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Solar parabolic trough collectors: A review on heat transfer augmentation techniques

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ABSTRACT

The earlier Parabolic Trough Collectors (PTC) with non-evacuated receiver delivered lower thermal-efficiency even with use of reflector having best optical characteristics due to convection and radiation losses. Hence heat transfer enhancement in PTC became essential to transfer maximum heat to Heat Transfer Fluid (HTF), which can further reduce the system size. The present study is focused on review and feasibility of various heat transfer augmentation techniques for PTC receiver. These include the use of evacuated receivers, nanofluids with/without inserts and use of inserts with base fluids. PTC with evacuated receivers have thermal-efficiency in the range of 65–70% which is about 10% higher than PTC with non-evacuated receiver. The enhancement in heat transfer by nanofluids is due to the combined effect of increase in effective thermal conductivity and decrease in thermal boundary layer thickness. Nanofluids in plain tube without inserts enhanced heat transfer in the range of 15–60%. The heat transfer enhancement by inserts is due to the combined effect of increased effective heat transfer area, swirl generation and increase in flow turbulence with interruption to the growth of boundary layer. Further rise in efficiency is observed for nanofluids with insert due to the combined effect. The enhanced heat transfer in laminar regime was 20–300% for base fluid with insert compared to that in plain receiver. Similarly the rise was 30–50% for nanofluid with insert. Since swirl generation is difficult in laminar regime, heat transfer enhancement is less compared to turbulent regime. The base fluids with insert augmented heat transfer by 10–200% in turbulent region compared to its flow in plane receiver. Likewise, the enhancement observed for nanofluid with insert was 15–340%. It can be concluded that, for PTC application use of insert with base fluid is beneficial in the laminar region and nanofluid with insert is justified for turbulent regime.

1. Introduction

In many solar thermal applications, temperature requirement is higher than those possible with flat plate collectors. This can be accomplished by the use of concentrating collectors which will focus the incoming solar radiation on an evacuated receiver having smaller area compared to the flat plate collectors (concentration ratio is 1). Parabolic Trough Collectors (PTC) is one of such concentrating collector which concentrates the solar insolation on the focal axis of a parabolic reflector where receiver is located. The receiver absorbs the thermal energy from incoming solar radiation and transfers the same to the Heat Transfer Fluid (HTF). The PTCs can effectively produce heat at high temperatures upto 400 °C [1]. At high receiver temperatures, it is necessary to transfer maximum amount of heat to the HTF. Otherwise, radiation heat loss from the receiver surface increases due to the increased emissivity of the receiver selective coating resulting in a lower thermal efficiency of the system. Moreover the receiver may be subjected to excessive thermal stress at high temperatures, which may lead to the failure of the tube or even damage the outer glass envelope which results in loss of vacuum. On the other side, the optimum utilization of solar radiation can cut down the overall size of the system. Hence, heat transfer enhancement in PTC is of major concern. Enhancement techniques are also adopted in other solar thermal systems such as solar cooker, using integrated evacuated heat pipes (Mehmet Esen [2]) and flat plate collectors, in which refrigerants are used in vacuum heat pipes (Esen et al. [3]). In-depth research in this field has proved the effective application of various heat transfer augmentation techniques. The present study is focused on review of such techniques with the interest of its practicability in case of PTC.

2. Heat transfer augmentation techniques

Various techniques employed for heat transfer enhancement in PTC are: use of evacuated receivers (currently a default feature in PTC), nanofluids with or without inserts and inserts in absorber tube.

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Nomenclature

G_r	Grashoff's number
MWCNT	Multi Walled Carbon Nanotubes
N_u	Nusselt number
PEC	Performance Evaluation Parameter
R_a	Rayleigh number
R_e	Reynolds number
S_w	Swirl parameter
y	Twist ratio
ϕ	Volume concentration of nanoparticles

2.1. Evacuated receivers

In the early years, during the development of PTC technology, plain tubes were used as receivers. Since plain tubes are directly exposed to the ambient, large amount of concentrated heat is lost by convection. Hence PTC with plain receiver had very less thermal efficiency. With the advancement of solar thermal technologies, evacuated receivers were developed which improves the thermal efficiency of the system. Here, plain metallic tube is surrounded by a glass envelope which is sealed to the absorber tube at both the ends. The annular space between plain metallic tube and the glass cover is vacuumed, which substantially eliminates the heat loss. A PTC was tested with two separate evacuated receivers of different diameters by Li et al. [4] to determine thermal efficiency and temperature variation with time and solar insolation for water and N_2 gas. The thermal efficiency of PTC was observed to be in the range of 68.4–76% for water when flow rate was increased from 0.0046 kg/s to 0.0342 kg/s in both the tubes. In other case, N_2 gas as HTF, the thermal efficiency drops from 40.2–28% for the flow rate of 0.0024 kg/s to 0.0012 kg/s under the temperature range of 320–463 °C. The thermal efficiency for N_2 gas was less than 40% for temperature of N_2 gas in the range of 320–463 °C. Further numerical results agree with the experimental values within ± 5.2% accuracy. Also the fluid behavior in the evacuated receiver was further numerically analyzed with varying solar irradiation and aperture area. This study is useful for further research on PTC with thermo-chemical energy storage of ammonia for continuous power generation. Daniel et al. [5] have numerically studied the performance of vacuum shell, non-evacuated and evacuated receivers in a PTC by simulating a one dimensional numerical model of the system using Matlab R-14. The vacuum shell without a selective coating was found to perform better by 10% compared to the non-evacuated receiver with selective coating. However the evacuated receiver with selective coating gave the best performance amongst all the configurations. Kasaeian et al. [6] have designed and manufactured a standard pilot model of PTC in order to investigate different methods for enhancing its performance characteristics. The optical and thermal performance, and the transient heat transfer characteristics of the system was compared using receivers viz. black painted vacuumed steel tube, bare copper tube with black chrome coating, glass enveloped non-evacuated copper tube with black chrome coating and vacuumed copper tube with black chrome coating. MWCNT/mineral oil based nanofluids with volume fraction of 0.2% and 0.3% was used for testing different receivers. The vacuumed receiver gave on an average 11% higher efficiency than bare tube due to the reduced convection and radiation losses. The maximum optical and thermal efficiencies of the system with vacuumed copper receiver was found to be 61% and 68% respectively due to high absorptivity of 0.98. In general, the global efficiency of PTC was enhanced by 4–5% for 0.2% concentration and 5–7% for 0.3% concentration of nanofluid compared to base fluid for the defined working conditions.

In PTC, the amount of heat available at the absorber tube is high due to the optical and geometrical configuration. With the use of plain receiver, substantial amount of available heat is lost to the surrounding. But with incorporation of evacuation technology to the PTC receiver, the available heat can be trapped on the absorber tube itself. Thus the quantum of heat available for HTF becomes significant. The application of heat transfer augmentation techniques can further increase the thermal efficiency of the system.

2.2. Nanofluids

Nanofluids are prepared by suspending nanoparticles (typically 2–100 nm in size) in a base fluid. The presence of nanoparticles in the base fluid increases the effective thermal conductivity of the mixture, thus increasing the overall heat transfer coefficient. Substantial studies on enhancement of heat transfer with nanofluids such as Al_2O_3/Synthetic oil, CuO/H_2O, $(CuO+Ni)/N_2$, TiO_2/H_2O, Fe_3O_4/H_2O and SiO_2/Therminol VP-1 have been performed by many researchers. The present review is focused on extending the comprehensive technique of heat transfer augmentation using nanofluids to PTC application.

The enhancement in thermal properties of various high temperature nanofluids which are used for solar thermal and thermal energy storage applications have been investigated by Shin et al. [7]. The eutectic of Li_2CO_3 and K_2CO_3 (62:38 by molar ratio) doped with SiO_2 nanoparticles (2 nm) was studied for its application in thermal energy storage systems due to its stability at high temperature. From the simulation results, the critical size of the SiO_2 nanoparticles was found to be approximately 15 nm based on interfacial thermal resistance. Experimental study was performed to evaluate the enhancement in specific heat capacity of SiO_2 (0.5%, 1%, and 2% by weight) dispersed in Therminol VP-1, eutectic of Li_2CO_3 and K_2CO_3 dispersed in SiO_2 (0.5%, 1%, and 2% by weight) and mixture of Li_2CO_3 and K_2CO_3 eutectic with MWCNT (0.05% and 1% by weight). The maximum enhancement in specific heat capacity was observed at 1% concentration of silica nanoparticles for SiO_2/Therminol VP-1 and Li_2CO_3+K_2CO_3 eutectic/SiO_2 nanofluid as 5.42% and 22.37% respectively. Similar trend was observed at 0.5% concentration of carbon nanotube for the mixture of MWCNT and eutectic of Li_2CO_3 and K_2CO_3 with maximum specific heat enhancement of 17.91%. Javadi et al. [8] have presented an overview of recent studies on performance enhancement of direct solar absorption collector by using nanofluid. It is evident from the discussion that, the nanofluids significantly enhanced the performance of such systems, but had little effect on conventional (non-direct) solar collectors. It was found that by decreasing the size of nanoparticles, the speed of sedimentation could be significantly decreased. The surface to volume ratio of nanoparticles is dominant than the surface size alone on thermal conductivity of the nanofluid. A mathematical model of PTC consisting of evacuated quartz receiver with spectrally selective coating and outer quartz cover working with $(CuO+Ni)/N_2$ nanofluid was developed by Risi et al. [9]. Further, the optimization of this model resulted in an optimum effective thermal efficiency of 62.5% with outlet temperature of 650 °C. Ghasemi et al. [10] have numerically studied the effect of Cu/H_2O nanofluid on performance of PTC. Various performance parameters such as field temperature distribution, thermal efficiency and mean outlet temperature were evaluated for the nanofluid based collector and the results were compared with the conventional PTC. The results revealed that when the flow velocity of the HTF was increased keeping all other parameters constant, the residence time of HTF in the receiver decreased. Moreover, the addition of nanoparticles to the base liquid increases the radiation absorption characteristics of the resulting mixture and hence the thermal efficiency of PTC. Three dimensional numerical analysis of fully developed turbulent flow based mixed convective heat transfer in a PTC receiver have been carried out by Sokhansefat et al. [11] for Al_2O_3/synthetic oil nanofluid under non-uniform heat flux boundary condition. The effect of Al_2O_3 particle concentration in the synthetic oil on heat transfer has been investigated with various nanoparticle concentration ($\phi \le 5\%$) at operating temperatures of 300 K, 400 K and 500 K. The heat flux boundary condition