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Performance Assessment of Parabolic Trough Collector Receiver with Al_2O_3 Nanofluid

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ABSTRACT

This paper discusses the experimental and theoretical performance of a parabolic trough receiver using a nanofluid. The main aim of this work is to analyze the performance enhancement of the parabolic trough collector system. The thermal model is developed using Engineering Equation Solver (EES). Experimental analysis was done with a water volume flow rate of 10 L/min and water inlet temperature range from 0 to 45 ^{O}C, also the volume fraction of Al_2O_3 nanoparticle varied from 1% to 5%. Experimental analysis conducted using Al_2O_3 nanoparticle mixed with water and used as heat transfer fluid in solar parabolic trough collector. Results compared and observed that the model has very good acceptance with the experimental results. It is observed that the thermal efficiency of the collector increased by 2 to 4% and receiver heat loss decreased from 0.82% to 2.72%. The receiver water temperature increased by 15% for the range of Al_2O_3 nanoparticle volume fraction. This work was carried out to investigate the use of renewable energy for water heating applications on rural farms in India. Small-sized PTC is simple in construction, economical, and does not require special skills to operate. However, considering the space requirement it would be better to investigate the method to improve the performance of PTC without changing the dimensions. One way to improve the performance is with the use of nanofluids. This work's main finding is that the Nanoparticle with a volume fraction of 4 will improve the performance. It was observed that the temperature of the water was improved by 15% and the thermal efficiency was increased by 4%.

Keywords: *Parabolic Trough Collector; Nanofluid; Heat Transfer; Thermal Analysis*

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INTRODUCTION

High energy cost, fossil fuel depletion, and global warming; are the issues that attracted many researchers to the use of renewable energy [1]. Many researchers are focusing on the various ways of enhancing the performance of solar systems. The free and abundant availability of solar energy is very much useful for heat production [2]. Parabolic trough collectors are made of a parabolic shape sheet. Such a sheet is highly reflective and points all incoming solar radiation to the central receiver tube as shown in Fig. 1. Working fluid flows through the central receiver tube and absorbs the heat energy focused by the parabolic sheet. For better efficiency and minimum loss, this central receiver tube was covered with a glass tube. Various methodologies are suggested for the improvement of parabolic performance through the collector including the use of nanoparticles [3, 4]. Sahin et. al. conducted the experimental analysis using Al_2O_3 / H_2O base fluid with a volume fraction ranging from 0.5% to 4%. It is observed that for constant heat flux conditions, higher heat transfer is observed for a Reynold number of 8000 and a volume fraction of 0.5% [5].

Working fluid used in the receiver of the parabolic trough collector is important to the

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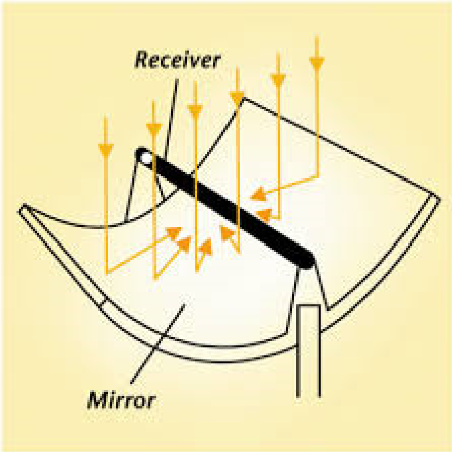

Fig. 1. Parabolic Trough Collector

enhancement of thermal performance. Hence the aim is to increase the thermal conductivity of the working fluid. Arani et. al. conducted the experimental analysis of a PTC using TiO2/H2O nanofluid with a volume fraction of 0.01, 0.02%, and different nanoparticle sizes. It is observed that the performance of a PTC was maximum for a size of 20nm [6]. Kayhani et. al. also conducted the experimental analysis using TiO2/H2O nanofluid and reported that the Nusselt number was improved by 8% which is the main reason for the higher performance of PTC compared with water as a working fluid [7]. Masuda et. al. [8] reported an experimental analysis for nanofluids with a volume fraction of 1.4 to 4.3%. It is observed that the performance was enhanced by nearly 32%. The use of nanofluids is one approach to enhance the performance of the PTC among many other approaches. Adding nanoparticles to the water enhances its thermal physical properties and in this regard, extensive work was carried out by Al-oran et al. [9-10]. Ekiciler et al. (2021) [11] reported the use of three different hybrid nanoparticles with Syltherm 800 as a base fluid. They reported that with the use of hybrid nanofluid Ag-MgO (4% volume concentration) thermal efficiency of the PTC was improved by 15%. The use of swirl inserts with and without SiO_2 nanofluid was reported by Abed et al. (2021) [12]. The base fluid was Therminol VP1 and the numerical investigation was performed. It was observed that with a concentration of 6% and swirl insert energy efficiency was improved by 15%.

In India many rural farmers are performing various farm processes like winter water heating, cleaning of farm products like potatoes and other fruit vegetables; heating and drying of farm products like grapes drying, onion drying, etc. Some processes like the production of banana chips and potato chips need hot oil. The author who belongs to said rural areas, observed these practices from his childhood first handed. For water heating applications, PTC is useful since it works on renewable energy sources and there is no need to rely on conventional sources.

Heated fluid would be then used for the various farm processes. This analysis would be then useful to decide the dimensions of the PTC setup for the heating and drying application of the farm products. While developing this mathematical model heat transfer between fluid to the receiver, receiver to cover, and loss to surroundings are considered to have a good prediction of outlet water temperature. Theoretical results are compared with experimental results for the validation of the developed model.

Many researchers reported the numerical studies; however, the experimental studies reported are few. Few experimental results are reported; however, they consider the use of deionized water as a working fluid or thermal oils. In rural areas of India, these types of water or thermal fluids are not available or even the cost is the factor. For this analysis, the hypothesis considers the addition of nanoparticles to the water (that is readily available on the farms) would increase the temperature of the water and heated water would be then used for the farm processes. Hence, the main aim of this analysis was to obtain the performance of a PTC using nanoparticles of various volume fractions and enhancement of the heat transfer fluid temperature (HTF).

Table 1. Technical specifications of the PTC system for thermal modeling [9]

Parameter	Symbol Used	Dimensional details
Width	W	5.0 m
Length	L	7.8 m
Focal distance	F	1.84 m
Aperture	A_a	39.0 m^2
Concentration ratio	C	22.74
Absorber inner diameter	D_{ri}	$66 \cdot 10^{-3}$ m
Absorber outer diameter	D_{ro}	$70 \cdot 10^{-3}$ m
Cover inner diameter	D_{ci}	$109 \cdot 10^{-3}$ m
Cover outer diameter	D_{co}	$115 \cdot 10^{-3}$ m
Cover emittance	ε_c	0.86
Cover transmittance	τ	0.95
Absorber absorbance	α	0.96
Concentrator reflectance	ρ_m	0.83
Intercept factor	γ	~1
Maximum optical efficiency	η_{opt}	0.757

DEVELOPMENT OF MATHEMATICAL MODEL

Parabolic Trough Collector

The simplest design of a solar parabolic trough collector consists of the parts like a parabola shape structure, mirrors or reflective surface, tracking system, and central receiver tube as illustrated in Fig. 1. Reflective material sheets are bent to form the parabolic shape. The receiver is placed at the focal point and all the sun rays falling on the parabola are reflected towards the receiver. The receiver is covered with a glass tube to reduce the loss of heat energy due to convection and radiation [9]. An evacuated receiver with a Glass cover is used to minimize the heat loss.

For this analysis, dimensions of the model are selected similar to the LS2 type PTC using Al_2O_3 nanoparticles mixed with water as a base fluid. PTC under study has a concentration ratio of 22.74 and an aperture area of 39 m^2 [9]. Other details of the PTC are explained in Table 1.

Thermal Model

This section explains the basic equations used for the development of a thermal model of the PTC under consideration. The thermal model is developed using Engineering Equation Solver (EES). This software is selected because it provides many useful specialized functions and equations for the solution of thermodynamics and heat transfer problems. Also, the software has its fluid properties laboratory and could be called up while developing a thermal model [12].

Thermal efficiency (η_{th}) is the ratio of useful heat (Q_u) to the available solar radiation (Q_s) and the available solar radiation is the product of direct beam radiation (G_b) and aperture area (A_a). This study considers the nominal irradiation level as 1000 W/m^2 because during the winter days when the trial was conducted, average solar radiation varied from 1000 to 1200 W/m^2 [13].

$$\eta_{th} = \frac{Q_u}{Q_s} \tag{1}$$

$$Q_s = G_b \times A_a \tag{2}$$

Useful heat energy and energy absorption are represented as

$$Q_u = \dot{m} c_p \left(T_{out} - T_{in} \right) \tag{3}$$

$$Q_u = h A_{ri} \left(T_r - T_{fm} \right) \tag{4}$$

Where, T_r is the average receiver temperature and taken as an average of the temperature measured at 5 locations along the length of the receiver tube. T_{fm} is the mean fluid temperature given by the equation

$$T_{fm} = \frac{T_{out} - T_{in}}{2} \tag{5}$$

Heat loss from the collector is estimated by equations 6 and 7

$$Q_{loss} = \frac{A_{ro} \sigma \left(T_r^4 - T_c^4 \right)}{\frac{1}{\varepsilon_r} + \frac{1-\varepsilon_c}{\varepsilon_c} \left(\frac{A_{ro}}{A_{ci}} \right)} \tag{6}$$

$$Q_{loss} = A_{co}h_{air}\left(T_c - T_{am}\right) + A_{co}\sigma\varepsilon_c\left(T_c^4 - T_{sky}^4\right) \quad (7)$$

Since the analysis considers the steady state conditions, thermal losses as explained above are considered the same. In the above equation, ambient temperature is considered as 300 K and the sky temperature is estimated by equation 8.

$$T_{sky} = 0.0553T_{am}^{1.5} \quad (8)$$

The convective heat transfer coefficient is estimated using equation 9 with a wind velocity of 1 m/s, which is nearly 10 $W/m^2.K$

$$h_{air} = 4.V_{wind}^{0.58}.D_{co}^{-0.42} \quad (9)$$

Using an energy balance net heat received must be equal to the sum of heat utilized and heat loss and the equation can be established as:

$$Q_s\eta_{opt} = Q_u + Q_{loss} \quad (10)$$

The heat transfer coefficient for the absorber fluid is calculated using the Nusselt number. The receiver tube length was long enough to ensure that the flow is fully developed during the experimentation. Readings were obtained after the hydraulic entry length to ensure that the flow is fully developed. For turbulent flow, Dittus-Boelter equation 11 was used and the heat transfer coefficient is calculated using equation 12.

$$N_u = 0.023R_e^{0.8}P_r^{0.4} \quad (11)$$

$$N_u = \frac{hD_{ri}}{k} \quad (12)$$

$$R_e = \frac{4\dot{m}}{\pi D_{ri}\mu} \quad (13)$$

$$P_r = \frac{\mu c_p}{k} \quad (14)$$

Thermal Properties of the Nanofluid

For this analysis, Al_2O_3 nanoparticles are selected because of their easy availability in nearby locations of the study. Table 2 represents the summary of the properties of the selected nanoparticles

Properties of the nanofluid are calculated based on the volume fraction of the nanoparticle (ϕ). Equations 15 to 18 are used to estimate density, specific heat, thermal conductivity, and viscosity:

$$\rho_{nf} = \rho_{bf}\left(1-\phi\right) + \rho_{np}\phi \quad (15)$$

Khanafer and Vafai [10] conducted thermo-physical characterization for the nanofluids and suggested the formula for the calculation of the nanofluid's specific heat.

$$c_{pnf} = \frac{\rho_{bf}\left(1-\phi\right)}{\rho_{nf}}c_{pbf} + \frac{\rho_{np}\phi}{\rho_{nf}}c_{pnp} \quad (16)$$

Duangthongsuk and Wongwises [11] suggested the equation for calculating the thermal conductivity of the nanofluid:

$$k_{nf} = k_{bf}\left[\frac{k_{np} + 2k_{bf} + 2\left(k_{np} - k_{bf}\right)\left(1+\beta\right)^3\phi}{k_{np} + 2k_{bf} - \left(k_{np} - k_{bf}\right)\left(1+\beta\right)^3\phi}\right] \quad (17)$$

$$\mu_{nf} = \mu_{bf}\left(1 + 2.5\phi + 6.2\phi^2\right) \quad (18)$$

The above equations are then used for performance analysis as well as solving the mathematical model. Input parameters used are defined in Table 1, 2 and 3

PTC TEST SETUP

Solar parabolic trough converts solar energy into thermal energy. This thermal energy is then used to heat the heat transfer fluid passing through the receiver tube located at the focus of the collector. The parabolic-shaped reflector is a metal sheet covered with highly reflective material. The reflected solar radiation is then concentrated on the receiver. The geometry of the parabolic trough collector includes rim angle, concentration ratio, focal length, collector length, receiver tube diameters, etc.

Rim Angle $\varnothing$ is the angle between the optical

Table 2. Properties of the nanofluid [9]

Property	Symbol Used	Value	Unit
Density	ρ	3960	kg/m^3
Specific Heat	c_p	773	$kJ/kg.K$
Thermal Conductivity	κ	40	$W/m.K$

Table 3. Specifications of the PTC system

Parameter	Symbol Used	Dimensional details
Width	Wa	1.6 m
Length	L	2.5 m
Focal distance	f	0.486 m
Rim angle	Ø	40^{O}
Absorber inner diameter	D_{ri}	0.0224
Absorber outer diameter	D_{ro}	0.0254
Cover emittance	ε_c	0.86
Cover transmittance	τ	0.95
Absorber absorbance	α	0.9
Concentrator reflectance	ρ_m	0.83
Intercept factor	γ	~1

axis and the collector axis and is given by the equation:

$$\sin(\varnothing) = \frac{w_a}{2r}$$

Where w_a is the aperture width and r is the radius of the parabola. Focal length is the distance between the focal point and the collector rim, given by the equation:

$$f = \frac{w_a}{4\tan\left(\frac{\varnothing}{2}\right)}$$

The concentration ratio is the ratio of the collector aperture area and the receiver surface. It is given by the equation:

$$C = \frac{w_a}{\pi d_o}$$

Where d_o is the receiver's outer diameter.

Based on the above parameters a small size PTC system was manufactured with the specifications represented in table 2. The reflector is made of mirror-finished stainless steel sheet with 86% reflectivity. The receiver is coated with matte black paint with an absorptivity of 0.9. The receiver is covered with a concentric acrylic tube with an annulus gap of 1.6 cm. The acrylic material has higher transmissivity and is stronger than glass. The PTC system is located in Maharashtra. The system is set on the North-South axis and provided with manual tracking. Experiments were conducted in Jan 2021. The heat transfer fluid was selected as water. Fig. 2 represents the photograph of the test setup used for experimentation. The water flow rate through the receiver was varied and hence the range of Reynolds number for this experimentation varied from 5000 to 25000. Also, it is observed that the Reynold number not only varies with velocity or mass flow of the fluid but it also varies due to changes in volume concentration. It is observed that with the increase in volume concentration density of the nanofluid increases. Another reason for an increase in density is because a very small change in the viscosity of the nanofluid.

Aluminum oxide nanopowder APS 80 nm ($\alpha - phase$) with 99% purity was purchased from the Indian industry Otto Chemie Pvt. Ltd. It has an average particle diameter of 60 – 80 nm. Various test fluids of different proportions were prepared by adding the nanoparticles to the distilled water. Sedimentation of the nanoparticle was avoided by maintaining a solution pH value equal to 7 and using an ultrasonic bath.

RESULTS AND DISCUSSION

Equations 1 to 18 are used in the development of a thermal model using an engineering equation solver. The base fluid is selected as water and the nanoparticle selected for study is Al_2O_3. For the present study concentration of these nanoparticles varied from 1% to 5%. Water inlet temperature varied from 0 to 45°C since the temperature of the water varies within these limits during the seasonal changes. Analysis was conducted for water volume flow rate of 10 L/min as overhead tanks constructed in the farms deliver the water at the nearly same rate.

Fig. 3 represents the effect of the volume concentration of nanoparticles on the thermal efficiency of the concentrator. It is observed that for the fixed water inlet temperature and flow rate thermal efficiency almost increases linearly with an increase in volume concentration from 1% to

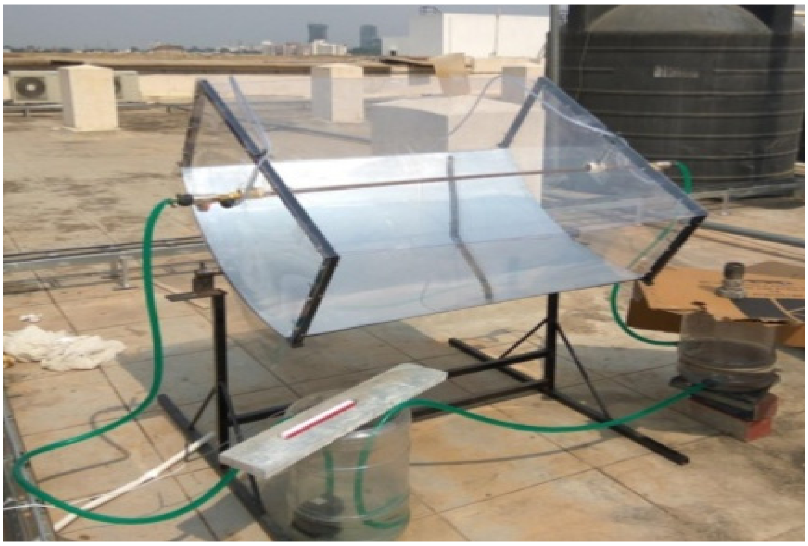

Fig. 2. Photograph of the experimental setup

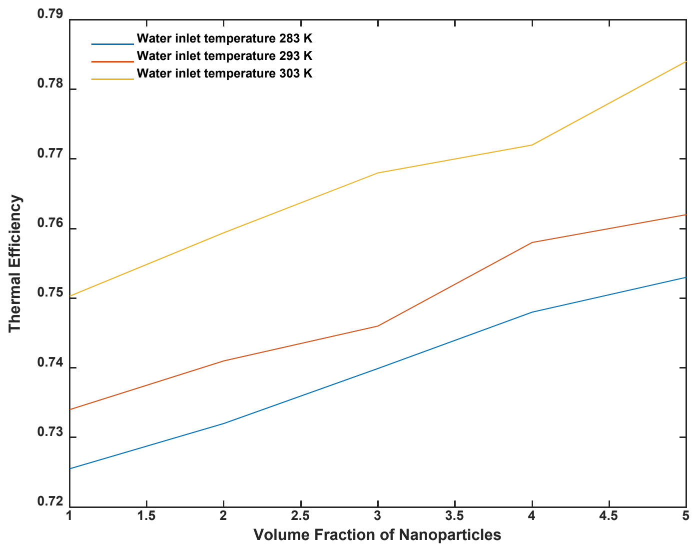

Fig. 3. Effect of volume concentration of Nanomaterials on thermal efficiency

5%. With the increase in volume concentration of nanoparticles from 1% to 5% at a water inlet temperature of 293K, thermal efficiency increased from 1.90% to 5.79%. It is also observed that with an increase in inlet temperature thermal efficiency decrease from 0.72% at 10^{O}C to 4.16% at 30^{O}C for a volume concentration of 1%. The rate of increase in thermal efficiency is higher for a concentration of 4% to 5% at high temperatures. Hence it is recommended to use nanofluids for higher water inlet temperature. Enhancement in thermal efficiency is observed because of the thermal conductivity of nanofluid increases with an increase in volume concentration of the nanoparticles. Fig. 4 indicates variation in thermal conductivity of the nanofluid with change in volume concentration of the nanoparticles. Hence it would be better to observe or compare the performance of various nanofluids under the same operating conditions. It is always better to select nanofluids of higher thermal conductivity of higher thermal efficiency. Table 4 represents the comparison of these results with published results [18]. It was observed that the thermal efficiency increases till the volume fraction of 4 and thereafter it is constant. The rate of rising in thermal efficiency is higher till the

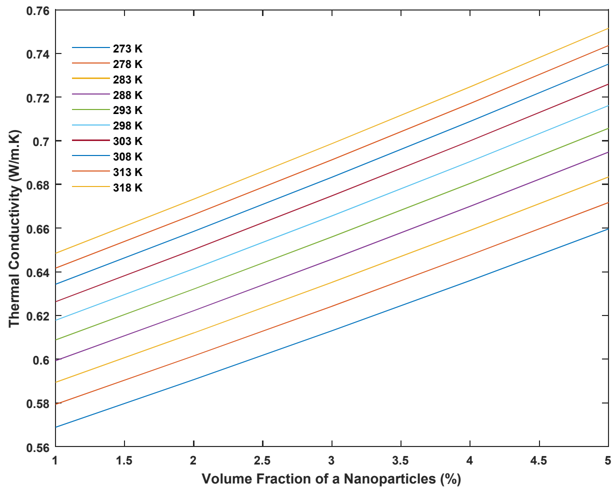

Fig. 4. Effect of volume fraction of nanoparticles on thermal conductivity of nanofluids

Table 4. Comparison of present work with the previous work

Volume fraction of the nanoparticles	Thermal Efficiency (Present work)	Thermal Efficiency (Yanjuan Wang et al. 2016) [18]
1	0.750	0.7725
1.5	0.755	0.7728
2	0.760	0.773
2.5	0.765	0.773
3	0.770	0.7735
3.5	0.772	0.7735

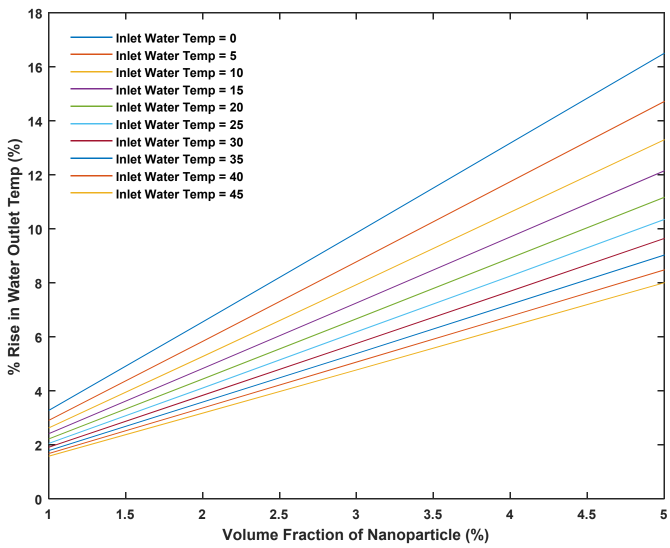

Fig. 5. Effect of volume fraction of the nanoparticle on receiver water outlet temperature

volume fraction of 4. Thus the volume fraction for the higher thermal efficiency is considered as 4 which is agreed with the previously published work of Wang et al. [18]

Fig. 5 represents the receiver exit water temperature. The main objective is to enhance the water temperature because this heated water would then use for any application. It is observed that the temperature of water increases almost linearly. For a water inlet temperature of $0^{O}C$ rise in temperature is

Table 5. Comparison of Experimental and Theoretical Results

Findings	Theoretical Model	Experimental
% change in water temperature	21%	16%
Thermal Efficiency	0.786	0.775

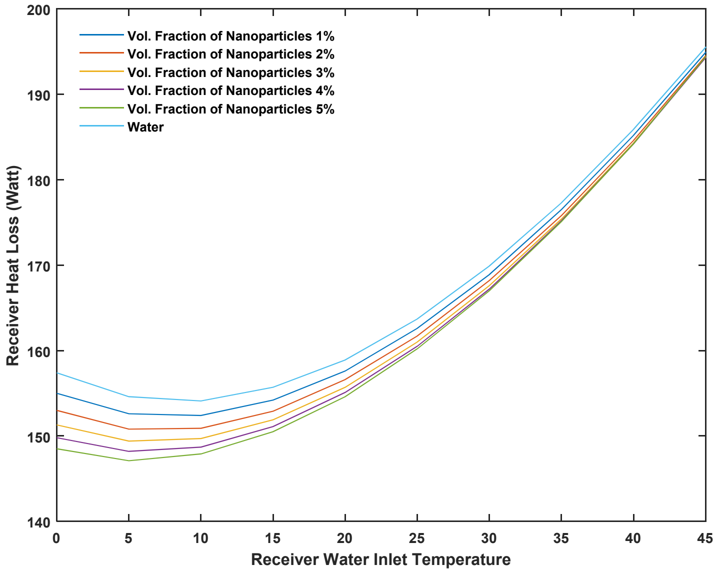

Fig. 6. Effect of volume fraction of the nanoparticle on the receiver heat loss

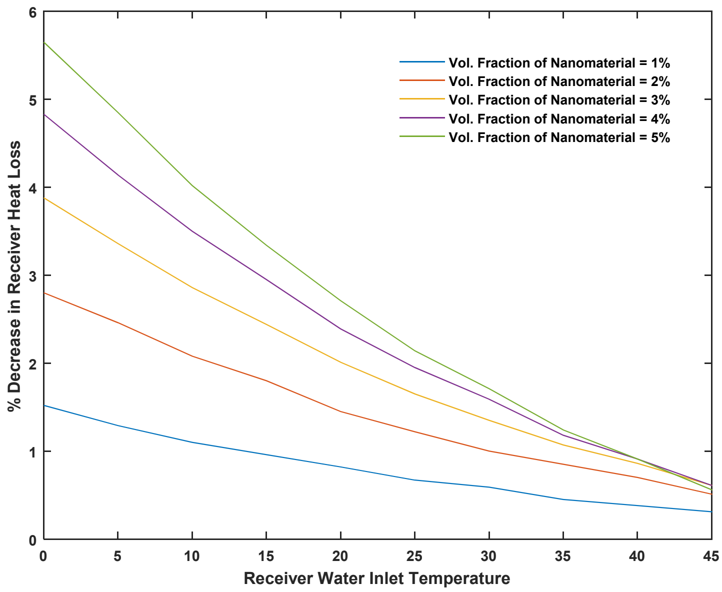

Fig. 7. Effect of volume fraction of the nanoparticle on receiver heat loss

observed from 3 to 16% with an increase in volume fraction of nanoparticles from 1 to 5%. However, for higher inlet water temperature rise is observed too from 2 to 8% this is because with an increase in temperature of the receiver heat loss increases as represented in Fig. 6 and 7. It is observed that for the inlet water temperature of 20^{O}C receiver heat loss increases from 0.82% to 2.71% as the volume fraction of nanoparticle increases from 1 to 5%. Heat loss from the receiver tube was increased this

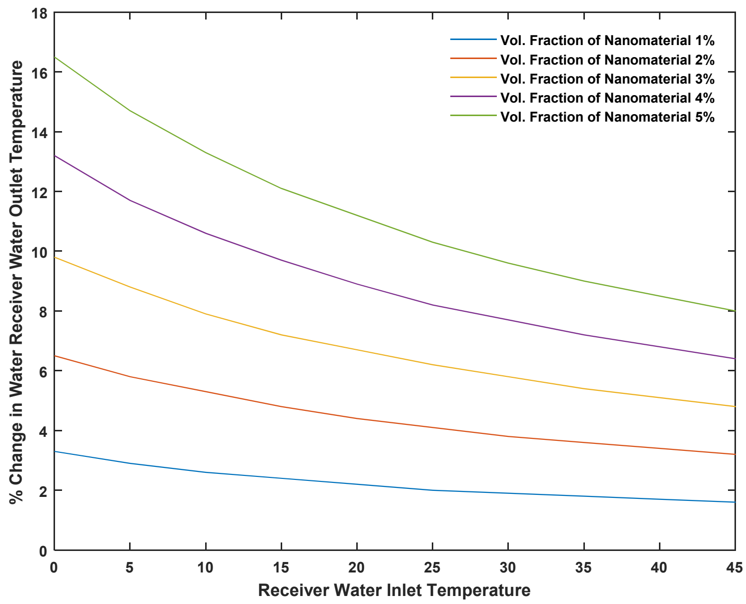

Fig. 8. Effect of Volume fraction on receiver water outlet temperature

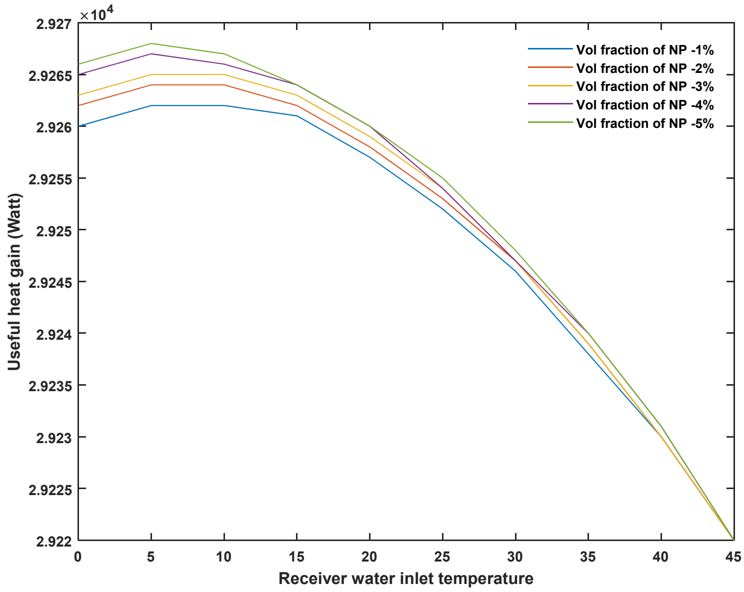

Fig. 9. Effect of Volume fraction on receiver useful heat gain

is because of the increased thermal conductivity of the nanofluid. An increase in thermal conductivity reduces the thermal resistance in the heat transfer and results in more heat loss from the receiver tube.

Fig. 8 represents the percentage change in receiver water outlet temperature; it is observed that as the volume fraction of nanoparticle increase from 1 to 3% receiver outlet temperature increases by 3 to 4% only. For a higher volume fraction of nanoparticles (4 to 5%), water outlet temperature increases by 8 to 16%. An increase in water temperature is observed even though there is an increase in heat loss this is because of a higher heat transfer coefficient. It is observed that HTC increases linearly from 1.8 to 8.4 %.

Useful heat gain for receiver water is represented in Fig 9. It is observed that for a lower water inlet temperature from 0 to 15 heat gain is increased

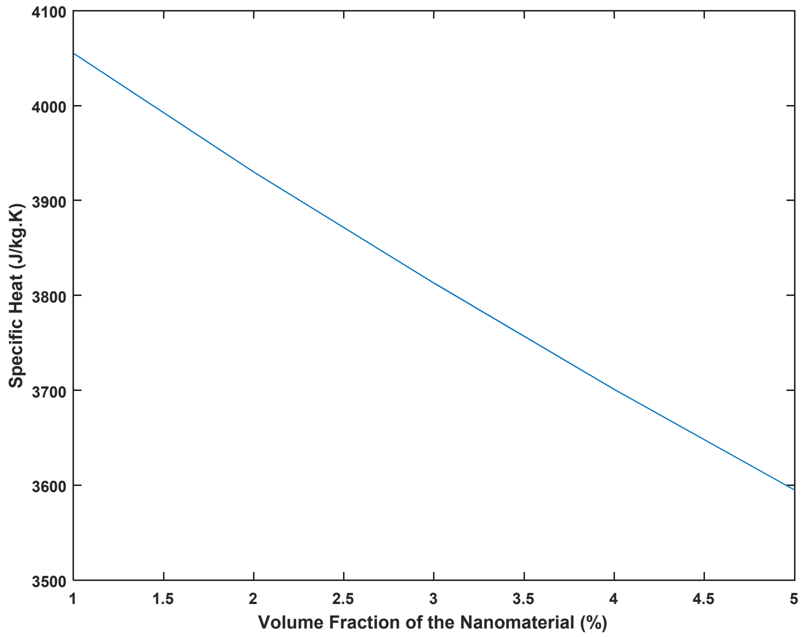

Fig. 10. Effect of volume fraction of the nanoparticle on the specific heat of nanofluid

and observed as high for 5% of nanoparticle volume fraction. With an increase in water inlet temperature above 25^{O}C it decreases rapidly. This is because the specific heat of the nanofluid decrease as represented by Fig. 10.

CONCLUSIONS

The use of nanoparticles for the thermal enhancement of the parabolic trough collector was investigated through mathematical modeling and experimental analysis. The mathematical model was analyzed using Engineering Equation Solver (EES). The developed model was analyzed with a volume flow rate of water as 10 L/min and a range of inlet temperature of water from 0 to 45 ^{O}C, also the volume fraction of Al_2O_3 nanoparticle varied from 1% to 5%. Following are the conclusions made from the study

- PTC performance was an improvement by using Al_2O_3 nanofluids. The temperature of the water was increased by 15%. The addition of the nanoparticle with volume concentration 4 increases the water temperature and hence can be used for farm applications like vegetable cleaning, banana chip, and potato chip formation, and other agricultural products
- Thermal efficiency of the PTC was improved by 2 to 5% with the use of using 4-5% of Al_2O_3 water base nanofluid
- During winter water temperature is low on the farms. During the experimentation, it was observed that for a low water temperature thermal efficiency increased from 1.90% to 5.79%. The rate of increase in thermal efficiency is higher for nanoparticle concentrations 4% to 5%. Hence, it is recommended to use nanofluids during the winter season to improve process water temperature.
- At higher water temperature heat loss from the receiver increases. This is due to the larger variation of the thermal conductivity hence during the summer season nanoparticle volume concentration should be lower by up to 3%
- An increase in water temperature is observed even though there is an increase in heat loss this is because of a higher heat transfer coefficient. It is observed that HTC increases linearly from 1.8 to 8.4 %.
- PTC receiver with spiral tape and nanofluid is recommended for further improvements in the water temperature. The use of spiral tape will result in turbulence and hence the heat transfer coefficient. However, there is a need for experimental investigation as it would result in a larger pressure drop along the tube length.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

NOMENCLATURE

ANI	Aperture normal irradiance (W/m^2)
A_a	Aperture area (m^2)
A_r	Receiver area (m^2)
A_{ir}	Inside the cross-sectional area of the absorber tube (m^2)
C_p	Specific heat (kJ/kg.K)
D_{ci}	The inner diameter of a glass cover (m)
D_{co}	The outer diameter of a glass cover (m)
D_i	Inner diameter of absorber tube (m)
DNI	Direct normal irradiance (W/m^2)
D_o	Outer diameter of absorber tube (m)
HTF	Heat transfer fluid
k_c	Thermal conductivity of a glass cover
L	Collector length
Q_{abs}	Solar radiation absorbed by the receiver tube
Q_u	Net energy transfer to the HTF inside the receiver tube
T_a	Ambient Temperature
T_i	Receiver inner surface temperature
T_{co}	The outer surface temperature of a glass cover
T_{ci}	The inner surface temperature of a glass cover
T_{fi}	HTF temperature at the inlet of the receiver
T_{fm}	Mean fluid temperature
T_{sky}	Sky temperature
Wa	Parabola's aperture width
nf	Nanofluid

GREEK LETTERS

α_c	Absorptance of receiver surface coating
γ	Intercept Factor
σ	Stephan Boltzmann's Constant (5 x 10^{-8} W/m^2.K^4)
$\varnothing$	Latitude location of the solar field
μ	Absolute viscosity of heat transfer fluid
$\eta_{optical}$	Optical efficiency
$\eta_{thermal}$	Thermal collector efficiency
θ	Angle of Incidence
θ_z	Zenith Angle
ρ_{cl}	Clear mirror reflectivity
ρ_{nf}	Density of nanofluid
ρ_{bf}	The density of the base fluid
τ	The transmittance of the glass cover
ε_{ci}	Emittance of glass covers the inner surface
ε_{co}	Emittance of glass covers the outer surface
ε_r	Emittance of receiver

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