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Numerical analysis of performance of solar parabolic trough collector with Cu-Water nanofluid

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ABSTRACT

In the present work the effect of Cu-Water nanofluid, as heat transfer fluid, on the performance of a parabolic solar collector was studied numerically. The temperature field, thermal efficiency, mean-outlet temperatures have been evaluated and compared for the conventional parabolic collectors and nanofluid based collectors. Further, the effect of various parameters such as fluid velocity, volume fraction of nanoparticles, concentration ratio and receiver length has been investigated. The results show that, by increasing the volume fraction of nanoparticles, the performance of the solar parabolic collector enhances.

Keywords: *Solar energy; Solar parabolic trough collector; Cu-Water nanofluid; Numerical analysis; Thermal Performance.*

INTRODUCTION

Solar energy currently represents the most abundant, inexhaustible, non-polluting, effective and free energy resource available in almost all parts of the world [1-3]. If the available solar energy on the earth is properly harnessed the world may not have need for fossil fuel any more [4, 5]. In recent years, considerable attention has been paid to solar thermal concentrating systems which are regarded as environmentally friendly alternatives to conventional thermal power systems. In solar thermal concentrating systems, incident solar radiation is converted into thermal energy at the focus [6]. These systems are classified as either point focus concentrators (parabolic dishes and central receiver systems) or line focus concentrators (parabolic trough collectors and linear Fresnel collectors).

The Parabolic Trough Collector focuses direct normal irradiance or beam radiation onto a focal line on the collector axis. An absorber tube with water or temperature stable synthetic oil flowing inside absorbs the concentrated solar energy and raises its temperature at the focal line.

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Recent studies have indicated that the addition of nanoparticles to conventional working fluids can improve efficiency of a flat-plate solar collector [7]. PH values of the nanofluid have also been indicated to be effective by Yousefi et al [8]. They investigated the impact of using water with carbon nanotubes on the efficiency of a flat-plate solar collector and concluded that an increase on the difference between PH of the nanofluid and that of the isoelectric point causes the increase in the efficiency. The experimental study by Yousefi et al. also for flat-plate collectors showed an increase of 28.3% in the efficiency of the collector when operating with Al_2O_3-water nanofluid instead of pure water [9]. This paper attempts to extend that work by analyzing the heat transfer and flow aspects of the operation of a concentrated solar collector in order to optimize its operations and achieve higher efficiencies. The focus of this paper has been primarily on parabolic trough collectors which are currently used for electricity generation as well as process heating. Conventional parabolic trough collectors harness the solar energy using long parabolic curved mirrors which direct the sunlight towards a fluid flowing through a set of tubes. In order to improve the efficiency of this system nanoparticles may be added to the fluid flowing in a transparent tube and as a result direct heating of the fluid could be possible. The fundamental difference between the conventional and nanofluid based collector lies in the mode of heating of the working fluid. In the former case the sunlight is absorbed by a surface (and is subsequently transferred to the working fluid through convection and conduction mechanisms), whereas in the latter case the sunlight is directly absorbed by the working fluid (through radiative heat transfer). Moreover the presence of these nanoparticles enhances the absorption characteristics and hence the temperature of the fluid at the exit of cylindrical parabolic collectors is expected to be higher. This study numerically models the flow of nanofluids in the collector and evaluates the rate at which sunlight is being absorbed by the nanofluid and finally compares those results with that of a conventional collector. Such a model predicts the operating efficiency of the collector and optimizes the geometry of the parabolic trough collector.

EXPERIMENTAL

Mathematical Modeling

In order to theoretically analyze the linear parabolic solar collector, the radiation source, receiver, nanofluid, and concentrator have been modeled numerically. Radiation source i.e. the sun has been modeled as a perfect blackbody with a surface temperature of 5800 K. This is a fair assumption as the solar radiation spectra reasonably resemble the radiation spectra of a perfect blackbody at 5800 K. Now the radiations emitted (spectral distribution) by a blackbody is a function of wavelength and temperature, and is defined by Planck distribution [10]:

$$I_{b\lambda}(\lambda,T_{sun})=\frac{2hc_0^{\ 2}}{\lambda^5[\exp(\frac{hc_0}{\lambda k_B T_{sun}})-1]} \qquad (1)$$

where, Tsun is the Sun surface temperature, h is Planck’s constant, kB is the Boltzmann constant, co is the speed of light in vacuum, and λ is the wavelength. So in this manner the spectral intensities of incident solar radiations have been calculated. Also as a very significant portion of the energy emitted by the sun falls in the wavelength range of 0.2 μm - 6 μm [11], so the current analysis has been restricted to this range only and further for simplicity atmospheric attenuation of solar radiations has been neglected. Receiver has been geometrically modeled as a long circular duct horizontally placed along the focal axis of the linear parabolic concentrator. To simplify the model it has been assumed that receiver is made up of glass (having transmissivity of 1) whose primary function is to house the nanofluid. Nanofluid has been modeled as a semitransparent participating medium (moving with constant velocity) in which intensity attenuation and subsequent energy transfer takes place through absorption and Rayleigh scattering mechanisms (also attenuation is assumed to take place only along radial direction) [13]. The attenuation of radiations by water and nanoparticles has been independently treated and the resultant attenuation has been calculated using law of superposition. As scattering effect of water molecules is relatively negligible so attenuation in water is primarily due to absorption, on the contrary, attenuation of radiations due to interaction with the nanoparticles is due to the combined effect of scattering and absorption. Concentrator converge the incoming solar (beam) radiations on to the receiver, and to quantify the extent of convergence a parameter known as concentration ratio (ratio of average energy flux on the receiver to that on the aperture) has been defined [14]. Its value depends on the desired output temperatures (direct relationship).

The schematic of nanofluid-based linear parabolic solar collector is shown in Figure 1.

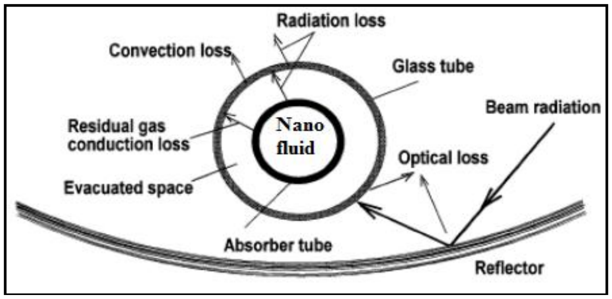

Fig. 1. Schematic of nanofluid-based concentrated parabolic solar collector

The incoming solar radiations are incident on the concentrator, which scales up the heat flux to the required value and directs it to the receiver positioned along the focal axis. In this analysis it has been assumed that the receiver is uniformly irradiated radially by these reflected radiations. On reaching the receiver the solar radiations transfer energy to the nanofluid (copper nanoparticles + water) via scattering and absorption. As stated earlier the radiation intensity is assumed to attenuate only in one dimension (i.e. radial direction). The modified form of Beer's equation (Eq. (2)) has been used to calculate this attenuation and the resulting intensities at various radial locations. Mathematically it is of the form:

$$\frac{d(I_{\lambda}.r)}{dr} = -(K_{a\lambda} + K_{s\lambda}).I_{\lambda}.r = -K_{e\lambda}.I_{\lambda}.r \qquad (2)$$

Where Ka is the spectral absorption coefficient, Ks the spectral scattering coefficient, and Ke is the spectral extinction coefficient. The present analysis has been restricted to low values of concentration ratio (hence relatively low values of outlet temperatures) therefore emission has not been accounted for. Also in order to further simplify the model the effect of in-scattering has not been considered. Intensity attenuation in nanofluids can be thought of as the combined effect due to base fluid (water) and nanoparticles (copper). The attenuation of radiations as they pass through water occurs primarily due to absorption; however nanoparticles scatter as well as absorb the incoming radiations.

Also in the present model the mean diameter of nanoparticles used is of the order of 8 nm, therefore the approximation of Rayleigh scattering (a scattering regime in which particle size is much smaller than the wavelength of incident radiation) has been applied. A special case (nanoparticles) of generalized relation quantitatively defining extinction coefficient is given by the Eq. (3) [15]:

$$K_{e\lambda(nanoparticles)} = \frac{3\varphi Q_{e\lambda(\alpha,m)}}{2D} \qquad (3)$$

Where φ is the particle volume fraction and $Q_{e\lambda}$ is the extinction efficiency, D is the diameter of the particles, α is the size parameter, and m is defined as the normalized refractive index of the particles. This may be mathematically represented as follows [10, 16]:

$$\alpha = \frac{\pi D}{\lambda} \qquad (4)$$

$$m = \frac{m_{particles}}{n_{fluid}} \qquad (5)$$

$$m = n + ik \qquad (6)$$

The value of extinction efficiency in the Rayleigh regime is given by the following relation [15, 17]:

$$Q_{a\lambda} = 4\alpha\,\mathrm{Im}\{\frac{m^2-1}{m^2+2}[1+\frac{\alpha^2}{15}(\frac{m^2-1}{m^2+2})\frac{m^4+27m^2+38}{2m^2+3}]\} \qquad (7)$$

$$Q_{s\lambda} = \frac{8}{3}\alpha^4 \left| \left(\frac{m^2 - 1}{m^2 + 2} \right) \right|^2 \qquad (8)$$

$$Q_{e\lambda} = Q_{a\lambda} + Q_{s\lambda} \qquad (9)$$

The net resultant extinction coefficient for the nanofluid has been found by the superposition of extinction coefficients of base fluid and nanoparticles. Substituting this value into the modified Beer's law (Eq. (2)) the attenuation law for the nanofluid in a radial flow system has been obtained**.** The magnitude of intensity at various radial locations has been quantitatively calculated and once these values were known then heat transfer rates within the nanofluid was calculated. The whole analysis till this point was directed towards the formulation of the energy generation $(\dot{E}_{gen})$ term of the generalized energy balance equation:

$$\dot{E}_{in} - \dot{E}_{out} + \dot{E}_{gen} = \dot{E}_{st} \qquad (10)$$

Where $\dot{E}_{in}, \dot{E}_{out}, \dot{E}_{gen}, \dot{E}_{st}$ represent rate of energy transfer into the system, energy transfer out of the system, energy generation in the system, and energy stored in the system respectively. This generalized energy balance equation was applied to the two dimensional steady state models in order to find out the two dimensional temperature field. Once the temperature field within the nanofluid was known the mean outlet temperatures at various values of *x* (i.e. along the length), optical and thermal efficiencies etc. were evaluated.

Numerical implementation

Finite difference technique (specifically forward difference implicit method) has been applied to solve these sets of equations; the whole control volume has been discretized into elementary control volumes with node points at their centers [18]. Receiver of radius 35 mm and length 2m was discretized radially as well as along the length (*x* direction). The numbers of nodes along the radial direction(*r*-axis) and along the flow direction (*x*-axis) were taken equal to 70 and 2000 respectively. Hence the node sizes in the respective directions were 0.5 mm and 1 mm respectively. The value of node size was chosen such that the iterations gave convergent and stable solutions. The velocity of flow in *x* direction has been assumed to be constant and for the current analysis has been assumed to be 1.5 mm/s. The temperature of the fluid entering the collector and the ambient temperature were taken as 25°C. The convective heat transfer coefficient of the ambient air was taken equal to 6.43 W/m^{2}K. The value of incident solar radiation flux (*G*) was taken to be equal to 1000 W/m^2 [7]. The nanoparticle diameter (*D*) was taken as 9 nm, and the particle volume fraction (φ) was chosen as 0.02%.

$$P_{nanofluid} = \varphi P_{particle} + (1-\varphi) P_{basefluid} \qquad (11)$$

Where P is thermo-physical property (here specifically the density and specific heat), and φ is the volume fraction of the nanoparticles. These property values have been mathematically calculated and are represented in tabulated form in Table 1. The optical properties of water and copper were obtained from Ref [20].

Table 1. Thermophysical properties

	ρ(kg/m^3)	C$_p$(J/kgk)
Pure Water	997.1	4179
Cu	8933	385
Cu- Water (ϕ =0.02%)	999.5	4177.8

Finally various system performance indicators such as thermal and optical efficiencies, mean outlet temperatures etc, were evaluated. These performance indicators serve as standards for comparing two different systems working under given set of conditions, and they directly or indirectly aid in result validation process.

RESULTS AND DISCUSSION

After the theoretical and numerical formulation of the model was complete, the results were obtained using a code developed in

FORTRAN programming. The two dimensional temperature field for two collectors (nanofluid based collector and conventional collector) is shown in Figure 2.

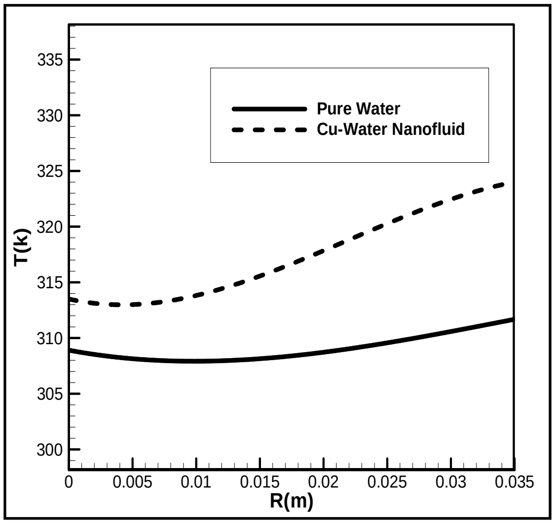

Fig. 2. Two dimensional temperature fields for pure water and cu-water nanofluid (φ=0.02% , L=2 m)

Also all the operating conditions being the same the two dimensional temperature fields in case of conventional linear parabolic concentrators employing pure water as the working fluid.

The two cases have been compared as shown in the Table 2.

Table 2. Comparison of two collectors

	Mean outlet temperature (k)	Thermal efficiency (%)	Optical efficiency (%)
Pure water	311.5	28.7	32.1
Cu- Water (ϕ =0.02%)	322.6	93.4	97.3

The above table reveals that nanofluid based collector has a higher efficiency than a conventional collector under similar operating conditions. This implies that the conventional collector can be considerably improved just through addition of trace amounts of nanoparticles into the working fluid.

In the face of lack of experimental data (pertinent to the current model involving direct volumetric absorption in a linear parabolic collector) in the literature, the model was only theoretically validated. For the theoretical validation of the numerical model the value of % error was minimized, which is defined as follows:

$$\%error = \frac{\dot{E}_{in} - \dot{E}_{out} + \dot{E}_{gen} - \dot{E}_{st}}{\dot{E}_{st}} \qquad (12)$$

Where energy terms are represent the energy interactions in totality. In the current model the node size was chosen such that this % error reduced to approx. 0.1 & subsequently the model gave convergent and stable solutions. Now that it has been established mathematically that for a given set of conditions, nanofluid based collector performs better than conventional linear parabolic collector, the attention is focused towards optimization of the proposed model. This has been achieved by varying the operating parameters and analyzing the effects it has on the performance indicators. In this regard, operating parameters like, concentration ratio, volume fraction, receiver length, and flow velocity, etc were varied and their corresponding effect on performance indicators was obtained in the form of plots. Next the effect of change in concentration ratio (while keeping all other parameters constant) is analyzed. It was observed that optical and thermal efficiencies were independent of concentration ratio, but the mean outlet temperature varied linearly with concentration ratio as shown in Figure 3.

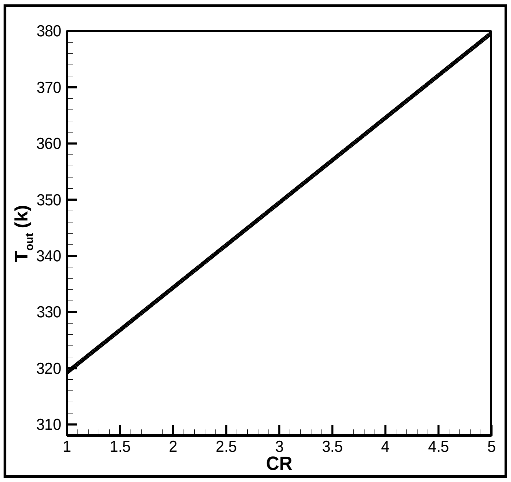

Fig. 3. Mean outlet temperature variation with concentration ratio

Next, variation of the volume fraction of nanoparticles (all other parameters fixed) is treated. Variation of volume fraction has marked effect on all the three performance indicators. It is apparent from Figure 4 that the mean outlet temperature increases sharply with volume fraction up to certain value and then becomes constant. This observation reveals that there is a limiting value of volume fraction after which no further improvement in mean outlet temperatures occurs. Similar kind of trend is shown in case of thermal and optical efficiencies (as shown in Figure 5 and Figure 6).

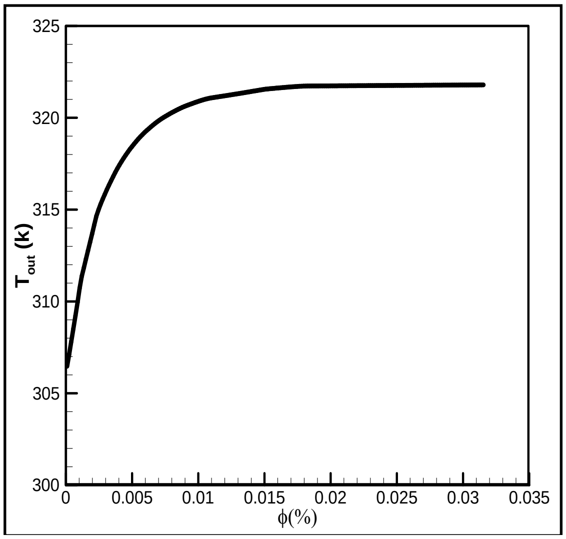

Fig. 4. Mean outlet temperature variation with volume fraction.

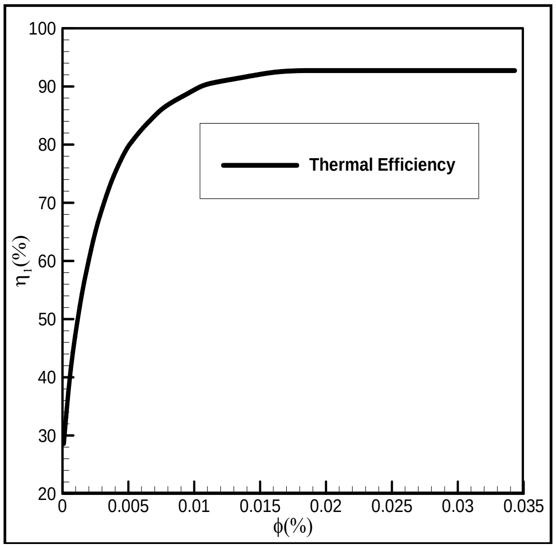

Fig. 5. Thermal efficiency variation with volume fraction

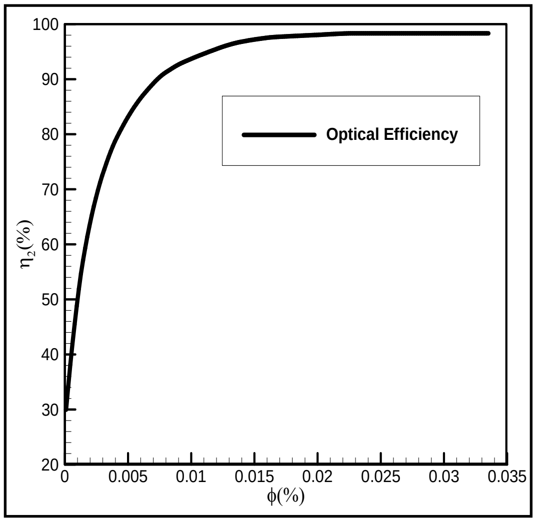

Fig. 6. Optical efficiency variation with volume fraction

Next, the effect of receiver length (all other parameters fixed) on the performance indicators is considered. This has been graphical represented in the Figure 7.

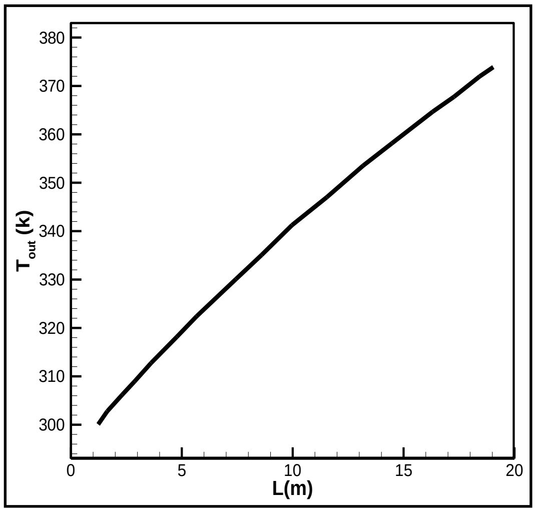

Fig. 7. Mean outlet temperature variation with receiver length.

This behavior follows from the basic understanding that flow velocity remaining constant the time spent by a particular chunk of working fluid in the receiver increases with increase in length of the receiver. So the fluid has more time to get heated up. On the contrary thermal efficiency decreases with increase in receiver length. This follows from the basic understanding that as the length of the receiver and hence the time spent by the working fluid in the receiver increases, the heat loss through convection also increase. Although the mean outlet temperature is increasing but the heat loss through convection is predominant, therefore thermal efficiency steeply decreases (as shown in Figure 8) with increase in length.

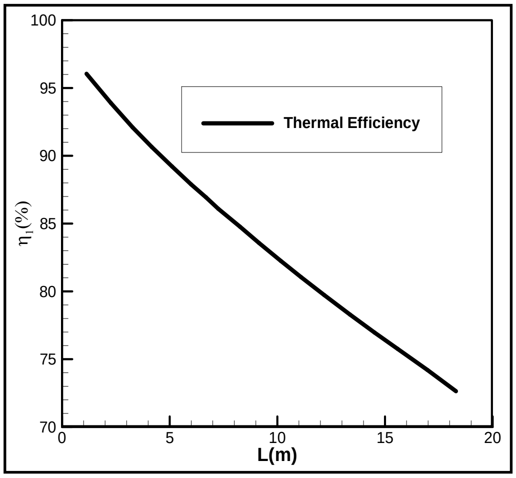

Fig. 8. Thermal efficiency variation with receiver length.

Lastly, the effect of flow velocity on the on the performance indicators is analyzed. As the flow velocity increases (all other parameters fixed) the time spent by the working fluid in the receiver decreases i.e., it has relatively less time to raise its temperature through radiation absorption. This is graphically represented in Figure 9.

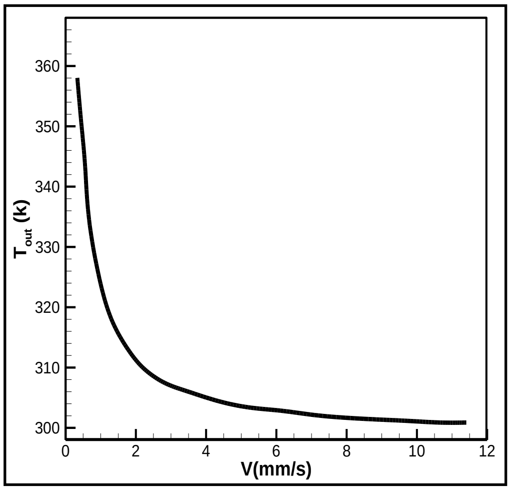

Fig. 9. Mean outlet temperature variation with flow velocity

By the same token, increase in flow velocity (decrease in radiation–fluid interaction time) decreases the convective heat loss and hence thermal efficiency of the system increases. This is graphically represented as Figure 10.

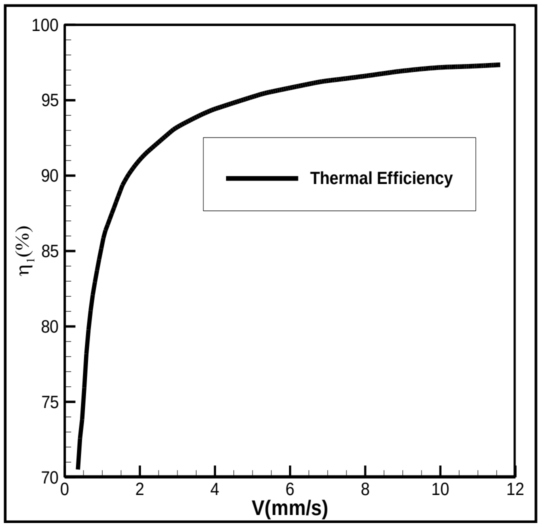

Fig. 10. Thermal efficiency variation with flow velocity

CONCLUSIONS

Addition of trace amounts of copper nanoparticles into the base fluid (water) considerably improves its absorption characteristics. This is seen in face of improved thermal and optical efficiencies and higher outlet temperatures. Also, the effect of concentration ratio, volume fraction of nanoparticles and length of collector was studied. As a whole this nanofluid based linear parabolic concentrator has a higher efficiency than a similar conventional collector.

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