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Effect of Radiative Heat Transfer in Nanofluid for Volumetric Solar Collector

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ABSTRACT

The use of nanofluids as a heat transfer fluid in solar energy conversion systems greatly improves photothermal conversion. In this study, numerical studies have been carried out using a volumetric solar collector to convert solar radiation into thermal energy. Because the collector is a translucent medium, 2D radiative heat transfer and energy equations are solved using ANSYS Fluent, which takes into account the absorption and scattering of nanoparticles. The results show that, when hybrid nanofluids are used, the amount of heat obtained from solar radiation increases due to the temperature rise in the collector, hence improving the storage capacity of the collector.

Keywords: solar energy, hybrid nanofluids, volumetric solar collector, radiative heat transfer

NONMENCLATURE

Abbreviations	
nf	nanofluid
conv	convection
rad	radiation
Symbols	
Ra	Rayleigh number
ε	emissivity
Nu	Nusselt number
u	velocity vector (m/s)
v	velocity vector (m/s)
g	gravitational acceleration (m/s^2)
T	temperature (K)
T_0	initial temperature (K)
I_λ	radiation intensity (W/m^{2}µm)
$\vec{r}$	position vector
$\vec{s}$	direction vector
α_λ	spectral absorption coefficient (1/m)
σ_s	scattering coefficient (1/m)
$I_{b\lambda}$	black body intensity (W/m^{2}µm)
$\vec{s}'$	scattering direction vector
n	refractive index
Φ	phase function
ϕ	dissipation function
Ω'	solid angle
ψ	internal energy
ρ	density (kg/m^3)
p	Pressure (Pa)
μ	dynamic viscosity (Ns/m^2)
β	thermal expansion coefficient (1/K)
q''	heat flux (W/m^2)
q'''	volumetric heat generation (W/m^3)

1. INTRODUCTION

Most of the energy needed today is provided by hydrocarbon-based resources such as coal, collectively known as fossil fuels [1]. Although the use of fossil fuels has the highest rate in the energy sector, environmental impacts arising from the use of these fuels are growing. Firstly, fossil fuels are limited resources, and gases such as SO_x and NO_x, which are harmful to human health, are released into the atmosphere as a result of the combustion of hydrocarbon fuels [2]. Therefore, these gases, which cause the 'greenhouse effect', cover the atmosphere and prevent the sun's rays as they come to the Earth from reflecting and returning to Space [3]. Renewable energy, also called clean energy sources, is expected to overcome all these problems as it does not produce an environmentally hazardous by-product. Natural resources that have the potential to be converted into useful works such as the sun, wind, water, groundwater, and wave motion are seen as renewable energy sources. Although solar energy is regard as one of the most effective solutions in the supply of energy, solar radiation must be effectively converted into thermal energy. In a typical flat-plate solar collector, the efficiency decreases due to heat losses when the heat absorbed is transferred to the heat transfer fluid [4]. However, the efficiency of a volumetric solar collector is usually high since the fluid acts as both a heat transfer fluid and an absorbing medium [5].

When the literature is analysed, some challenges may be encountered. There are not still enough studies for hybrid nanoparticles, even though there are studies which are related to mono nanoparticles. In addition, because the inside of the collector is translucent, there may be a change in the path of the energy from the radiation as the scattering effect of the nanoparticles causes both a decline and an increase in energy [6]. Therefore, the heat and flow characteristics of the heat transfer fluid inside collector change. Consequently, the objective of the present work is to analyse and understand the effect of radiative heat transfer on the thermal performance of a volumetric solar collector enclosure storage system. A volumetric solar collector model is developed by Computational Fluid Dynamics to further examine the heat transfer and fluid flow processes which occur inside the collector with specific operating conditions.

2.MATERIAL AND METHODS

A schematic of a nanofluid based volumetric solar collector is illustrated in Figure 1. Two-dimensional numerical heat transfer and fluid flow model is developed to investigate the collector performance. The top wall of the collector is covered with a glass surface, allowing solar radiation to pass through and encouraging both nanofluid heating and heat loss to the environment by radiation and convection.

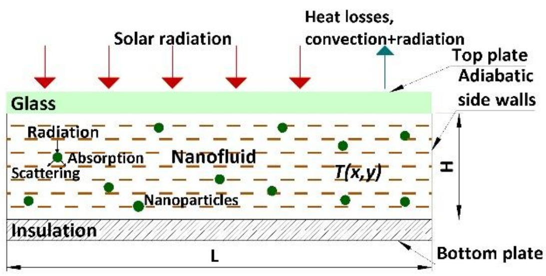

Figure 1. 2D schematic of nanofluid volumetric solar collector

Because the radiative transport equation includes scattering, emitting and absorbing factors, the Discrete Ordinates method is used to solve the radiation equation. The radiative transfer, continuity, momentum, and energy conservation equations [6] are, respectively, described as follows,

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

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (2)$$

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

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho_{nf}}\frac{\partial p}{\partial y} + \frac{\mu_{nf}}{\rho_{nf}}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + \frac{(\rho\beta)_{nf}}{\rho_{nf}}g(T-T_0) \quad (4)$$

$$\rho\frac{D\psi}{Dt} = \rho\left(\frac{\partial\psi}{\partial t} + \mathrm{v}\cdot\nabla\psi\right) = -\nabla\cdot q'' - p\nabla\cdot\mathrm{v} + \mu\phi + q''' \quad (5)$$

In numerical studies, the developed computer code has to be accurate in order to ensure the precision of the results. For this, various studies from the existing literature have been chosen. This validation is carried out by comparing current results with numerical studies by Ridouane [7] and Alvarado [8]. In this comparison (see Table 1), the combined radiation and natural convection of the square cavity filled with air is investigated. The side walls of the cavity are kept in an adiabatic condition while the bottom wall and top wall are kept at constant cold and hot temperatures, respectively. The average radiative and convective Nusselt numbers on the hot wall are calculated and, as shown in Table 1, a good agreement is obtained matching the benchmark models.

A grid is another factor that affects the accuracy of the numerical simulations. The results of grid sensitivity analysis for volumetric absorbed radiation with four mesh numbers for water-based Al nanofluid with 100 ppm is shown in Figure 2. This shows that small differences have been obtained and can be neglected after mesh number of 64000.

Table 1. Validation of the present code with benchmark

	Ra	ε	Nu_{conv}	Nu_{rad}
Ridouane et al. [7]	$2x10^6$	0	7.617	0
Alvarado et al. [8]			7.665	0
Present			7.644	0
Ridouane et al. [7]	10^6	0.5	6.267	6.599
Alvarado et al. [8]			6.107	6.249
Present			6.183	6.475
Ridouane et al. [7]	$4x10^5$	1	4.722	11.462
Alvarado et al. [8]			4.591	10.871
Present			4.683	11.215

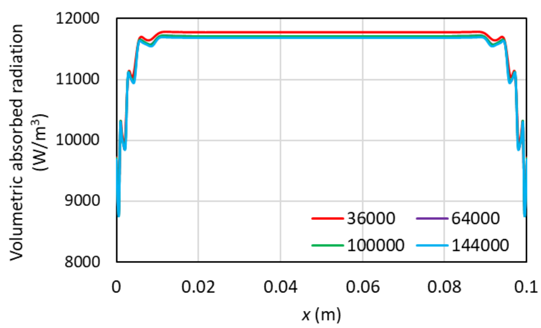

Figure 2. Grid refinement test of volumetric absorbed radiation with four different grids

3. RESULTS AND DISCUSSION

In this work, water is used as a base fluid and the useful heat gain and enthalpy difference of water are 23 kJ/kg and 48 kJ/kg, respectively.

As seen in Figure 3, the addition of nanoparticles increases the nanofluid's ability to absorb solar radiation, thereby increasing the temperature of the nanofluid. When the Al nanoparticles are added to the pure water, the useful heat gain of nanofluid reaches up to 45 kJ/kg. However, since the total extinction capacity of hybrid nanofluids depends on the extinction coefficient of each nanoparticle type, hybrid nanofluids have the capacity to absorb more solar radiation. Thus, with the addition of hybrid nanoparticles, the heat gain is increased by more than four times, reaching 215 kJ/kg.

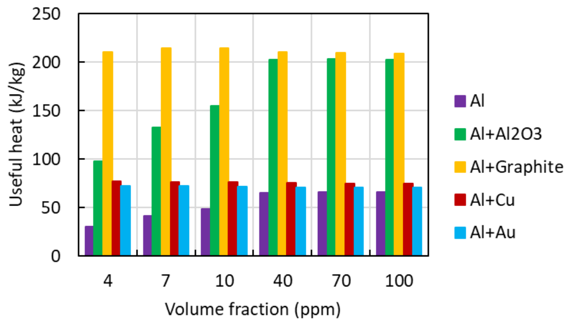

Figure 3. Useful heat capacities of nanoparticles

With the energy that solar radiation brings to the system, the temperature of the working fluid changes, and thus both the sensible heat capacity changes (see Figure 3), and heat can be generated due to energy conversion. Therefore, because this heat depends on the initial and final conditions of the heat transfer fluid, the amount of stored heat equals the enthalpy change [9]. As can be seen in Figure 4, the enthalpy difference of mono nanoparticles reaches up to 90 kJ/kg with the addition of Al nanoparticles. The storage capacity becomes approximately 250 kJ/kg with hybrid Al+Graphite nanoparticles.

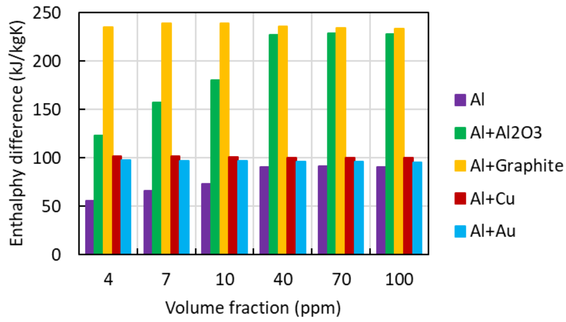

Figure 4. Storage capacities of nanoparticles

As seen in both Figures 3 and 4, the useful heat and enthalpy difference is reduced slightly after 10 ppm. The reason for this can be that although the increase in the volumetric concentration increases the thermal conductivity and radiative properties of the nanofluid, the nanoparticles close to the upper wall and its surroundings absorb the solar radiation more and less solar radiation reaches the bottom of the collector.

4. CONCLUSION

In this study, the effects of radiation heat transfer and hybrid nanoparticles on a volumetric solar collector have been analysed. Because nanoparticles have higher optical properties than water, when the nanoparticles are added to pure fluids, the radiation absorption capacity of nanofluids increases, and so the fluid's average temperature and the average volumetric heat generation increase. Thus, the performance of the cavity is enhanced. In addition, various types of nanoparticles have different optical properties. Because of this, the extinction capacities of the nanofluids are different from each other and they affect the thermal performance of the collector differently. Moreover, because the absorption capacity of the hybrid nanofluids is higher than mono nanofluids, there is greater improvement in the thermal performance of the collector. Therefore, hybrid nanofluids can be taught as a new heat transfer fluid and used in solar applications thanks to these advantages.

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