17th UK Heat Transfer Conference (UKHTC2021)
4-6 April 2022, Manchester, UK

EFFECTS OF COMBINED RADIATION AND FORCED CONVECTION ON A DIRECTLY CAPTURING SOLAR ENERGY SYSTEM

Oguzhan Kazaz[1], Nader Karimi[1, 2], Shanmugam Kumar[1], Manosh C. Paul[1*], Gioia Falcone[1]

[1]Systems, Power & Energy Research Division, James Watt School of Engineering, University of Glasgow, Glasgow, G12 8QQ, UK
[2]School of Engineering and Materials Science, Queen Mary University of London, London, E1 4NS, United Kingdom

ABSTRACT

The demand of energy is increasing on a daily basis because of the increase in economic growth, industrial development, modernization, and population. In order to meet this increasing demand, the use of energy produced from convectional energy sources including fossil sources such as coal, petroleum or natural gas, is increasing. Depending on this increasing use, however, energy generation from alternative energy sources has become more important because of the limited availability of fossil fuels and their harmful effects on both the environment and humans such as respiratory diseases, cancer, acid rain, climate change or global warming. Alternative energy generation is, therefore, critical to the survival of both humans and nature. In addition, it is important to find new and non-conventional energy sources and to use these energy sources efficiently. An inexhaustible resource can be obtained by protecting nature with environmentally friendly renewable energy sources such as solar, wind, or biomass. Because the energy types in the world originate from the sun, the use of solar energy is higher than other renewable energy sources for various reasons such as ease of use, high efficiency and potential, and low maintenance costs. The application of nanofluids as a working fluid in solar energy systems contributes to the improvement of solar energy absorption and photo-thermal energy conversion. In the current work, a numerical study has been performed on a nanofluid-based direct absorption solar collector using different types of hybrid nanoparticles to investigate heat transfer and fluid flow process. Because the heat transfer medium is a transparent in which absorption, emitting and scattering effects are taken into account, a 2D finite volume method is used to solve the radiative transport and Navier-Stokes equations. The results demonstrate that the radiation absorption capacity of the heat transfer fluid increases with the addition of hybrid nanoparticles into the pure water. As a result, the amount of volumetric absorbed radiation inside the collector also improves, resulting in an enhancement in the photo-thermal conversion efficiency.

1. INTRODUCTION

As a renewable energy source, solar energy can meet increasing energy demands whilst also protecting the climate and environment. For this, initially, it is necessary to use solar collectors in order to capture the solar radiation which may then be converted into thermal energy and used in daily life. In conventional solar collectors, the radiation is captured by the absorber and the heat is transferred to the working fluid and, as heat losses increase during this transfer, the efficiency of the collector decreases [1]. In order to overcome this negative feature, it may be necessary to absorb solar radiation directly. For this, direct absorption solar collectors (DASCs) are used because the heat transfer fluid acts as both an absorbing medium and a working fluid; therefore, the radiation is directly converted into thermal energy, resulting in an increase in the performance of the collector [2].

Taylor et al. [3] investigated the DASC as a closed cavity by experimentation and modelling. They found that the optical and thermal properties significantly changed at low volume concentrations. The efficiency of DASC was improved by the addition of mono nanoparticles. The results showed that nanoparticles could be added in order to absorb solar radiation with a small quantity of density or rise in viscosity. Sani et al. [4] experimentally analysed thermal and optical properties of single wall

---

[*]Corresponding author: Manosh.Paul@glasgow.ac.uk

carbon nanohorns in a closed direct absorber. It was observed that the addition of nanoparticles led to an improvement in optical properties, resulting in higher solar radiation absorption. Based on these results, with the increase in photothermal conversion efficiency, this nanofluid could be considered as a new type of fluid. Thakur et al. [5] experimentally studied DASC in order to calculate the exergy and thermal efficiencies, entropy generation rate, pump power and performance evaluation criteria using hybrid nanofluid. Thermal efficiency was found to be 72.82% and 59.23%, respectively, when alumina/fly ash (80:20) based nanofluid and silica/fly ash (80:20) based nanofluid were used. They found that the exergy efficiency was 73% with alumina/fly ash (80:20) based nanofluid while it was 68.09% with silica/fly ash (80:20) based nanofluid. Vakili et al. [6] experimentally examined the performance of a volumetric solar collector with different concentrations 0.0005%, 0.001% and 0.005%. Different inlet temperatures with different flow rates of 0.0075, 0.015 and 0.225 kg/s were also used. Their results showed that the thermal efficiency increased with increasing nanofluid fraction. The efficiency was 70% with pure fluid while it was 83.5%, 89.7% and 93.2% with nanofluid concentrations of 0.0005%, 0.001% and 0.005%, respectively.

When reviewing the existing literature, the challenge in the application of DASCs is particularly associated with the type of nanoparticle, the concentration of nanofluids and the method of study. There are several studies which show that the use of nanofluids improves the collector efficiency for both conventional solar collectors and DASCs. However, there are very limited studies involving hybrid nanofluids for DASCs. Therefore, there is not enough information about the thermal performance of hybrid nanofluids in DASCs. In addition, stationary nanofluids have been used in most of the DASC studies in order to examine the photo-thermal conversion performance. Because the velocity of the fluid is affected by the construction of the collector, another feature that affects the photo-thermal conversion efficiency are the flow conditions. Notably, because the medium in which the solar energy is directly absorbed is a translucent medium, the optical properties of the heat transfer fluid gain importance, because the absorbing and scattering effects of the fluid directly affect the absorption of solar energy. Because it can lead to a change in the energy path from the emission, it can cause both a reduction and a boost in energy [7]. Therefore, the flow and heat characteristics of heat transfer fluid inside the collector change. In addition, because various nanoparticles have different optical and thermophysical characteristics, their effects on the photo-thermal conversion efficiencies are different. Moreover, the volume fraction influences the radiative and thermophysical properties of nanoparticles. Because very low volume concentrations are used in the DASCs, high concentrations of nanofluids need to be investigated. Consequently, the main aim of this research is to analyse and understand the effect of combined radiation and forced convection heat transfer and fluid flow on the photo-thermal conversion performance of the hybrid nanofluid based DASC in the framework of these parameters.

2. MATERIAL AND METHODS

The system consists of a DASC, a pump, a heat exchanger, and a tank where the nanofluid is stored. By absorbing the nanofluid radiation entering the collector from the storage tank, its temperature rises. This heat gain is transferred to the water through the heat exchanger. Because the nanofluid is the basic fluid in the system, it constantly circulates in the system through a pump.

The schematic of nanofluid based DASC is illustrated in Figure 1. The thermal performance of the DASC is investigated by developing a two-dimensional heat transfer and fluid flow model and solving it numerically. Solar irradiation penetrates the collector in a vertical direction and the heat transfer fluid flows horizontally inside the collector. The top wall of the collector is enclosed by a highly transparent glass surface to allow most of the irradiation to pass through. Because the top surface of the collector is exposed to the atmosphere, it loses heat to the environment through combined radiation and convection. The bottom plate is considered to be adiabatic.

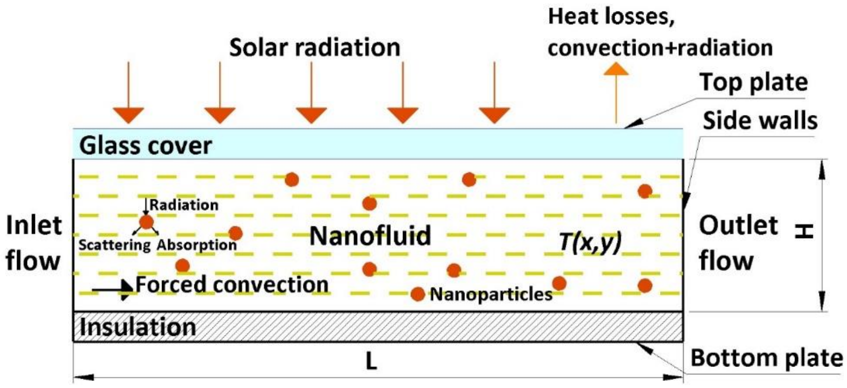

Figure 1: 2D schematic of nanofluid direct absorption solar collector

As seen in Equation (1), emitting, absorbing, and scattering do affect the Radiative Transport Equation (RTE) [8]. Therefore, the RTE is solved using the Discrete Ordinates (DO) technique.

$$\nabla\cdot(I_\lambda(\vec{r},\vec{s})\vec{s})+(\alpha_\lambda+\sigma_s)I_\lambda(\vec{r},\vec{s})=\alpha_\lambda n^2 I_{b\lambda}+\frac{\sigma_s}{4\pi}\int_0^{4\pi}I_\lambda(\vec{r},\vec{s}')\Phi(\vec{s}\cdot\vec{s}')d\Omega' \tag{1}$$

where I_λ is the radiation intensity, $\vec{r}$ is the position vector, $\vec{s}$ is the direction vector, α_λ is the spectral absorption co-efficient, σ_s is the scattering co-efficient, $I_{b\lambda}$ is the black body intensity, $\vec{s}'$ is the scattering direction vector, n is the refractive index, Φ is the phase function and Ω' is the solid angle.

Assuming incompressible, laminar, Newtonian, and steady-state fluid flow inside the collector, the governing and energy transport equations are, respectively, expressed as:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{2}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial x}+\frac{\mu_{nf}}{\rho_{nf}}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{3}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial y}+\frac{\mu_{nf}}{\rho_{nf}}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \tag{4}$$

$$\rho_{nf}c_{p_{nf}}\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=k_{nf}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)-\frac{\partial q_r}{\partial y} \tag{5}$$

where the boundary conditions are set to be:

At the inlet:

$$u=U_{in}, T=T_{in}, v=0 \tag{6}$$

At the outlet:

$$p=0 \tag{7}$$

At the top surface:

$$q=h(T-T_{amb})+\varepsilon\sigma(T^4-T_{amb}^4) \tag{8}$$

At the bottom surface:

$$\frac{\partial T}{\partial y} = 0 \tag{9}$$

At the solid walls:

$$u = v = 0 \tag{10}$$

where the subscripts nf, in, amb, and r denote the nanofluid, inlet, ambient and radiative respectively, u and v are the velocity vectors in the x and y directions, respectively (ms^{-1}), ρ is the density (kgm^{-3}), p is pressure (Pa), μ is the dynamic viscosity (Nsm^{-2}), c_p is the specific heat of the heat transfer fluid (JKg^{-1}K^{-1}), T is the temperature (K), k is the thermal conductivity (Wm^{-1}K^{-1}), q is the heat flux (Wm^{-2}), U is the velocity of the heat transfer fluid (m/s), h is the heat transfer coefficient (Wm^{-2}K^{-1}), ε is the emissivity and σ is the Stefan-Boltzmann constant (Wm^{-2}K^{-4}).

The photothermal conversion efficiency of the solar collector, which is the ratio of the useful heat gain to the incident solar energy, can be defined as [9]:

$$\eta = \frac{\dot{m}c_p(T_{out} - T_{in})}{AG} = \frac{\rho H U c_p(T_{out} - T_{in})}{LG} \tag{11}$$

where $\dot{m}$ is the mass flow rate (kg/s), T_{out} and T_{in} are the average outlet and inlet temperatures (K), respectively, U is the velocity of the working fluid (m/s), A is the top surface area of the collector (m^2), H is the height of the collector, L is the length of the collector and G is the solar irradiation (W/m^2).

The experimental and numerical studies from the literature are used for the validation in order to evaluate the accuracy of the numerical technique. Therefore, the work of Otanicar et al. [10] is chosen for the initial validation. They used DASC at irradiance level 1000 W/m^2, mass flow rate 42 ml/h and combined convective and radiative heat loss to the ambient, h = 23 Wm^{-2}K^{-1} using graphite/water nanofluid. As seen in Figure 2(a), as a function of the volume fraction, the present numerical solutions are in good agreement with the reference model [10]. Tyagi et al. [11], who analysed the DASC efficiency using Al nanoparticles as a function of the collector height has also been selected for the second validation case. The top wall is exposed to the solar irradiation, 1000 W/m^2 and the convective heat loss, h = 6 Wm^{-2}K^{-1} with the adiabatic bottom wall. As shown in Figure 2(b), there is a good agreement between the reference study and present results.

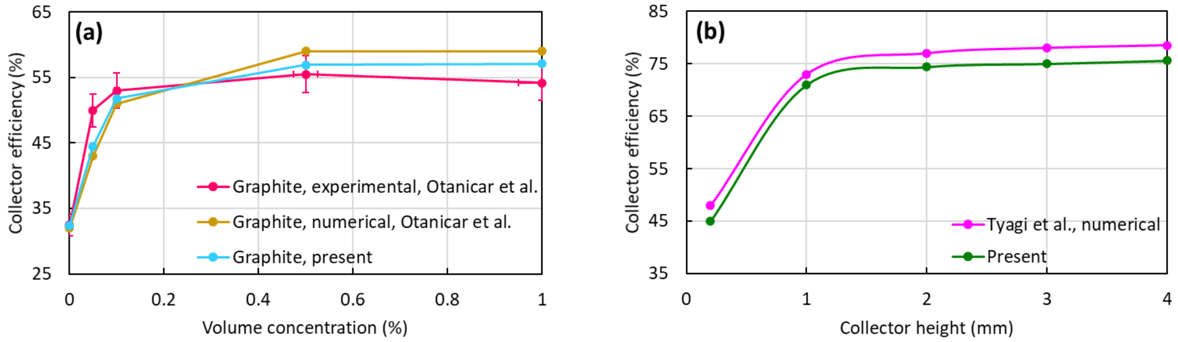

Figure 2: Comparison of the present results with benchmark cases [10, 11]

3. RESULTS AND DISCUSSION

Figure 3 shows that the volume concentration of the nanofluid is a factor that significantly affects the system performance. Because the absorption of pure fluids dominates attenuation, the scattering effects can be neglected [11]. In this system, the absorption coefficient of pure water is 20 1/m. As shown in Figure 3(a-b), the absorption and scattering coefficients of the heat transfer fluid are increased because of the hybrid nanofluids which are added to pure water. These properties of hybrid nanoparticles formed by the combination of mono nanoparticles depending on the optical properties of the mono nanoparticles in their combination [12]. Moreover, the increase in these coefficients continues with increasing volume concentration. As also shown in Figure 3(c-d), there is a relationship between the collector efficiency and heat loss. The lower the heat loss, the higher is the efficiency. This is due to the heat loss in the collector taking place as a result of both the radiation and convection from the upper wall and the heat loss depending on the upper wall temperature of the collector. As shown in Figure 3(a), despite the absorption coefficient increasing with the rise in the volume concentration, the amount of heat loss decreases (See Figure 3(c)). This is because a lower volume concentration causes more solar energy to be absorbed in the nanofluid. Therefore, the upper wall temperature is reduced with the increase in the volume concentration, as a result the efficiency of the collector increases as shown in Figure 3(d). While the efficiency of pure water is 0.54, this efficiency reaches up to 0.92 because of the hybrid nanofluid. This is a result of the higher thermal conductivity and optical properties of the nanoparticles compared to pure water. The results further show that, as the radiation absorption capacity of the nanofluid increases, the amount of volumetric heat generation by the radiation inside the solar collector also increases, resulting in an improvement in the efficiency of the collector. In addition, because each nanoparticle has different optical and thermophysical properties, their use has different effects and Graphite+MgO/water-based hybrid nanofluid has the highest efficiency.

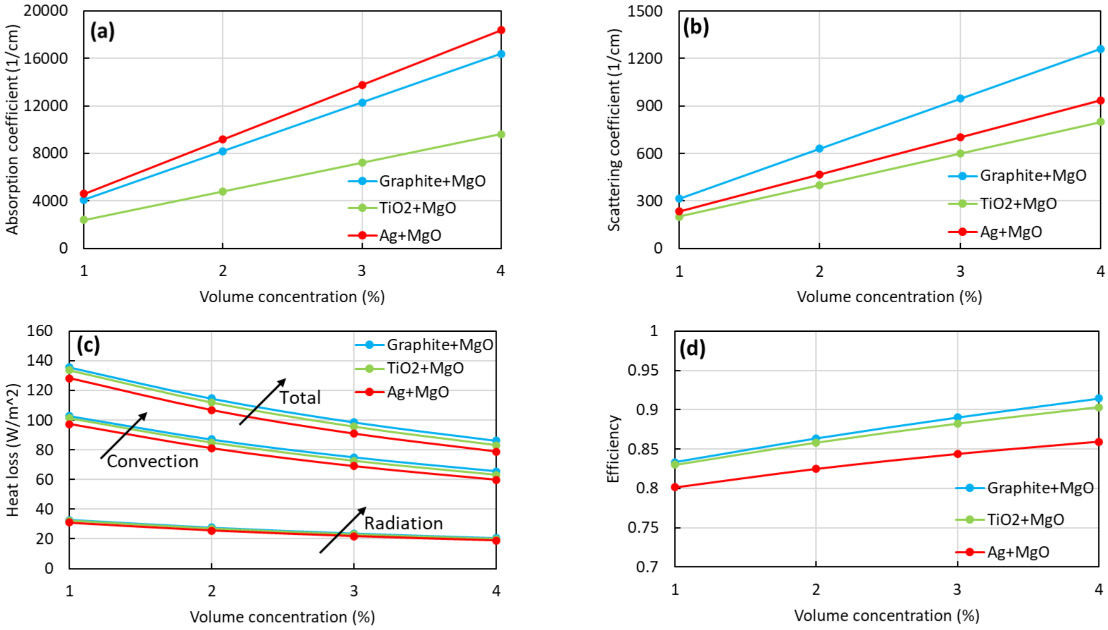

Figure 3: Effect of hybrid nanofluids on the thermal performance of the DASC

4. CONCLUSION

A direct absorption solar collector (DASC) using different hybrid nanofluids was examined in this study. The effects of volume concentration and different type of nanoparticles (Graphite, MgO, Ag and TiO_2) on the optical properties and collector efficiency were investigated. A 2-D heat transfer and fluid flow model based on the radiative heat transfer including the scattering, emitting, and absorbing effects was developed and numerically solved. It was found that a remarkable improvement in the optical properties achievable with the addition of nanoparticles to the base fluid which is water. It was further observed that these properties increase with the increase in nanoparticle concentration. The numerical model showed that the collector efficiency increases with increasing volume concentration. The collector had the maximum thermal efficiency at a volume fraction of 4% with Graphite+MgO/water hybrid nanofluid and it was 70% higher than using water as a heat transfer fluid under the same conditions. In addition, it was discovered that the heat loss to the environment decreases with increasing volume fraction. Moreover, because different nanoparticles have different optical properties, their effect on the thermal performance of the collector was found to be different. As a result, the extinction (absorption+scattering) capacity of hybrid nanoparticles is higher than the base fluid, and also the enhancement of the thermal performance of the DASC is higher. Hence, it is suggested that hybrid nanofluids are favourable for solar energy applications. Furthermore, it is understood that with the increase in the efficiency of the collector, the capacity of the system to capture solar energy will also increase and, therefore, the amount of sensible heat storage produced in the collector will also increase.

ACKNOWLEDGEMENT

This work is supported by the Turkish Ministry of National Education, Republic of Turkey.

REFERENCES

[1] A. Lenert & E. N. Wang, Optimization of nanofluid volumetric receivers for solar thermal energy conversion. *Solar Energy*, 86(1) (2012) 253–265.

[2] R. Bertocchi, J. Karni, & A. Kribus, Experimental evaluation of a non-isothermal high temperature solar particle receiver. *Energy,* 29(5-6) (2004) 687–700.

[3] R. A. Taylor, P. E. Phelan, T. P. Otanicar, R. Adrian & P. Ravi, Nanofluid optical property characterization: towards efficient direct absorption solar collectors. *Nanoscale Research Letters*, 6(225) (2011) 1–11.

[4] E. Sani, S. Barison, C. Pagura, L. Mercatelli, P. Sansoni, D. Fontani, D. Jafrancesco & F. Francini, Carbon nanohorns-based nanofluids as direct sunlight absorbers. *Optics Express,* 18(5) (2010) 5179–5187.

[5] P. P. Thakur, T. S. Khapane & S. S. Sonawane, Comparative performance evaluation of fly ash-based hybrid nanofluids in microchannel-based direct absorption solar collector. *Journal of Thermal Analysis and Calorimetry,* 143 (2021) 1713–1726.

[6] M. Vakili, S. M. Hosseinalipour, S. Delfani, S. Khosrojerdi, & M. Karami, Experimental investigation of graphene nanoplatelets nanofluid-based volumetric solar collector for domestic hot water systems. *Solar Energy*, 131 (2016) 119–130.

[7] M. F. Modest, *Radiative Heat Transfer* Academic Press, (2013).

[8] *ANSYS Fluent User's Guide* ANSYS Inc., (2013), Canonsburg.

[9] H. Duan, R. Chen, Y. Zheng & C. Xu. Photothermal properties of plasmonic nanoshell-blended nanofluid for direct solar thermal absorption. *Optics Express*, 26(3) (2018) 29956-29967.

[10] T. P. Otanicar, P. E. Phelan, R. S. Prasher, G. Rosengarten, & R. A. Taylor, Nanofluid-based direct absorption solar collector. *Journal of Renewable and Sustainable Energy,* 2(3) (2010) 033102-13.

[11] H. Tyagi, P. Phelan, & R. Prasher, Predicted Efficiency of a Low-Temperature Nanofluid-Based Direct Absorption Solar Collector. *Journal of Solar Energy Engineering*, 131(4) (2009) 041004–7.

[12] H. M. F. Rabbi, A. Z. Sahin, B. S. Yilbas, & A. Al-Sharafi, Methods for the determination of nanofluid optical properties: A review. *International Journal of Thermophysics*, 42(9) (2021) 1–42.