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Directly absorbing nanofluid based solar thermal collectors for Cairo

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Abstract

Directly absorbing nanofluid based solar thermal collectors are being proposed for heating and cooling of residential and industrial buildings. In these solar thermal collectors (STCs), nanoparticles absorb the incident radiation, convert it into heat and finally transfer to the working fluid in full volume. The performance of these collectors depends on parameters such as material (metallic, non-metallic, and graphite), size and shape of the nanoparticles (sphere, spheroid, ellipse, ellipsoid, buckyball etc.) and the dielectric constant of the base fluid. A numerical study (using finite difference method) on nanofluid (graphite nanoparticles dispersed in ethylene glycol) based STC has been conducted. The results shows that the Graphite nanoparticles have high absorptivity (in the visible solar spectrum) and ethylene glycol sufficiently high boiling point (to achieve high fluid temperature in the solar collector, 170 – 190 °C). The study shows that 0.005% is an optimum volume fraction of the graphite nanoparticles. The results shows that the outlet temperature dependents on the mass flow rate of the nanofluid and irradiation and it increases with decrease of mass flow rate and increase of irradiation. Further, Analysis of Variance study shows that the mass flow rate and irradiation are two important parameters and having 90% contribution in the temperature rise of the nanofluid.

Keywords: Graphite nanoparticles, Nanofluid, Analysis of Variance (ANOVA), Solar thermal collector

1. Introduction

The nanofluid based solar collectors[1] are being increasingly investigated for an efficient harnessing of solar energy [2] in which the nanoparticles absorb electromagnetic waves to generate heat[3–6]. In the present paper, a numerical model has been used to study the effect of parameters which influence the performance of the nanofluid based solar collector. For the numerical modeling, the equations have been solved with finite difference technique by using forward difference implicit method. The most suitable nanoparticle material candidate and its optimum volume fraction in nanofluid has been identified. Further, the effect of working fluid flow rate and irradiation has been predicted. Finally, the contribution of three interfering parameters, volume fraction, mass flow rate and irradiation, towards the performance of nanofluid based solar collectors has been evaluated using Analysis of Variance (ANOVA) technique [7].

2. Numerical modeling of nanofluid based solar collector

The schematic of a solar collector using nanofluid comprising of nanoparticles suspended in base fluid (Ethylene glycol) as working fluid is shown in figure 1. The length of the cylindrical receiver is 1800 mm and diameter 43 mm. For numerical modeling following assumptions have been considered:

- **a)** the bottom surface of the receiver is transparent
- **b)** the flow of fluid is laminar
- **c)** the in-scattering from the nanoparticles is negligible
- **d)** there is no emission from the nanoparticles and
- **e)** the scattering is independent scattering.

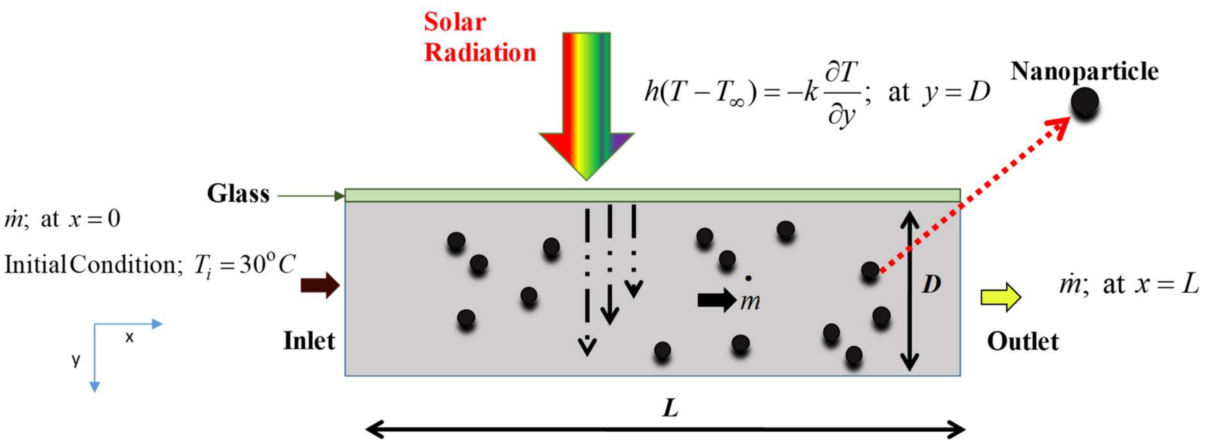

Figure 1: Schematic of a directly absorbing nanofluid based solar collector

In order to simulate the intensity distribution within the receiver (along the diameter of the pipe) equation 1, which is a radiative transfer equation (RTE), has been used [8,9].

$$\frac{dI_\lambda(\Omega)}{dy} = -(K_{s_\lambda}+K_{a_\lambda})I_\lambda(\Omega)+K_{a_\lambda}I_{b_\lambda}+\frac{K_{s_\lambda}}{4\pi}\int_{4\pi} I_\lambda(\Omega^{'})p(\Omega^{'}\rightarrow\Omega)d\Omega\,, \tag{1}$$

where I_λ is the spectral incident intensity, I_b is the black body intensity, Ω is solid angle, $p(\Omega^{'}\rightarrow\Omega)$ is phase function and $K_{a\lambda}$ and $K_{s\lambda}$ are respectively the spectral absorption and scattering coefficients.

In case of pure fluid (ethylene glycol), the attenuation of irradiation is due to absorption and the absorption coefficient ($K_{a\lambda,\,EG}$) for pure fluid is evaluated by equation 2.

$$K_{a\lambda,\mathrm{EG}} = 4\pi\kappa/\lambda\ , \tag{2}$$

Where κ is index of absorption and λ is the wavelength.

Hence the RTE for pure fluid can be represented by equation 3, which is given as

$$\frac{dI_\lambda}{dy} = -(K_{\mathrm{a\lambda,EG}})I_\lambda \,, \tag{3}$$

But with the addition of nanoparticles in the fluid, the absorption and scattering by nanoparticles take place, then absorption ($K_{a\lambda,\text{nanoparticle}}$), scattering coefficients ($K_{s\lambda,\text{nanoparticle}}$) and extinction coefficients ($Ke_{\lambda,\text{nanoparticle}}$) of nanoparticles are described by equations eq. 4, 5 and 6 respectively[10].

$$K_{a\lambda,\text{nanoparticle}} = \frac{6\pi f_v}{\lambda}\,\mathrm{Im}\left\{\frac{m^2-1}{m^2+2}\left[1+\frac{\pi^2 d^2}{15\lambda^2}\left(\frac{m^2-1}{m^2+2}\right)\frac{m^4+27m^2+38}{2m^2+3}\right]\right\}, \tag{4}$$

$$K_{s\lambda,\text{nanoparticle}} = \frac{4\pi^4 d^3 f_v}{\lambda^4}\left|\frac{m^2-1}{m^2+2}\right|^2, \tag{5}$$

and

$$K_{e\lambda,\text{nanoparticle}} = \frac{6\pi f_v}{\lambda}\,\mathrm{Im}\left\{\frac{m^2-1}{m^2+2}\left[1+\frac{\pi^2 d^2}{15\lambda^2}\left(\frac{m^2-1}{m^2+2}\right)\frac{m^4+27m^2+38}{2m^2+3}\right]\right\} + \frac{4\pi^4 d^3 f_v}{\lambda^4}\left|\frac{m^2-1}{m^2+2}\right|^2, \tag{6}$$

where $K_{e\lambda}$ is extinction coefficient, which is sum of absorption and scattering coefficient, *d* is the diameter of the nanoparticle, *m* is complex refractive index $\left(m = m_{particles}/n_{fluid}\right)$, f_v is volume fraction of nanoparticles in the base fluid.

Finally the attenuation of incident light for nanofluid can be evaluated by equation 7

$$\frac{\partial I_\lambda}{\partial y} = \left[-K_{a\lambda,\text{water}} + \left(-K_{e\lambda,\text{nanoparticles}}\right)\right]I_\lambda, \tag{7}$$

Since, in this model we assume independent scattering, hence we can add two intensities.

Finally, to find out the temperature gain in the nanofluid, RTE is solved simultaneously with steady state two dimensional heat transfer equation. The heat transfer equation is given in equation 8 [11].

$$k\frac{\partial^2 T}{\partial y^2} - \frac{\partial r_h}{\partial y} = \rho C_p \frac{\partial T}{\partial t}, \tag{8}$$

where *k* is the thermal conductivity of the nanofluid, r_h is radiative heat flux, and C_p is the specific heat of the fluid. The algorithm used to evaluate the spatial temperature distribution of nanofluid based solar collector has been shown in figure 2.

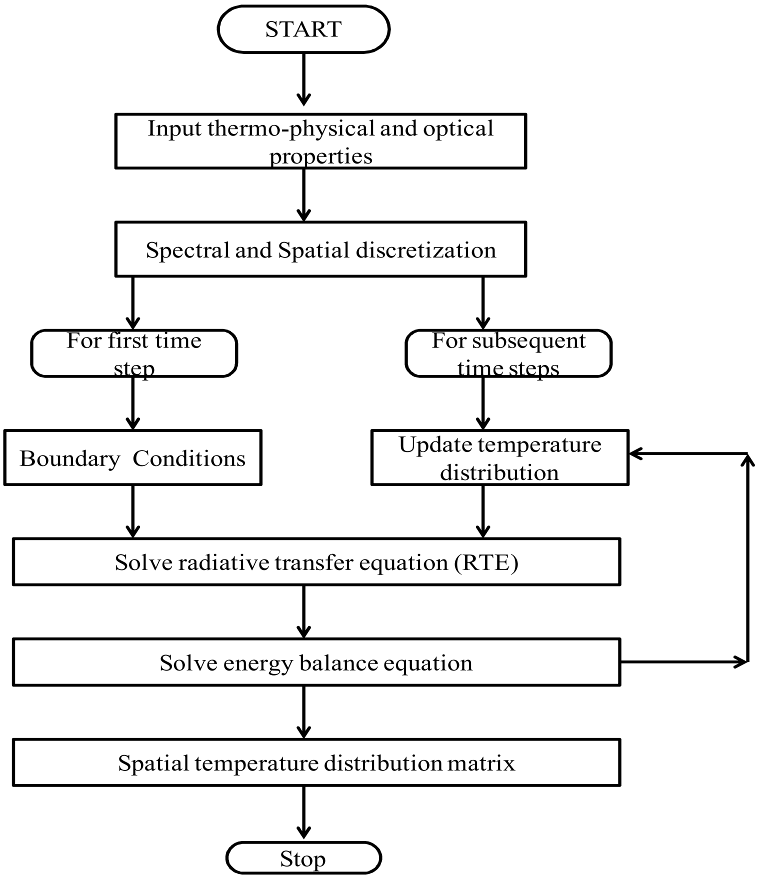

Figure 2: Algorithm for spatial temperature distribution in nanofluid based solar collector.

3. Results and Discussion

(a) Effect of the nanoparticle materials

In order to find the most suitable nanoparticle material able to deliver heat at highest outlet temperature of nanofluid, for a predetermined flow rate and other parameters fixed, with minimum volume fraction shown in Figure 3, four candidate materials aluminum, silver, copper and graphite (diameter *d* = 25 nm) were chosen. The optical properties of these materials have been taken from Pallick et al[12]. It can be seen in Figure 3 that with the graphite nanoparticles 70-75% higher temperatures can be achieved as compared to other nanoparticles. This is because the graphite has broadband solar spectrum as compared to other nanoparticles[13], due to which graphite is able to absorb more irradiation as compared to other nanoparticle materials. Due to higher temperature rise, graphite was chosen for further study.

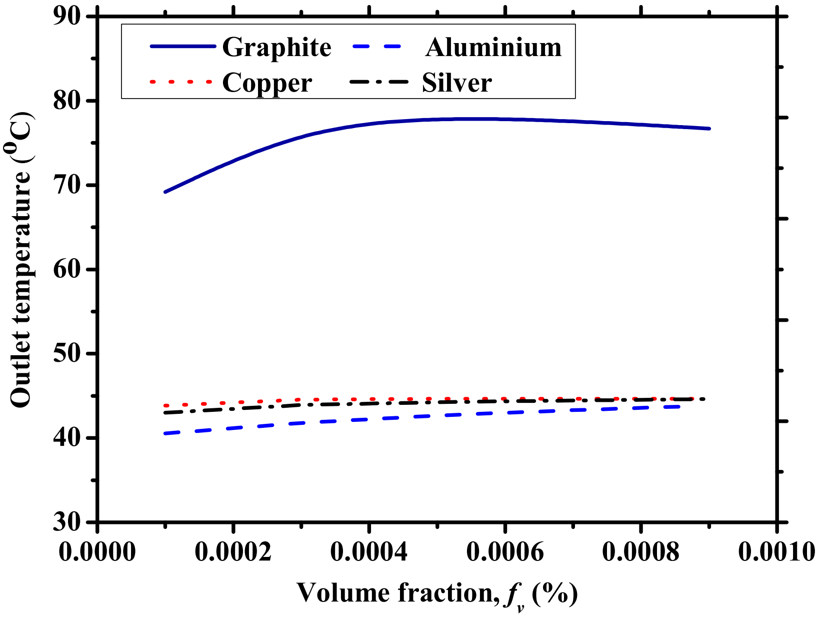

Figure 3: Effect of different materials on the temperature rise.

(b) Effect of volume fraction

Five volume fractions (0.0001, 0.0003, 0.0005, 0.0007 and 0.0009%) of graphite nanoparticles have been considered and their effect on temperature predicted as shown in figure 4. The results show that 0.0005% is an optimum volume fraction on the basis of a highest temperature that could be achieved. The ability of a nanofluid based solar collector in delivering heat at a desired temperature will obviously depend on the volume fraction of nanoparticles because a higher volume fraction will result into a larger attenuation of the sunlight. The attenuation varies exponentially with the extinction coefficient and hence also with the volume fraction of the nanoparticles. So, there has to be an optimum volume fraction of the nanoparticles corresponding to which the temperature gain is maximum.

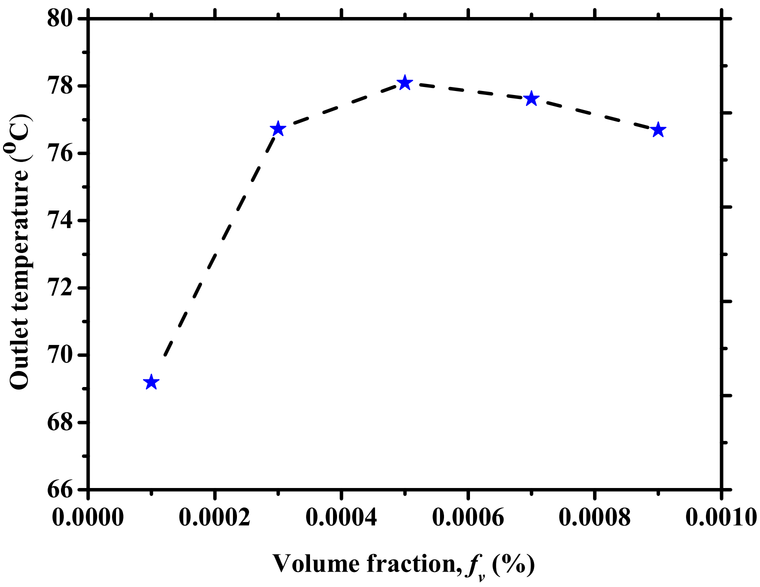

Figure 4: Effect of volume fraction on nanofluid temperature

(c) **Effect of mass flow rate**

In order to ascertain the effect of mass flow rate, different mass flow rates (0.001, 0.002, 0.03, 0.004, 0.005, 0.006 and 0.007 kg/s) have been considered. The results show that the outlet temperature decreases with increase of mass flow rate, see figure 5. This is due to fact that an increase in the fluid flow rate leads to reduction in the time for which the fluid is allowed to absorb sunlight, therefore leading to decrease the nanofluid temperature at the receiver outlet.

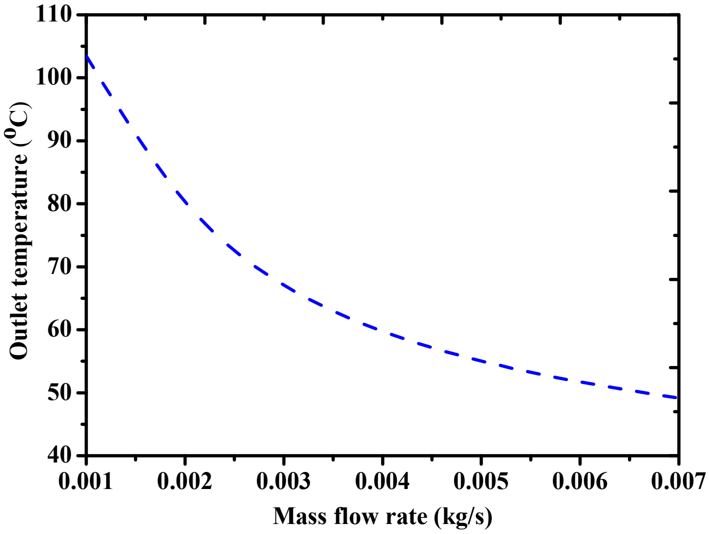

Figure 5: Effect of mass Flow rate on outlet temperature of the nanofluid

(d) Effect of irradiation

The effect of flux on the outlet temperature has been shown in figure 6. The outlet temperature was found to increase with rising flux. It can be concluded that in order to achieve high nanofluid temperature the mass flow rate should be low and the irradiation should be high.

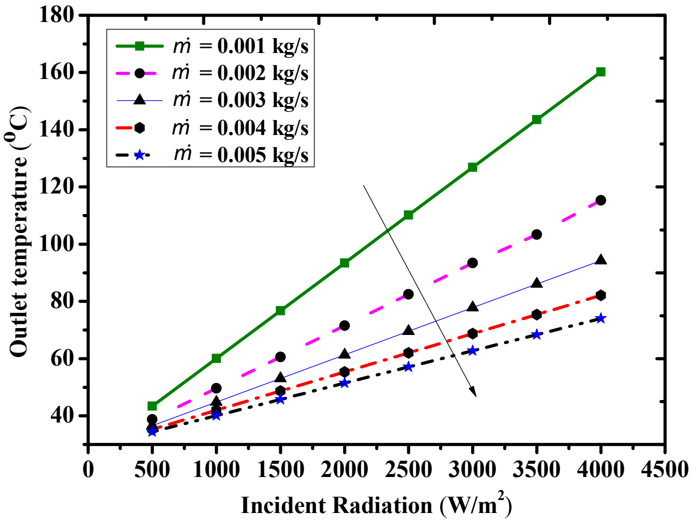

Figure 6: Effect of irradiation on the temperature of nanofluid

(e) **Percentage contribution of each factor**

Analysis of Variance (ANOVA) has been performed to investigate the relative significance of three interfering parameters studied - volume fraction, mass flow rate and irradiation - on the outlet temperature of the nanofluid. The study has shown that incident flux and mass fraction have maximum individual contributions, see figure 7. A combined contribution of 90% was attributed to these two factors. The pooled error that accounts for combined factors or interaction effects had a 0.62% contribution.

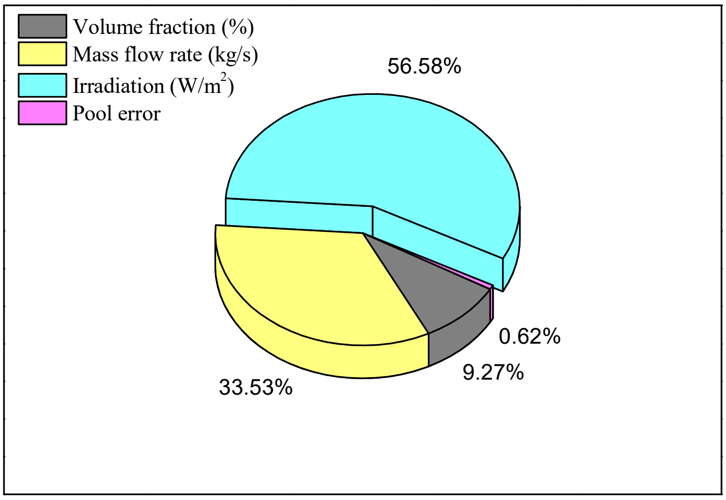

Figure 7: ANOVA predicted contributions of interfering parameters studied on the outlet temperature of nanofluid.

4. Conclusion

The suitability of graphite nanoparticles for directly harnessing of solar irradiation at a low volume fraction of 0.0005% to achieve high nanofluid temperatures has been predicted. Further, in order to achieve a high temperature the mass flow rate of the nanofluid should be proportionately low. The combined contribution of the incident flux and the mass flow rate on the temperature rise was found to be 90%, which shows that future studies should focus on the incident flux and mass flow rate of nanofluid to identify optimum design parameters for directly absorbing solar thermal collectors.

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