{9/16}]^{4/9}}, 10^5 \leq Ra \leq 10^{10}, \quad (3)$$

The Nusselt correlations for the forced convective heat loss from Reynolds number (Re) and Prandtl number (Pr) (Incropera and DeWitt, 2002) from the dish receiver is expressed in Eq. (4),

$$Nu_{forced, laminar} = 0.322 Re^{1/2} Pr^{1/3}, \quad 0.6 < Pr < 50, Re < 5 \times 10^5 \quad (4)$$

The combined free based on Grashaff number (Gr) and forced convection occurs on the vertical surface of the receiver owing to Gr/Re^2 lies between 0.1 and 10, the combined free and forced convection coefficient is expressed as:

$$Nu_{convection} = (Nu_{forced}^n \pm Nu_{free}^n)^{1/n} \quad (5)$$

In Eq. (5), the plus or minus sign indicates the assisting or opposing nature of forced convection on free

convection respectively. The value of n can be considered 3 to 4 for vertical to horizontal surfaces. Convective heat loss coefficient (h) can be found from the combined Nusselt number.

The convective heat losses are calculated from the following expression:

$$Q_{\text{convection}} = hA_r(T_w - T_a) \quad (6)$$

The radiative heat loss from the receiver is given by Eq. (7),

$$Q_{\text{radiation}} = \sigma A_r \varepsilon (T_w^4 - T_a^4) \quad (7)$$

where, A_r - surface area of the receiver, T_w - average receiver surface temperature, σ - Stefan-Boltzmann constant, ε - emissivity of receiver surface and T_a - ambient temperature.

The instantaneous efficiency of the receiver is defined as the ratio of useful heat gained by the HTF to the incident solar energy on the PDC and is given in Eq. (8),

$$\eta = \frac{Q_u}{A_c I_b} \quad (8)$$

The assumptions made for exergy analysis are steady state, steady flow energy equation, negligible potential and kinetic energy effects, no internal heat generation as well as no chemical or nuclear reactions. Exergy received by the collector by expression¹⁷ in terms of solar energy input, ambient and Sun temperature is given as:

$$E_{xi} = Q_i \left[1 - \frac{4}{3} \frac{T_a}{T_{sun}} + \left(\frac{T_a}{T_{sun}} \right)^4 \right] \quad (9)$$

where, Q_i is the heat input to the concentrator, T_a is ambient temperature and T_{sun} is the Sun's temperature (1580 K). The exergy gained by HTF in the receiver can be calculated based on the inlet/outlet temperatures (T_i , T_o), ambient temperature (T_a), specific heat of HTF (C_p) and mass flow rate of HTF (\dot{m}) is expressed in the following equations by¹⁸:

$$Ex_u = \dot{m} C_p \left[(T_o - T_i) - T_a \ln \frac{T_o}{T_i} \right] \quad (10)$$

Exergy efficiency is the ratio of exergy gained by HTF in the solar receiver to solar radiation exergy input and expressed as:

$$\eta_x = \frac{Ex_u}{Ex_i} \times 100 \quad (11)$$

4. Results and Discussion

During the outdoor experiments, the mass flow rate of water to the solar receiver was maintained constant (75, 100 and 125 kg/h) with flow control valve and the liquid phase of HTF only considered. Sunny days with similar solar beam radiation intensity (550 – 750 W/m²) were alone accounted for the energy and exergy analyses. The temperature increase of HTF, wind speed (varied from 0 to 1.75 m/s) and the ambient temperature (34 to 37°C) was measured during the tests.

The highest thermal gain by HTF was observed for the lower mass flow rate of 75 kg/h flow rate and the highest receiver wall temperature was observed for the higher mass flow rate of 125 kg/h from Figure. 2. The HTF outlet temperature was maintained at 25°C, 16°C and 12°C during the once-through flow for 75, 100 and 125 kg/h respectively. Receiver wall temperature was higher for the larger mass flow rate of water. The increase in temperature gain of HTF is higher for the lower mass flow rate of HTF. A single reflector is capable of preheating oil once-through mass flow rate of 25 kg/h (about 140 kW output) around 100°C.

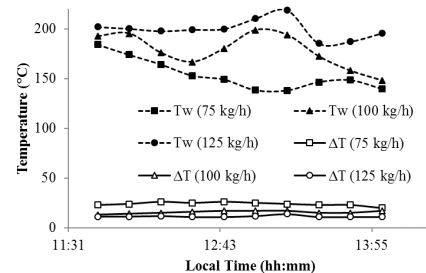


Figure 2. Receiver temperature and HTF temperature gain (OTF).

The highest thermal gain by HTF was observed for the 75 kg/h flow rate. The highest receiver wall temperature was observed for 100 kg/h due to the lower wind speed and reduced convective heat losses (Figure 3). The average difference between receiver exit and entry temperature of HTF are maintained at 24 °C, 20 °C and 16.6 °C for 75, 100 and 125 kg/h respectively during the recirculation.

The convection and radiation losses were determined based on the receiver surface temperature and the least heat loss was observed for the OTF due to increased residence time of HTF inside the receiver and effective heat absorption.

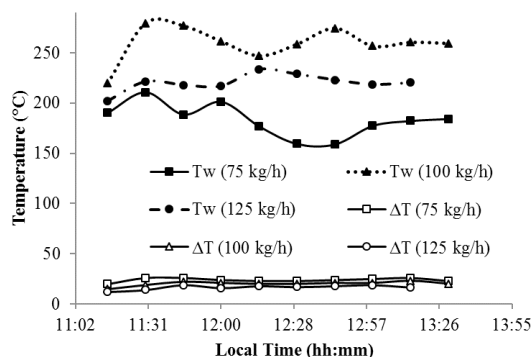


Figure 3. Receiver temperature and HTF temperature gain (RF).

The RF was maintained at a higher surface temperature so the heat loss was comparatively higher than the once-through mode. The heat loss was around 500 W for once-through mode and 800 W for the recirculation mode. The convective and radiation loss during the once-through mode decreased by 37.5% when compared to recirculation of HTF (Figure 4).

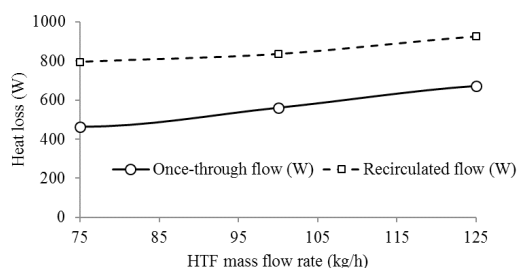


Figure 4. Receiver heat losses.

The increase in HTF mass flow rate increases the energy efficiency of the receiver significantly in Recirculated Flow (RF). Higher exergy efficiency of 8.7% was obtained during the Once-Through Flow (OTF). A little variation in exergy efficiencies is observed during the increase in the HTF mass flow rate in recirculation mode, as illustrated in Figure 5. The exergy destruction is higher in the recirculation mode of HTF by mixing of HTF in the storage tank, but this effect may be alleviated by constant fluid temperature (once-through mode) or by varying the flow rate for a particular solar radiation intensity level. However, the exergy utilization is around 3% higher for the once-through mode flow than recirculation mode of HTF.

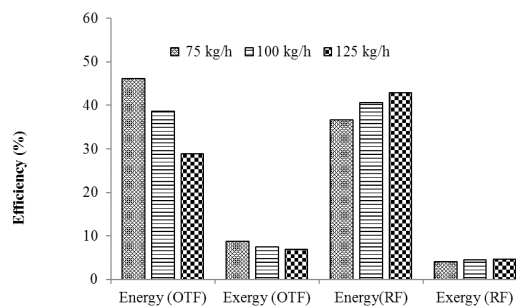


Figure 5. Instantaneous energy and exergy efficiencies of solar receiver.

The uncertainties in the measurement as follows, temperature ($\pm 0.5^\circ\text{C}$), solar radiation ($\pm 3 \text{ W/m}^2$), wind speed ($\pm 0.1 \text{ m/s}$), mass flow rate ($\pm 1 \text{ kg/h}$) and area measurement ($\pm 2\%$). The uncertainty in the experimental efficiency measurement is well below 5% through soot mean square method and it indicates that the instruments and measurements are in the sufficient range of reliability.

5. Conclusions

The solar receiver in PDC can be operated at once-through and recirculation mode based on the application requirements like preheating of fuel oil or combustion air or domestic hot water. The working fluid of once-through flow was reached around 100°C during the HTF flow of 25 kg/h. The highest instantaneous energy and exergy efficiency of once-through mode flow were 46.2% and 8.7% and for the recirculation mode flow, 42.9% and 4.66% respectively. The exergy efficiency of OTF was more than the RF of HTF which was due to exergy destruction in the recirculation mode by mixing (poor stratification) in storage tank and higher surface temperature in receiver and piping. The once-through flow has an advantage over recirculation by the way of less thermal stress effect on the receiver and piping.

6. References

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