Experimental study of concentrated thin-film receiver with phase change material

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Abstract. A Scheffler type parabolic dish solar concentrator (PDSC) of 16 m² aperture area was used to concentrate the incident beam radiation onto a solar thin receiver. Magnesium chloride hexahydrate (MgCl₂·6H₂O) phase change material (PCM) was incorporated into the thin receiver based on the availability, thermophysical properties and cost. The average energy efficiency of the thin receiver was 26.37%, 39.56% and 54.20% without PCM and 29.47% and 44.20% and 59.10% with the PCM for flow rates of water of 0.01 kg/s, 0.02 kg/s and 0.03 kg/s respectively.

Keywords: Parabolic dish solar concentrator, phase change material, thin receiver, vapourization, energy, exergy.

1. Introduction

The solar concentrators and the thermal energy storage systems (TES) are the essential components of any solar thermal system to meet the energy demand during non-solar times. The various solar collectors are discussed by several researchers [1-4]. A study on the PCM incorporated solar receiver was made for the performance improvement of the gas turbine [5,6]. The heat transfer process in a solar dish concentrator is a coupling heat transfer, where the radiation, conduction, convection and phase change coexist. The maximum temperature of the working fluid was reduced by the rotation of the receiver thereby minimizing the excess local heating and also lowered the temperature difference inside the receiver [7]. The melting of the D-mannitol PCM were determined and was affected by the free convection at the inner wall [8]. This study is mainly done on a thin solar receiver to produce steam.

2. Materials and methods

A Scheffler type parabolic dish concentrator (PDC) of 16 m² aperture area was utilized to concentrate the incident beam radiation on to the receiver surface area. The geometric and the actual concentration ratio are around 120 and 100 respectively. The PDC's two-axis tracking was done using a gear mechanism for the east-west and a clamp-lever tool. MgCl₂·6H₂O was chosen based on the availability, latent heat, physical nature, melting point and the cost. Fourteen PCM capsules with 31 mm diameter and 75 mm height on hollow cylinders were incorporated. The properties of the MgCl₂·6H₂O PCM are listed in the Table 1. The outdoor testing of the concentrated thin receiver was done on sunny days in Chennai (13°N and 80° E). A pyranometer, cup shaped anemometer, infrared

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gun and thermocouples were utilized to measure the global radiation, wind velocity, receiver surface temperature and the PCM temperature respectively. The test was conducted around the noon to ensure the maximum availability of the direct radiation.

Table 1. Thermophysical properties of the MgCl₂·6H₂O PCM

| Property            | Value       |
|---------------------|-------------|
| Density             | 1570 kg/m³  |
| Melting point       | 118°C       |
| Specific heat       | 2.25 kJ/kg.K |
| Latent heat         | 167 kJ/kg   |
| Thermal conductivity| 0.704 W/m.K |

The useful heat gained by the heat transport fluid i.e., water is a sum of the sensible and the latent heat and is expressed in the Equation (1).

\[ Q_{useful} = \dot{m}c_p(T_0 - T_i) + \dot{m}h_{fg} \]  

The energy absorbed is shown in the Equation (2) and the incident energy is expressed in the Equation (3).

\[ Q_{receiver} = Q_{sun}\eta_{optical} \]  
\[ Q_{sun} = I_bA_c \]  

where the receiver’s total energy loss is given by the Equation (4) and the energy and exergy efficiency of the thin receiver are given by the Equation (5) and Equation (8) respectively. The useful and the source exergy are expressed in the Equation (6) and (7) respectively.

\[ Q_{loss} = h_{air}A_r(T_{rec} - T_{amb}) + \sigma\varepsilon_rA_r(T_{rec}^4 - T_{amb}^4) \]  
\[ \eta_{energy} = \frac{Q_u}{A_cI_b} \]  
\[ E_{useful} = Q_{useful} - \dot{m}c_pT_{amb}\ln\left(\frac{T_{out}}{T_{in}}\right) - \dot{m}c_pT_{amb}\frac{\Delta \rho}{\rho_{T_m}} \]  
\[ E_{source} = Q_s(1 - \frac{4}{3}\frac{T_{amb}}{T_{sun}}) + \frac{1}{3}\left(\frac{T_{amb}}{T_{sun}}\right)^4 \]  
\[ \eta_{exergy} = \frac{E_{useful}}{E_{source}} \]  
\[ h_{air} = 2.8 + 3V_{air} \]

3. Results and discussion

Three different flow rates i.e., 0.01 kg/s, 0.02 kg/s and 0.03 kg/s of the water were taken for testing the receiver and the observations and performance curves are discussed. For comparison, the average values of the parameters at the corresponding flow rates without and with the PCM are taken. The PCM chosen has a melting temperature of 118°C. The energy stored inside the PCM is due to the sensible and the latent energy. The heat energy stored in the PCM was transferred to the HTF inside the receiver during the fluctuation in the radiation input and reduced the total heat input to the receiver known as the buffering. The PCM temperature was measured at five nodal points on the PCM enclosure in the receiver, and the average PCM temperature was used to study the charging behavior. A sudden increase in the energy storage was observed when the average PCM temperature crossed its melting temperature on all the trials.
Figure 1. Heat stored vs, Temperature and Time

From the Figure 2, the peak temperature of the PCM was 162°C during the trials which indicates that the PCM had melted.

4. Conclusions
The concentrated thin receiver with PCM capsules was investigated using a PDC. Despite the fluctuating radiation, the heat gained by the water remained steady during the trials. The PCM based receiver maximum energy efficiency was 59.10%, corresponding to irradiation of about 700 W/m² for the flow rate of 0.03 kg/s and the maximum exergy efficiency was about 6.88% for the same conditions.
References

[1] Tian Y, Zhao, C Y, 2013, “A review of solar collectors and thermal energy storage in solar thermal applications”, Applied Energy, 104, 538–553.

[2] M A Bashir, A Giovannelli, 2019, “Design optimization of the phase change material integrated solar receiver: a numerical parametric study”, Applied Thermal Engineering 160, 114008.

[3] Senthil, R., Nishanth, A.P., 2017, “Optical and thermal performance analysis of solar parabolic concentrator”, International Journal of Mechanical and Production Engineering Research and Development 7(5), 367–374.

[4] Senthil, R., Prabhu, S., Cheralathan, M., 2017, “Effect of heat transfer fluid input parameters on thermal output of parabolic dish solar receiver using design of experiment techniques”, International Journal of Mechanical Engineering and Technology 8(11), 850–856.

[5] Senthil, R., Senguttuvan, P., Thyagarajan, K., 2017. Experimental study of a parabolic dish concentrator of cylindrical cavity receiver with PCM, International Journal of Mechanical Engineering and Technology 8(11), pp. 910–917.

[6] Senthil, R., Sundaram, P., 2018. Improvement of thermal energy storage density of parabolic dish solar absorber with organic phase change materials, IOP Conference Series: Materials Science and Engineering 402, 012046.