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EFFECT OF NANOFLUID PROPERTIES AND MASS-FLOW RATE ON HEAT TRANSFER OF PARABOLIC-TROUGH CONCENTRATING SOLAR SYSTEM

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Abstract:

Sustainable power generation, energy security, and global warming are the big challenges to the world today. These issues may be addressed through the increased usage of renewable energy resources and concentrated solar energy can play a vital role in this regard. The performance of a parabolic-trough collector's receiver is here investigated analytically and experimentally using water based and therminol-VP1based CuO, ZnO, Al2O3, TiO2, Cu, Al, and SiC nanofluids. The receiver size has been optimized by a simulation program written in MATLAB. Thus, numerical results have been validated by experimental outcomes under same conditions using the same nanofluids. Increased volumetric concentrations of nanoparticle is found to enhance heat transfer, with heat transfer coefficient the maximum in W-Cu and VP1-SiC, the minimum in W-TiO2 and VP1-ZnO at 0.8 kg/s flow rate. Changing the mass flow rate also affects heat transfer coefficient. It has been observed that heat transfer coefficient reaches its maximum of 23.30% with SiC-water and 23.51% with VP1-SiC when mass-flow rate is increased in laminar flow. Heat transfer enhancement drops during transitions of flow from laminar to turbulent. The maximum heat transfer enhancements of 9.49% and 10.14% were achieved with Cu-water and VP1-SiC nanofluids during turbulent flow. The heat transfer enhancements of nanofluids seem to remain constant when compared with base fluids during either laminar flow or turbulent flow.

Keywords: Solar energy, parabolic trough concentrator, nanofluids, heat transfer coefficient.

NOMENCLATURE

Nu	Nusselt number
Re	Reynolds number
Pr	Prandtl number
C_p	Specific heat
D	Receiver tube diameter
d	Nanoparticle diameter
h	Heat transfer coefficient
K	Thermal conductivity
m	Mass flow rate
r	Nanoparticle radius

Greek symbols

μ	viscosity
ρ	Density
φ	Volume fraction

Subscripts

b_f	Base fluid
n_f	Nanofluid
l	Layer
p	Particle
f	Fluid

1. Introduction

Parabolic-trough concentrating solar (PTCS) system is one of the potential solar-energy harvesting systems wherein intense heating of the fluid is an important concern. Generally, heat-transfer enhancement techniques are based on structural variation; e.g., injection or suction of the fluid, implementation of an electrical or

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magnetic field, addition of a heat surface area, and vibration of the heated surface (Bergles, 1973; Zeinali et al., 2007). Enhancement of the thermal properties of the heat-transfer fluid is important in enhancing the heat transfer rate. Conventional heat transfer fluids (HTF) (i.e., water, oil, therminol VP1, ethylene glycol, etc.) have inherently lower thermal conductivity. Fluids with suspended solid nanoparticles of metals or metal oxides are reported to possess comparatively better thermo-physical properties (Abedin et al., 2013; Sani et al., 2010; Prasher et al., 2006; Prasher et al., 2006a; Saidur et al., 2012), which are the key factors to enhance overall system performance (Kwak et al., 2010; Javadi et al. 2013). Incorporation of nanoparticles provide the benefit of reducing heat transfer area of the heat exchanger through enhancing heat transfer capability of the working fluid (Sokhansefat, 2014). An investigation on the temperature dependence of thermal conductivity showed that over a temperature range of 21^oC to 51^oC, thermal conductivity of a nanofluid can improve from 2-fold to even 4-fold of the original value (Das, 2003). A study of 35 nm Cu/deionized-water nanofluid flowing in a tube at constant heat flux showed that increasing the volume concentrations of nanoparticles in water by 0.5% to 1.2% improves the Nusselt number of the nanofluid from 1.05 to 1.14 at the same flow rate (Xuan and Li, 2000). Use of 0.02 and 0.04 volume fractions of Al_2O_3 in water in a horizontal tube with uniform heat flux was found to enhance convective heat transfer coefficient by 9% and 15% respectively (Tsai et al., 2004; Akbari and Behzadmehr, 2007). Duangthongsuk (2009) found that 0.2% TiO2 in water improves heat transfer coefficient by 6% to 11%. It was observed that random dispersion of nanoparticles in a fluid enhances the fluid's convective heat transfer (Xuan and Li, 2003). Numerical analysis also shows increased heat transfer in the laminar flow of Al_2O_3/ethylene glycol and Al_2O_3/water nanofluids in a radial-flow system (Palm et al., 2004; Roy and Lajoie, 2004). Carbon nanohorn-based nanofluids have the potential to increase the efficiency and compactness of solar thermal systems by enhancing the sunlight absorption rate (Sani et al., 2011). Lenert (2012) investigated a 28 nm carbon-coated cobalt-therminol VP1 nanofluid-based volumetric solar receiver in high solar flux and high temperature. Authors found that the receiver's efficiency was increase when both the nanofluid column height and the incident solar flux increased. Lu et al. (2011) experimented with water and water-CuO nanofluid in a high-temperature evacuated tubular solar collector and found 30% improvement of the evaporating heat transfer coefficient due to water-CuO.

Kasaeian et al. (2012) investigated synthetic oil-Al_2O_3 nanofluid in the receiver tube of a parabolic-trough collector and found that heat-transfer coefficient of the nanofluid was increased with increased concentration of the nanoparticles. It has been noticed by several researchers that use of nanofluid improve the solar absorption rate of the solar receivers. Saidur et al. (2012) and Taylor et al. (2011) found absorption of as high as 95% solar radiation when nanofluids were used in the receivers. Dnyaneshwar et al. (2014) conducted an experiment on parabolic-trough receiver with and without tape inserts, and with water or silver-nanofluid. Using tap inserts and of water/silver-nanofluid was found to increase Nusselt number by 1.25 to 2.10 times and enhance efficiency by 135%-205%.

Tagle-Salazar et al. (2018) proposed a thermal model of parabolic trough solar collectors for heating applications using nanofluid as heat transfer fluid. The Engineering Equation Solver (EES) was used as software to simulate the model and model predictions were found to be in good agreement with the experimental results. Kasaiean et al. (2018) devised a solar thermal heat transfer network for a parabolic trough collector is introduced, in which a nanofluid is considered as the heat transfer medium. The finite difference scheme (FDM) was adopted as the approach, and a code was created in MATLAB. Authors noticed an increase in radiant loss from 26.5 to 57.3 W/m in the range of 30 to 100^oC.

Enhanced heat transfer rate in a parabolic trough solar receiver has been obtained by Chang et al. (2018) by inserting rods and using molten salt as heat transfer fluid. O'Keeffe et al. (2018) modelled the efficiency of a nanofluid-based direct absorption parabolic trough solar collector and found that the nanofluid's temperature rise is linear as it flows through the receiver. Optical and thermal analysis of a parabolic trough solar collector for production of thermal energy in different climates in Iran has been conducted by Marefati et al. (2018), wherein authors observed that Shiraz city is the best region for solar concentrating system with an average annual thermal efficiency of 13.91% and annual useful energy of 2213 kWh/m^2.

Okonkwo et al. (2018) analysed the thermal performance of a parabolic trough collector using water based green-synthesized nanofluids and found that heat transfer performance of the nanofluids shows a mean enhancement in heat transfer coefficient of 128% and 138%. Very recently, numerical analysis of magnetic field effects on the heat transfer enhancement in ferrofluids for a parabolic trough solar collector has been carried out by Khosravi et al. (2019), wherein authors noticed that using magnetic field can increase the local heat transfer coefficient of the collector tube, thermal efficiency as well as output temperature of the collector.

Literature review shows that although many research has been conducted to explore the applicability and advantage of nanofluids in enhancing heat transfer very few researches focused their application in parabolic trough solar concentrating systems (PTCS). Hence, there is still scope to work with fluid flow and variation of volumetric concentration of nanoparticles in nanofluid in heat transfer enhancement thereby performance improvement of PTCS. In this article, water and therminol VP1 were chosen as the base fluids along with seven nanoparticles (CuO, ZnO, Al_2O_3, TiO_2, Cu, Al, SiC), to investigate the effects of nanofluid mass-flow rate and volumetric concentration of nanoparticles on the performance of a parabolic trough solar concentrator system.

2. Methodology

2.1 Model development

A model of the parabolic-trough concentrator system (PTCS) is shown in Fig. 1. The effect of nanofluid mass flow rate and volumetric concentration of nanoparticles on the performance of parabolic solar receiver has been investigated using the same design of PTC system. As can be seen from the figure solar insolation approaching the mirror is concentrated on the receiver positioned alongside the focused line and heats up the heat transfer fluid (HTF) contained in the receiver tube to an elevated temperature.

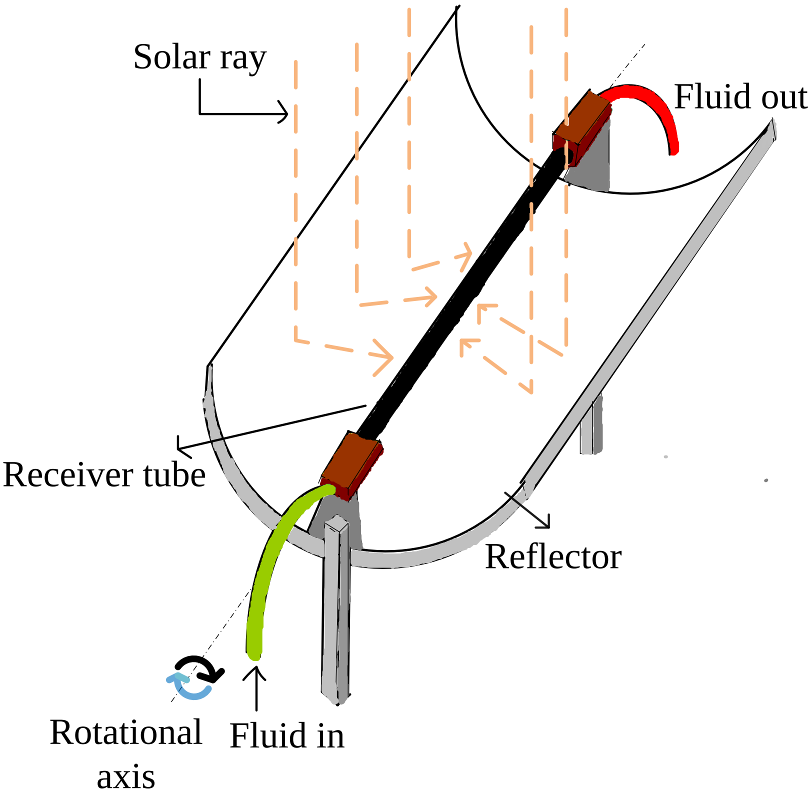

Fig. 1: Parabolic-trough concentrating solar (PTCS) system (Islam et al., 2015)

The design parameters and dimensions of the parabolic-trough system are as listed in Table 1. Table 2 lists the thermo-physical properties of water, therminol VP1, and selected nanoparticles.

Table 1: Dimensions of the system setup and operating conditions

Description	**Specifications**
Parabolic reflector:	
Length	2.0 m
Aperture	1.5 m
Focus	0.375 m
Receiver tube:	
Length	2.0 m

Inner diameter	48 mm
Tube thickness	4 mm
Mass flow rate	0.01 to 1.05 kg/s
Solid volume concentrations	up to 3%

Table 2: Thermo-physical properties of the base fluids and nanoparticles

Material	**K(W/(m².K)**	**Density (kg/m³)**	**Cp (J/kg.K)**	**Reference**
Water (34°C)	0.652	994	4174	(Holman, 1997)
Therminol VP-1 (34°C)	0.135	1053	1590	(www.therminol.com/pages/bulletins/therminol_vp1.pdf)
CuO (40 nm)	76	6320	565.11	(Eastman et al., 1997; Kole and Dey, 2012)
TiO_2 (25 nm)	8.4	4157	710	(Eastman et al., 1997; Kole and Dey, 2012)
Al_2O_3 (40 nm)	40	3960	773	(Sarkar, 2011; Kamyar et al., 2012)
Al (80 nm)	237	2700	904	(Sarkar, 2011; Kamyar et al., 2012)
Cu (35 nm)	401	890	385	(Sarkar, 2011; Kamyar et al., 2012)
ZnO (40 nm)	21	5610	523.25	(Eastman et al., 1997; Kole and Dey, 2012)
SiC (16 nm)	150	3370	1340	(Timofeeva et al.; 2010; Cengel, 2007; Pak and Cho, 1998)

2.2. Formulation of the heat transfer mechanism

The heat transfer coefficient of the nanofluid of the parabolic-trough receiver tube was calculated as follows (Brinkman, 1952):

$$h_{nf} = \frac{Nu_{nf} K_{nf}}{D_i} \tag{1}$$

The Nusselt number Nu_{nf} was calculated for laminar and turbulent flows as follows (Yu and Choi, 2003):

$$Nu_{nf} = 4.364 \tag{2}$$

with the constant heat flux considered and $Re_{nf} \leq 2300$.

$$Nu_{nf} = 0.023 \mathrm{Re}_{nf}^{0.8} \mathrm{Pr}_{nf}^{0.4} \tag{3}$$

where $2300 < Re_{nf} < 1.25\times10^5$ and $0.6 < Pr_{nf} < 100$.

In Equation (3), Re_{nf} *and* Pr_{nf} are the nanofluid's Reynolds and Prandtl numbers respectively; those were calculated as follows (Brinkman, 1952):

$$\mathrm{Re}_{nf} = \frac{4m_{nf}}{\pi D_i \mu_{nf}} \tag{4}$$

$$\mathrm{Pr}_{nf} = \frac{C_{Pnf} \mu_{nf}}{K_{nf}} \tag{5}$$

The thermo-physical properties of the nanofluids (density, viscosity, specific heat, and thermal conductivity) were calculated with the following correlations (Yu and Choi, 2003; Shahrul et al., 2014; Leong et al., 2006):

$$\rho_{nf} = \phi\rho_p + (1-\phi)\rho_{bf} \tag{6}$$

$$\mu_{nf} = \mu_{bf}(1-\phi)^{-2.5} \tag{7}$$

$$C_{Pnf} = \frac{\phi\rho_p C_{Pp} + (1-\phi)\rho_{bf} C_{Pbf}}{\rho_{nf}} \tag{8}$$

The nanofluids' effective thermal conductivity was calculated as follows (Hong and Yang, 2005):

$$Keff = \frac{(K_p - K_l)(2\beta_1^3 - \beta^3 - 1)\phi K_l + (K_p + 2K_l)[(K_l - K_f)\phi\beta^3 + K_f]\beta_1^3}{(K_p + 2K_l)\beta_1^3 - (K_p - K_l)(\beta_1^3 + \beta^3 - 1)\phi} \quad (9)$$

Equation (9) considers the effects of particle size, interfacial layer, and $\beta_1 = 1 + (h/d)\beta$, $\beta = 1 + h/r$. The rheological and physical properties were calculated at the inlet temperature. The Nusselt number and convective heat-transfer coefficient were calculated at constant and various mass-flow rates and various volumetric concentrations (0.025% to 3%).

3. Results and Discussion

3.1 Validation of the theoretical PTCS model

The theoretical model of the parabolic trough concentrator as described in the preceding section has been validated with the results obtained experimentally by the authors (Islam, 2016). For validation purpose, theoretical values two performance parameters, viz., heat gain and thermal efficiency have been compared with those obtained experimentally (refer to Fig. 2 and Fig. 3). Although experimental outcomes in all cases show relatively declining trend as compared to the corresponding theoretical values it may easily be ignored keeping in the mind that many external factors affect experimental results. Thus, it may be concluded that though there are discrepancies in terms of quantitative comparison the present theoretical model is qualitatively well validated by experimental results. Hence, further analysis using this theoretical model will be quite credible.

3.2 Nanofluid at constant mass-flow rate

The effects of the water-based nanofluids and therminol-VP1-based nanofluids with 2.5% nanoparticles at constant flow rate (0.8 kg/s) are presented and discussed in this section.

3.2.1 Effect on heat transfer coefficient

The effects of nanoparticles on heat transfer along the receiver tube are shown in Fig. 4 and 5, respectively for water and therminol-VP1-based nanofluids. The enhanced heat-transfer coefficients at 0.8 kg/s mass flow rate were found to be 4.30%, 3.36%, 5.89%, 2.71%, 9.49%, 7.95%, and 7.97%, respectively for W-CuO, W-ZnO, W-Al_2O_3, W-TiO_2, W-Cu, W-Al, and W-SiC nanofluids. With therminol-VP1 nanofluids, the enhanced heat-transfer coefficients at the same mass-flow rate were 6.46%, 6.34%, 8.20%, 7.08%, 9.78%, 9.23%, and 10.14%, respectively for VP1-CuO, VP1-ZnO, VP1-Al_2O_3, VP1-TiO_2, VP1-Cu, VP1-Al, and VP1-SiC. The results prove that the highest heat-transfer coefficient among water-based nanofluids is in W-Cu nanofluid, whereas the maximum heat transfer coefficient among therminol-VP1-based nanofluids is in VP1-SiC.

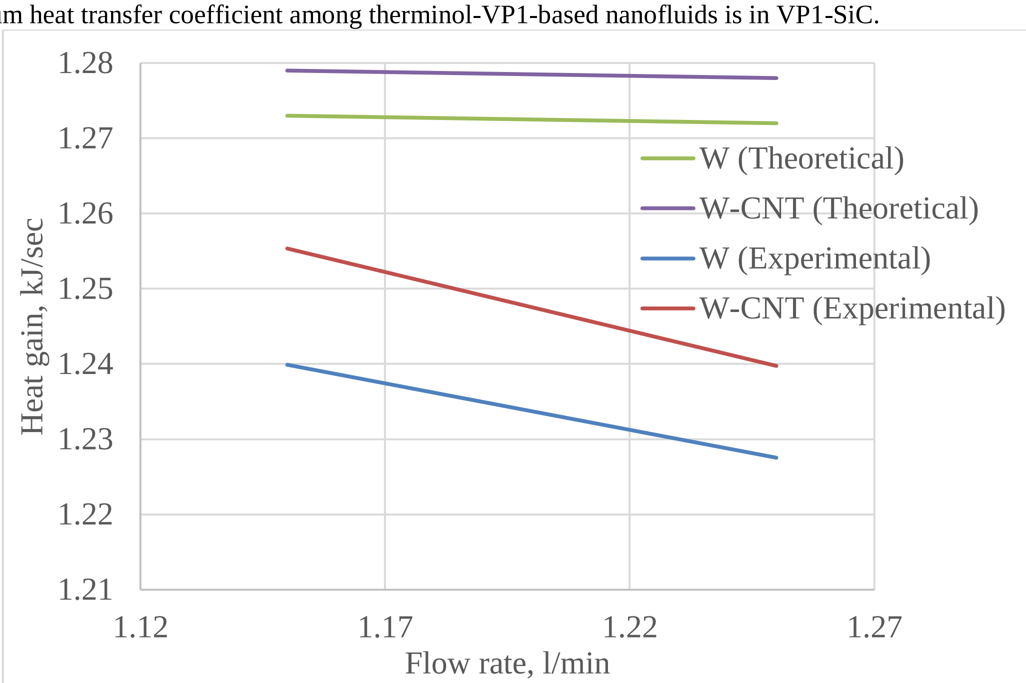

Fig. 2: Heat gain as a function of flow rate of working fluid (Irradiation 640 W/m^2)

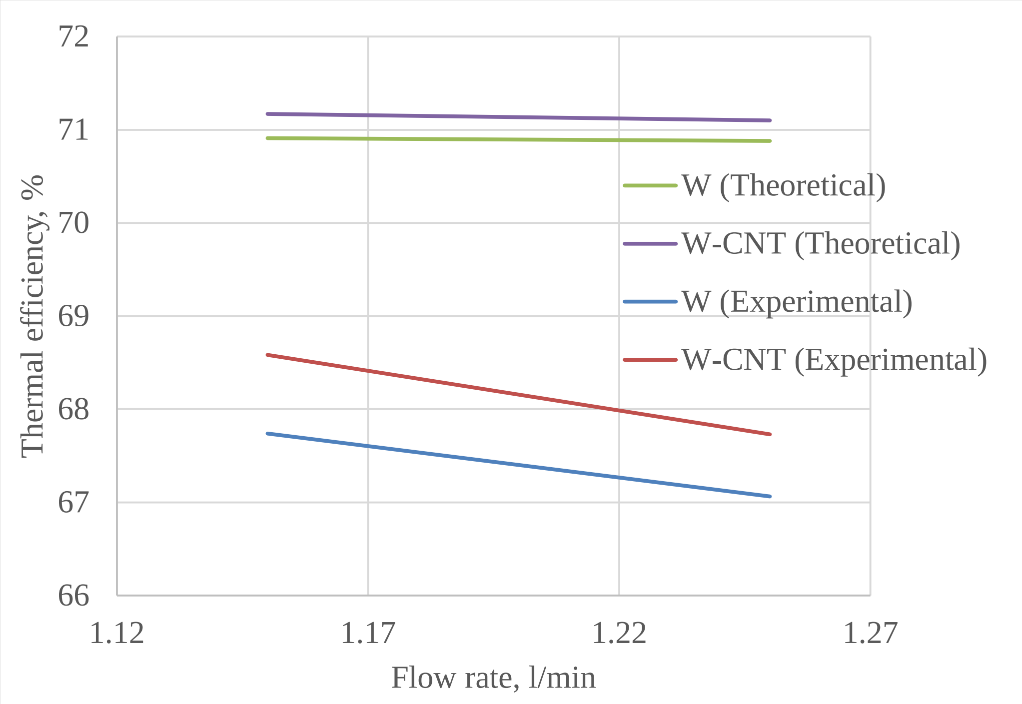

Fig. 3: Thermal efficiency as a function of flow rate of working fluid (Irradiation 640 W/m^2)

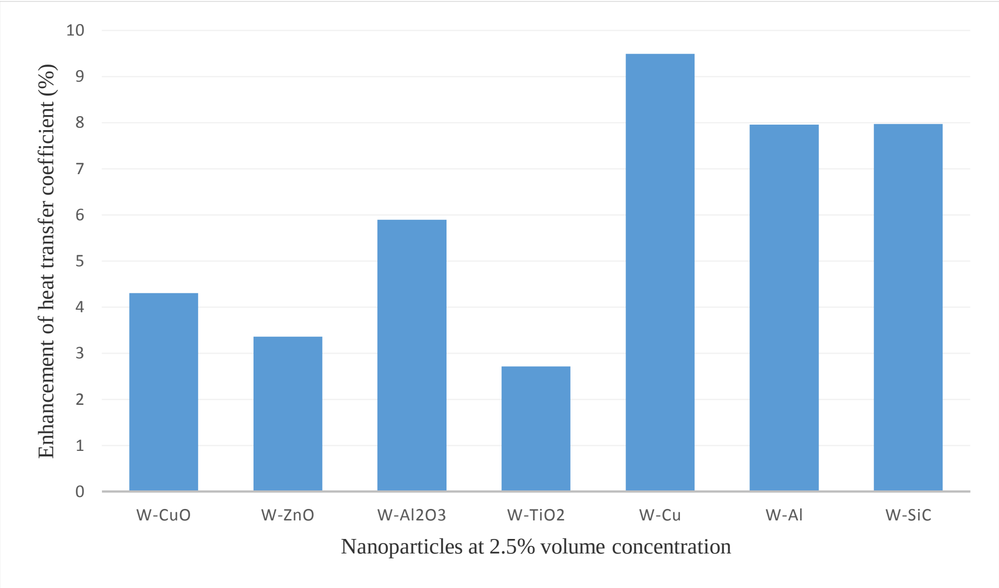

Fig. 4: Enhanced heat-transfer coefficient in water-based nanofluids at 0.8 kg/s mass flow rate

The specific heat of nanofluid is the main reason. Cu and SiC have higher specific heat than other nanoparticles. However, the thermal conductivities of W-Cu and W-SiC are 0.7688 and 0.7689 respectively, almost the same and the maximum among water-based nanofluids. Also, VP1-Cu and VP1-SiC have the same thermal conductivity (0.166 each). The specific heat of W-Cu nanofluid is 3.46% higher than that of W-SiC nanofluid, although the specific heat of SiC particle is 71.27% higher than that of Cu particle. The specific heat of water is also comparatively higher. The higher-density SiC particles thus dominate, leading to a comparatively higher-density nanofluid (1053 kg/m^3, which is 5.88% higher than the density of W-Cu), and produce 1138.5W/(m^2.K) heat transfer coefficient that is lower than that of W-Cu (1154.6 W/(m^2.K), the maxima among water based nanofluids). On the other hand, although the density of VP1-SiC is 5.58% higher than that of VP1-Cu, VP1-SiC is the one with the maximum heat-transfer coefficient. Here, the nanoparticle's specific heat is the cause of the increased specific heat of the nanofluid and the consequent increased heat-transfer coefficient. The specific heat of VP1-SiC nanofluid is higher than that of other therminol-VP1-based nanofluids which produces the highest heat-transfer coefficient 354.6 W/(m^2.K) and thus enhances heat transfer coefficient to the maxima (10.14%).

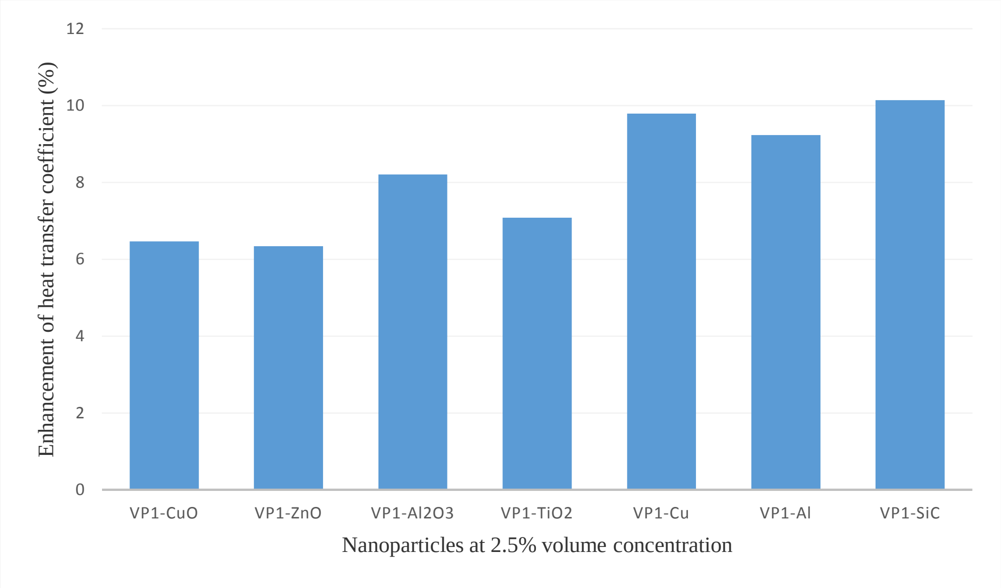

Fig. 5: Enhanced heat-transfer coefficient in therminol-VP1-based nanofluids at 0.8 kg/s mass flow rate

Other water-based nanofluids differ in their thermal conductivities, so thermal conductivity is a crucial element here. Nanofluids with higher thermal conductivity produce higher heat transfer coefficients, consequent higher heat transfer enhancement. W-TiO_2 nanofluid was found to have the lowest enhancement of heat transfer coefficient, owing to its low thermal conductivity (the lowest), although it's specific heat capacity is 4.44% and 3.28% higher than that of W-CuO and W-ZnO nanofluids respectively.

All therminol-VP1-based nanofluids have almost the same thermal conductivities. As with VP1-Cu and VP1-SiC nanofluids, specific heat capacity is the main cause for the increased heat-transfer coefficients in the other therminol-VP1-based nanofluids. Nanofluids with higher specific heat produce higher heat transfer coefficients and thus cause higher enhancement of heat transfer coefficients. But the VP1-ZnO causes the lowest enhancement of fig heat transfer although VP1-CuO possesses the lowest specific heat capacity (1453.3 j/(kg.K)). It is due to the both thermal conductivity 21 W/(m^2.K) and specific heat 523.25 j/(kg.K) of ZnO nanoparticle, respectively 72.4% and 7.4% lower than that of CuO.

3.3 Nanofluids at different mass flow rates

In this section the effects of nanofluids on heat transfer coefficient at various mass flow rates have been discussed. The nanofluids contain 2.5% nanoparticles on volumetric basis.

3.3.1 Effect on the heat transfer coefficient

The enhanced heat-transfer coefficients of water and therminol-VP1-based nanofluids are respectively as presented in Figures 6 and 7. The figures show that during laminar flow, enhancement of heat transfer coefficients does not change with change of the mass flow rate. In the transition period, the heat transfer coefficients drop until turbulent flow is reached. During turbulent flow, enhancement of the heat transfer coefficient remains constant while the mass-flow rate changed (because during laminar or turbulent flow, heat transfer enhances at the same rate in base fluid and nanofluids). Figure 4 shows 21.85%, 19.01%, 22.25%, 15.33%, 23.00%, 22.70%, and 23.30% enhanced heat-transfer coefficients in laminar flow, and 4.30%, 3.36%, 5.89%, 2.71%, 9.49%, 7.95%, and 7.97% in turbulent flow, both respectively in W-CuO, W-ZnO, W-Al_2O_3, W-TiO_2, W-Cu, W-Al, and W-SiC nanofluids. Figure 6 shows 22.94%, 22.22%, 22.63%, 20.96%, 23.08%, 23.04%, and 23.51% enhanced heat-transfer coefficients in laminar flow, and 6.46%, 6.34%, 8.20%, 7.08%, 9.78%, 9.23%, and 10.14% in turbulent flow, both respectively for VP1-CuO, VP1-ZnO, VP1-Al_2O_3, VP1-

TiO_2, VP1-Cu, VP1-Al, and VP1-SiC nanofluids. During laminar flow and according to Equation (1), thermal conductivity is the main enhancer of heat transfer coefficient (because Nusselt number is constant in all the nanofluids, as shown by Equation (2)). W-SiC and VP1-SiC nanofluids, with their maximum thermal conductivities, provide maximum enhancement of the heat transfer coefficient. The heat transfer coefficient of other nanofluids, too, have been found to depend on their thermal conductivities. During turbulent flow, the thermal conductivity of a nanofluid enhances the heat transfer coefficient of water-based nanofluids, with W-Cu and W-TiO_2 respectively having the maximum and the minimum enhancement of heat transfer coefficient. In therminol VP1-based nanofluids, however, specific heat instead is the main enhancer of heat transfer, with VP1-SiC and VP1-ZnO respectively having the maximum and the lowest heat transfer coefficient.

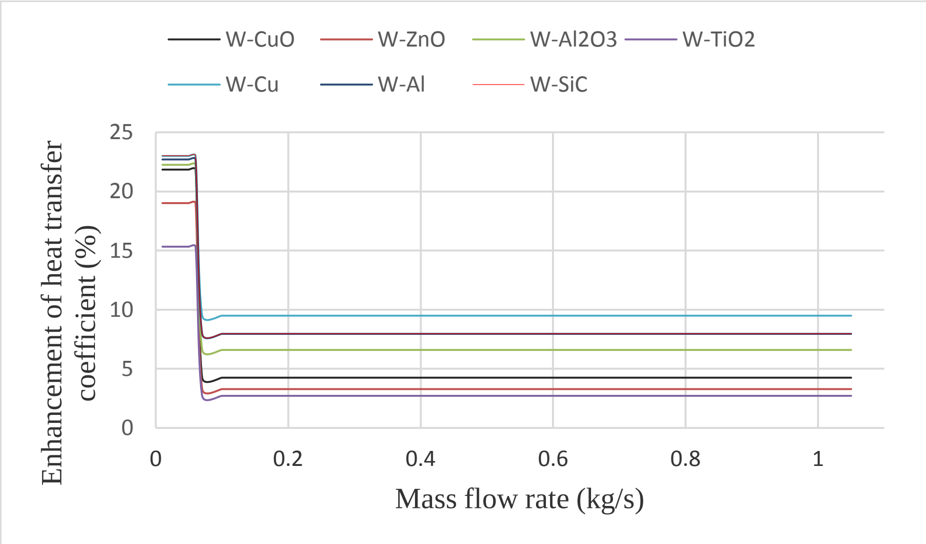

Fig. 6: Enhancement of heat transfer coefficient in water-based nanofluids at various mass-flow rates

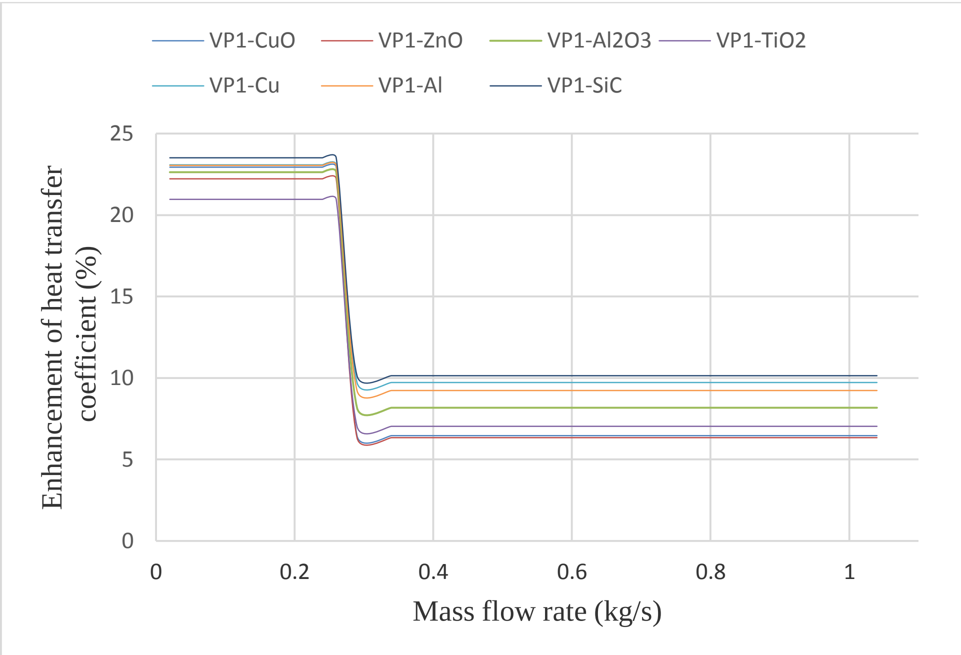

Fig. 7: Enhancement of heat transfer coefficient in therminol-VP1-based nanofluids at various mass-flow rates

3.4 Effect of volumetric concentrations of the nanoparticles

Figs. 8 and 9 illustrate the effects of the volumetric concentrations of the nanoparticles on the heat transfer coefficient. They show that adding low volumetric concentrations (0.025% to 3%) of nanoparticles (except below 0.05%) to base fluids significantly enhances the heat transfer coefficient. This indicates that the addition of nanoparticles improves the heat absorption of the heat-transfer fluid, increasing its temperature. Generally, high thermal conductivity in a nanoparticle increases the heat transfer coefficient of a fluid. The Brownian motion in nanoparticles with a large surface area for molecular collisions enhances thermal conductivity. High volumetric concentrations of nanoparticles cause high momentum, which carries and transfers thermal energy more efficiently and at a greater distance inside the base fluid, thus enhancing the heat-transfer rate of the fluid [39].

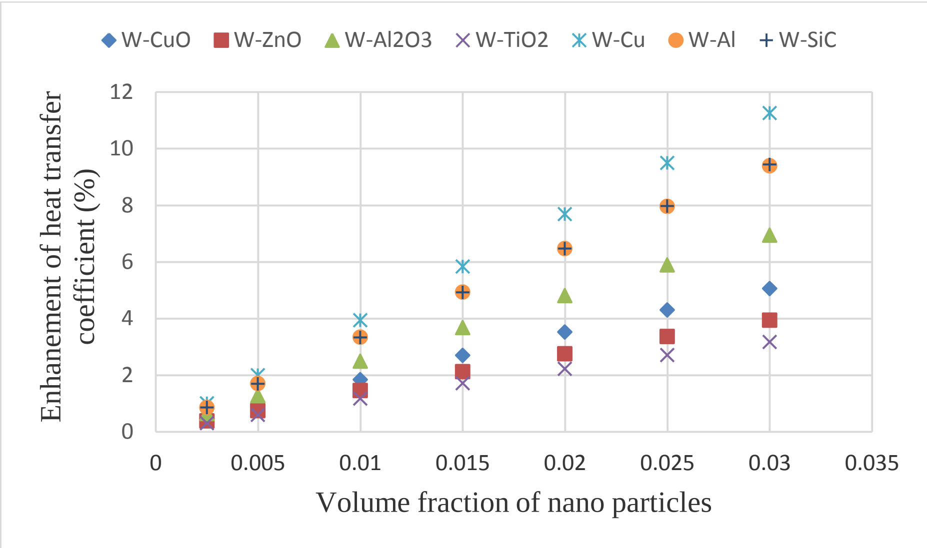

Fig. 8: Enhancement of heat transfer coefficient in water-based nanofluids with various volumetric concentrations of nanoparticles

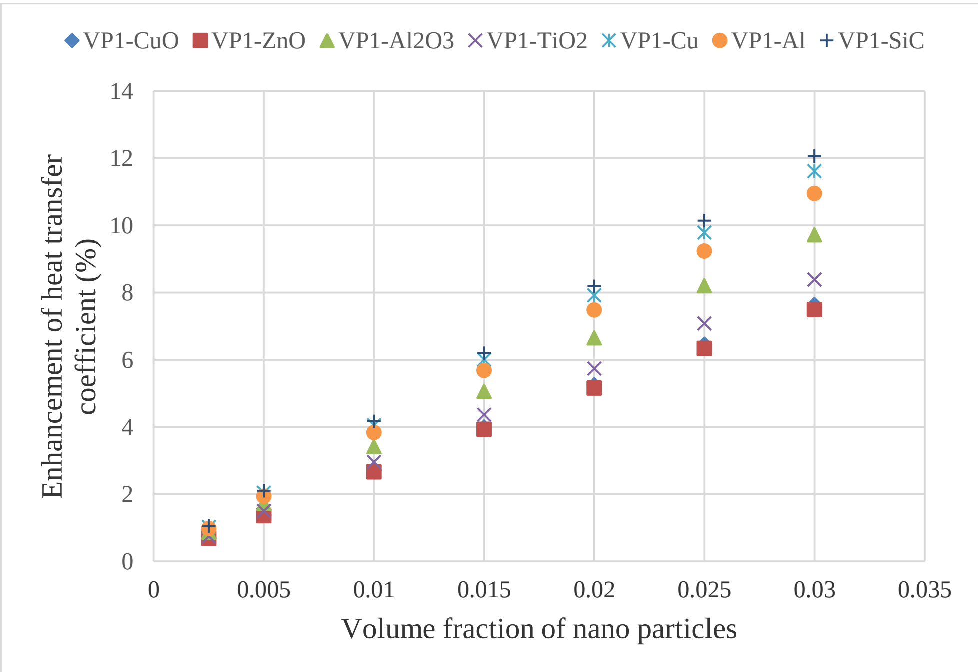

Fig. 9: Enhancement of heat transfer coefficient in therminol-VP1-based nanofluids with various volumetric concentrations of nanoparticles

4. Conclusions

The effect of mass flow rate of heat transfer fluid and the volumetric concentration of nanoparticle on the heat transfer rate and system performance of a parabolic trough concentrating system (PTCS) has been investigated in the present research. The conclusions of the research outcomes are given as below:

- At constant mass flow rate of 0.8 kg/s, the maximum enhancement of the heat transfer coefficient is 9.49% in W-Cu and 10.14% in VP1-SiC.
- During laminar flow, the maximum enhancement of the heat transfer coefficient is 23.3% in W-SiC and 23.51% in VP1-SiC.
- In laminar flow, the thermal conductivity of a nanofluid acts as the main enhancer of heat transfer rate.
- Enhancement in heat transfer drops during transition flow
- During turbulent flow, the maximum enhancement of the heat transfer coefficient is 9.49% in W-Cu and 10.14% in VP1-SiC;
- Specific heat is the main enhancer of heat transfer, as in W-Cu, W-SiC, and all therminol-VP1-based nanofluids; in other water-based nanofluids, thermal conductivity is mainly responsible.
- During laminar flow or fully developed turbulent flow, enhancement of the heat transfer remains constant due to enhancement of the heat transfer coefficients at the same rate in base fluid and nanofluids.
- Increasing the volumetric concentration of a nanofluid increases its heat transfer coefficient.

The outcomes of the present research are crucial for both industrial applications such as space heating to electricity generation and future research works. The real-world concentrating solar systems can readily apply the findings by making use of the nanofluids as recommended in this research findings, which will facilitate to improve the system performance as well as ensure commercial applicability of these systems.

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