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Investigation of thermal behaviour, pressure drop, and pumping power in a Cu nanofluid-filled solar flat-plate collector

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Abstract. The evaluations of the performance of solar flat-plate collectors are reported in the literature. A computer program developed by MATLAB has been applied for modelling the performance of a solar collector under steady state laminar conditions. Results demonstrate that Cu-water nanofluid would be capable of boosting the thermal efficiency of the collector by 2.4% at 4% volume concentration in the case of using Cu-nanofluid instead of just water as the working fluid. It is noteworthy that, dispersing the nanoparticles into the water results in a higher pressure drop and, therefore, a higher power consumption for pumping the nanofluid within the collector. It has been estimated for the collector understudy, that the increase in the pressure drop and pumping power to be around 30%.

1. Introduction

Solar flat-plate collectors (FPCs) as an effective renewable-based device for the energy supply of domestic and industrial sectors, provide a potential for the performance improvement with the aid of nanofluids. Nanofluids would be able to change the thermophysical properties of a base liquid once they were dispersed as additives. Conductivity, amongst the other thermophysical properties, is most affected by nanoparticles; however, the other properties of base fluids, such as viscosity, heat capacity, and density are not excluded from the change. The interactions between these properties of nanofluids during the heat transfer phenomenon, and flowing in the pipes, will determine the overall performance of solar collectors. In fact, the conductivity enhancement will lead to an improvement in the performance of a FPC whilst the increase of viscosity and density will result in a higher pressure drop and, consequently, a higher pumping power in a forced circulation solar FPC. Nasrin et al. [1] conducted a numerical method to study the thermal behaviour of a FPC using four different water-based oxide nanofluids. Said et al. [2] analysed the pressure drop and heat transfer in a FPC with the SWCNT-water working

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fluid. Lazarus et al. [3] examined the effect of the silver-water nanofluid on the thermal performance of a FPC by experimentation. Alim et al. [4] investigated the enhancement of the heat transfer performance and pumping energy required in the case of a water mixture with different oxide nanoparticles as the working fluid. Verma et al. [5] carried out an experimental research on the variety of oxide nanoparticles to realise the changes in efficiency and pumping power. Mahian et al. [6] undertook the study of heat transfer and pressure loss affected by nanofluids in a minichannel FPC.

This paper is concerned with evaluating the performance of a solar FPC working with a copper/water nanofluid. It is assumed that there is a constant velocity in the collector pipe to take into account the change of the mass flow rate by adding the nanoparticles. Furthermore, most of research studies have been carried out so far, have considered the same temperature for the inlet of the collector and the ambient temperature. Such a situation happens rarely in practice because it shows the conditions in which no thermal absorption takes place and only the optical performance of the collector plays the role of the heat transfer. This paper has considered a non-zero value for the difference of the inlet and ambient temperatures.

2. Problem description

The modelling and thermal behaviour evaluation of a solar FPC working with a Cu/water nanofluid has been considered in this study. The technical data of the collector understudy taken from the G-Series FPCs of Thermo Dynamics Ltd., are given in Table 1.

Table 1. The collector technical data

Collector Parameter	**Value [unit]**	**Collector Parameter**	**Value [unit]**
Collector tilt angle	25 [°]	Conductivity of bottom insulation	0.036 [W/m.K]
Optical efficiency	85 [%]	Conductivity of edge insulation	0.036 [W/m.K]
Tube spacing (pitch)	143 [mm]	Conductivity of bond	237 [W/m.K]
Number of risers	8	Length of bond	18 [mm]
Number of glass covers	1	Average thickness of bond	0.5 [mm]
Dimension [cm]	250×120×8.6	Emissivity of absorber plate	25 [%]
Riser tube diameter (in/out)	7 and 8 [mm]	Emissivity of glass cover	84 [%]
Header pipe diameter	14 [mm]	Wind velocity	3.2 [m/s]
Solar irradiance on collector	808 [W/m^2]	Conductivity of Al. absorber	237 [W/m.K]
Thickness of insulations	25 [mm]	Thickness of absorber plate	0.5 [mm]

3. Thermophysical properties of nanofluids

The main thermophysical properties of nanofluids consist of density, ρ, heat capacity, C_p, thermal conductivity, k, and viscosity, μ. The models and correlations for the estimation of the nanofluid properties have been presented in Table 2. In these equations, ϕ and d_p stand for the nanofluid volume concentration and diameter, and $\kappa_B = 1.381\times10^{-23}$ J/K is the Boltzmann constant.

4. Thermal efficiency of the solar collector

The thermal efficiency of a solar FPC is given by [7] as follows:

$$\eta_{eng} = \frac{Q_u}{A_c G_t} \tag{1}$$

where the useful heat gain, Q_u, from the available solar energy ($A_c . G_t$) is obtained from the following relations:

$$Q_u = \dot{m} C_p (T_{out} - T_{in}) = A_c [S - U_L (T_{pm} - T_a)] \tag{2}$$

which is related to the heat capacity and mass flow rate of the working fluid and its inlet and outlet temperatures. The first two are influenced by adding the nanoparticles and as a result, the outlet temperature will be affected. As observed from the last equation, the useful heat collection also depends on the effective radiation on the absorber of the FPC, $S = \eta_o G_t$, in which η_o represents the collector's optical efficiency; it is the product of the transmittance of the glazing and absorptance of the absorber, i.e., $\eta_o = (\tau\alpha)_{avg}$. Here T_{pm} and T_a are the absorber plate mean temperature and the ambient temperature in K.

Table 2. The correlations for prediction of the nanofluid properties

Property	**Model**	**Correlation**
Mass density	Principle of mixtures	$\rho_{nf} = \phi\rho_p + (1-\phi)\rho_{bf}$
Specific heat	Thermal equilibrium	$C_{p,nf} = \dfrac{\phi(\rho C)_p + (1-\phi)(\rho C)_{bf}}{\rho_{nf}}$
Thermal conductivity	Xuan	$\dfrac{k_{nf}}{k_{bf}} = \dfrac{k_p + 2k_{bf} - 2\phi(k_{bf} - k_p)}{k_p + 2k_{bf} + \phi(k_{bf} - k_p)} + \dfrac{\rho_p \phi C_p}{2k_{bf}} \sqrt{\dfrac{2\kappa_B T}{3\pi d_p \mu_{bf}}}$
Dynamic viscosity	Brinkman	$\dfrac{\mu_{nf}}{\mu_{bf}} = \dfrac{1}{(1-\phi)^{2.5}}$

5. Heat transfer criteria

The internal convection heat transfer, h_{fi}, appears in the collector's efficiency coefficient in the form of:

$$F' = \frac{1/U_L}{W[1/[U_L(D+(W-D)F] + 1/C_b + 1/\pi D_i h_{fi}]} \tag{3}$$

In fact, the factor F', as seen from Eq. (3), related the collector design parameters including tube pitch, W, diameter, D, fin efficiency, F, and bond conductance, C_b, to the operational parameters, such as the overall heat loss, U_L, from the collector enclosure. The overall heat loss consisted of three main components, i.e., from the back, edge and top sides, and the method of their calculation has been discussed in detail by [7] and [8]. On the other hand, the heat transfer coefficient is proportional to the Nusselt number and the conductivity of the nanofluid flow within the collector. The Nusselt number will be determined depending on the Reynolds number and Prandtl number. These dimensionless numbers are evaluated by means of the equations below:

$$h_{fi} = \frac{\mathrm{Nu}\, k_{nf}}{D_i} \quad (4) \qquad \mathrm{Re}_{nf} = \frac{\rho_{nf} V D_i}{\mu_{nf}} = \frac{4\dot{m}_{riser}}{\pi D_i \mu_{nf}} \quad (5) \qquad \mathrm{Pr}_{nf} = \frac{\mu_{nf} C_{p,nf}}{k_{nf}} \quad (6)$$

It can be seen that, the nanoparticles performed their duty by altering the properties of the working fluid and, consequently, via changing the aforementioned dimensionless numbers. In the laminar flow, i.e., Re < 2300, the heat transfer performance will be determined based on the thermal boundary condition. For the short circular tubes in which the hydrodynamic and thermal boundary layer are developing, the Heaton correlation is used to estimate the local Nusselt number with a constant heat flux:

$$\mathrm{Nu} = \mathrm{Nu}_{\infty} + \frac{a(\mathrm{Re}\,\mathrm{Pr}\,D_h/L)^m}{1+b(\mathrm{Re}\,\mathrm{Pr}\,D_h/L)^n} \tag{7}$$

where D_h and L are the hydraulic diameter and tube length, respectively.

The Goldberg's correlation is essentially similar to Heaton's but with different coefficients of a, b, m, and n. It will be useful for the evaluation of the average Nusselt number under constant-wall temperature conditions. The values of the constant numbers are specified in Table 3.

Table 3. Constants of Heaton's and Goldberg's correlation for the Nu. Number

Pr.		*a*		*B*		*m*		*n*	
q = cte	**T= cte**	**q = cte**	**T= cte**	**q = cte**	**T= cte**	**q = cte**	**T= cte**	**q = cte**	**T= cte**
0.7	0.7	0.00398	0.0791	0.0114	0.0331	1.66	1.15	1.12	0.82
10	5	0.00236	0.0534	0.00857	0.0335	1.66	1.15	1.13	0.82
∞	∞	0.00172	0.0461	0.00281	0.0316	1.66	1.15	1.29	0.84
$\mathrm{Nu}_{\infty,q=cte} = 4.4$					$\mathrm{Nu}_{\infty,T=cte} = 3.7$				

The constants a, b, m, and n may be interpolated for the different Prandtl numbers from the values of Table 3.

6. Pressure drop and pumping power

The pressure drop of the nanofluid flow across the collector risers is calculated at a tilt angle β by applying the Bernoulli equation to the riser tube inlet and outlet. The overall pressure loss in the FPC, including the riser tubes, manifolds, and fittings is estimated as follows. Then, the pumping power can be predicted based on the overall pressure loss:

$$\Delta p = [f\frac{L}{D}\rho_{nf}\frac{V^2}{2}]_{in/out} + [\rho_{nf}g(L\sin\beta + h_L)]_{riser+fitting} \tag{8}$$

$$h_L = \frac{8\dot{m}_{riser}^2}{\rho_{nf}\,g\,\pi^2 D_i^4}(f\frac{L}{D_i} + \sum K_L) \tag{9}$$

$$P = \frac{\dot{m}}{\rho_{nf}} \times \Delta p \tag{10}$$

where K_L is the coefficient loss taken as 2.0 for the laminar flow.

7. Results and discussion

In the present study, 25nm copper (Cu) nanoparticles were selected to analyse their effect on the performance of the collector under a steady state condition. The ambient temperature, its minimum difference with the inlet temperature, the sun's temperature, and the flow velocity in the header pipe were assumed to be 301 K, 2 K, 5770 K, and 0.3 m/s, respectively. An iterative method was required to obtain the FPC outlet temperature and its absorber temperature as well. MATLAB software was employed for solving the governing equations by a reasonable assumption for the plate's mean temperature as an initial guess. Assigning the given values, the desired parameters were evaluated and the results have been presented.

The addition of nanoparticles causes the specific heat of the fluid to decrease and its mass flow rate to increase, resulting from the density enhancement. The contribution of the specific heat to the change of the outlet temperature is more than density, which results in an increased outlet temperature according to Eq. (2). Therefore, the collector fluid's outlet temperature increases with the Cu nanofluid concentration. The mass flow innately influences the collector's performance via the mean temperature of the plate [8]; the higher the mass flow the lower the plate's temperature and, consequently, the lower the heat loss from the collector. As a consequence, a 3K drop in the plate's mean temperature is observed, leading to a lower heat loss and, hence, a higher heat gain as seen from Figure 1. As a result, the thermal efficiency of the FPC increased due to the greater amount of heat being absorbed by the collector. Figure 2 confirms this observation drawn for the different concentrations of the nanoparticles. The efficiency of the collector with a 25nm-copper-water working fluid improved from 70.3% for plain water to 72.7% with a 4% Cu/water nanofluid.

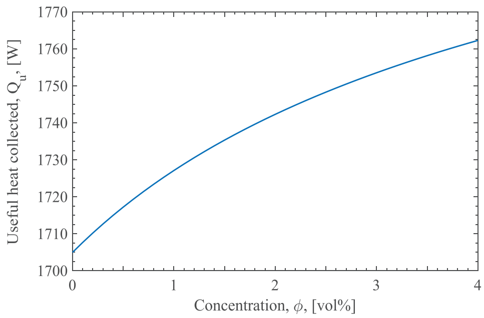

Fig. 1. Heat gain of the FPC with Cu nanofluid

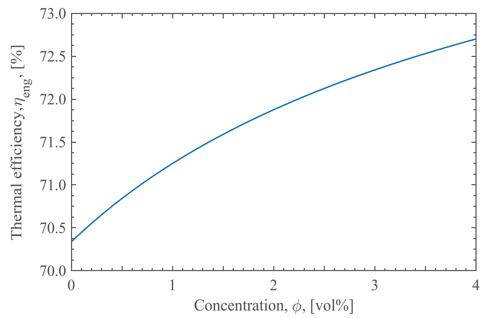

Fig. 2. Variations of the FPC thermal efficiency

The thermal behaviour of the collector in terms of the Nusselt number and heat transfer coefficient is depicted in Figures 3 and 4, respectively. Considering Eq. (6), the Prandtl number relates three important thermophysical properties of the water-copper nanofluid, i.e., specific heat, viscosity, and conductivity. With an increase of the volume fraction, the specific heat decreases, whilst the viscosity and conductivity increase. However, the values of the heat capacity and conductivity would be greater than the viscosity enhancement. The final interaction between the properties imposes a decrease of the Prandtl number with the volume concentration. The decrease of the Prandtl number overcomes the increase of the Reynolds number which causes the Nusselt number to be decreased, overall. The variation of the Nusselt number is not too much and sometimes it is assumed to be constant. Therefore, a small decrease in the Nusselt number is reported with the nanofluid concentration as shown in Figure 3.

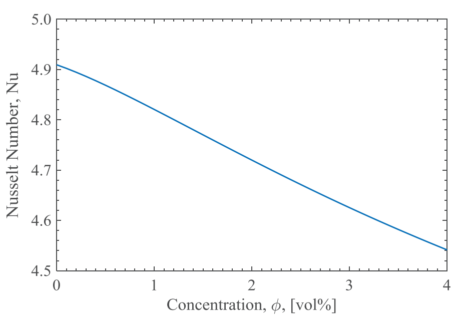

Fig. 3. Nusselt number of nanofluid in the FPC

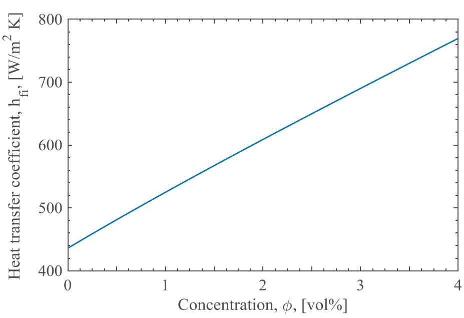

Fig. 4. Heat transfer coefficient of the FPC

Assuming either a constant or an insignificantly enhanced Nu number, it can be observed that the convective heat transfer coefficient shown in Figure 4 goes up based on Eq. (4). The increase would be more than 1.7 times with the 4vol% nanofluid concentration when compared to the values with water. The trends agree with [6].

Referring to Eq. (8) the pressure drop increases due to the addition of the copper nanoparticles and the resultant density enhancement when compared to the pure water. Figure 5 shows that the pressure drop could have been as high as 30% compared to the pure water. Owing to the pressure drop taking place in the collector pipes when using the nanofluid, the circulating pump consumed almost 30% more power at the maximum nanoparticle volume concentration according to Figure 6.

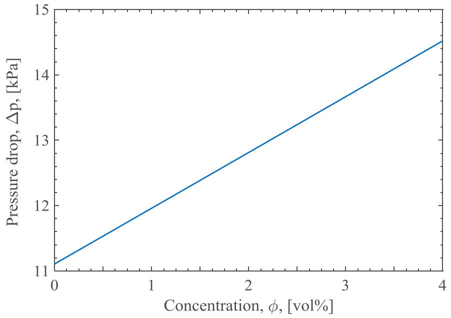

Fig. 5. Effect of nanoparticles on pressure drop

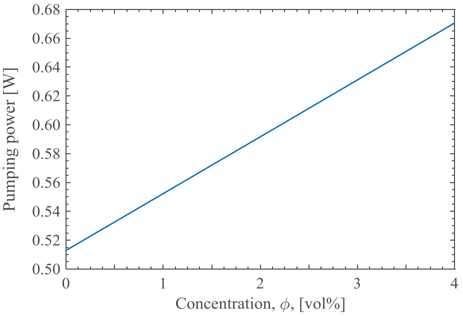

Fig. 6. Increased pumping power of the FPC

This affirms that although using nanoparticles, on one hand, improves the thermal behaviour of the collector by enhancing the conductivity, on the other hand, it worsens the pressure drop and pumping power via enhancing the viscosity and density of the flow. The quantities depend on the nanoparticle type and concentration.

Conclusions

In the current study, an analytical investigation has been undertaken using a computer program developed in MATLAB to determine the effect of copper nanoparticles on the thermal behaviour, pressure drop, and pumping power of a solar flat-plate collector under steady state laminar condition. The Results show that adding the copper nanoparticles into the water enhanced the energetic efficiency of the collector from 70.3% to 72.7%. Also, it can be deduced that using a copper-based nanofluid instead of water as the working fluid will lead to the increase of the collector's pressure drop and pumping power by approximately 30% at the maximum volume concentration.

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