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Investigating the collector efficiency of silver nanofluids based direct absorption solar collectors

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HIGHLIGHTS

- An analysis coupled with Radiation transfer, Maxwell and Energy equation is developed.
- Plasmonic Au and Ag nanofluids show better photo-thermal conversion properties.
- Collector height and particle concentration exist optimum solutions for efficiency.

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ABSTRACT

A one-dimensional transient heat transfer analysis was carried out to analyze the effects of the Nanoparticle (NP) volume fraction, collector height, irradiation time, solar flux, and NP material on the collector efficiency. The numerical results were compared with the experimental results obtained by silver nanofluids to validate the model, and good agreement was obtained. The numerical results show that the collector efficiency increases as the collector height and NP volume fraction increase and then reaches a maximum value. An optimum collector height (~10 mm) and particle concentration (~0.03%) achieving a collector efficiency of 90% of the maximum efficiency can be obtained under the conditions used in the simulation. However, the collector efficiency decreases as the irradiation time increases owing to the increased heat loss. A high solar flux is desirable to maintain a high efficiency over a wide temperature range, which is beneficial for subsequent energy utilization. The modeling results also show silver and gold nanofluids obtain higher photothermal conversion efficiencies than the titanium dioxide nanofluid because their absorption spectra are similar to the solar radiation spectrum.

1. Introduction

The increases in both the global population and living quality have increased the demand for electricity, but the amount of fossil fuels is limited. Moreover, the combustion of fossil fuels has resulted in many environmental concerns such as the greenhouse effect due to carbon dioxide emission and acid rain produced by acid gas emission [1,2]. Hence, the development of efficient sustainable energy is currently one of the most important challenges. Solar energy, as a clean and sustainable energy source, provides a potential solution to this challenge. For instance, the solar energy that reaches the Earth's surface over one hour is greater than the worldwide energy consumption for one year [3,4]. The challenges for solar energy lie in the effective absorption, conversion, and storage of solar radiation, which are significantly affected by the working medium [5–8]. To simplify the collector and enhance its efficiency, a so-called Direct Solar Absorption Collector (DASC) has been proposed [9]. Compared with a surface-based collector, the DASC directly absorbs solar radiation in a bulk fluid, and the temperature distribution becomes more uniform, resulting in a small heat loss at the capture surface [10]. In a DASC, solar energy is directly absorbed and then transferred by the working fluid. Hence, the working fluid needs to have good optical performance to maximize the absorption of solar energy and possess excellent heat transfer capabilities to decrease the temperature difference [11].

The application of a nanofluid as the working fluid of a DASC is a relatively new concept in the last decade [12,13], which was first demonstrated by Tyagi et al. [14]. Nanoparticles (NPs) dispersed in a base fluid offer the potential to improve the optical properties of nanofluids, which could lead to an increase in the collector efficiency due to the absorption and scattering of NPs. Additionally, it

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Nomenclature

A	area (m^2)
C	modify factor
c_0	speed of light in vacuum (m/s)
c_p	specific heat capacity (J/(kg·°C))
D	diameter (m)
f_v	volume fraction
G	heat flux (W/m^2)
H	height (m)
h	Planck's constant
h_c	heat transfer coefficient ($W/(m^2 \cdot °C)$)
I_λ	spectral intensity ($W/(m^2 \cdot \mu m)$)
k	thermal conductivity (W/(m·°C))
$k_{a\lambda}$	spectral absorption coefficient
k_B	Boltzmann constant
$k_{s\lambda}$	spectral scattering coefficient
$k_{e\lambda}$	spectral extinction coefficient
m	complex refractive index
n	refraction coefficient
q_r	radiative heat flux (W/m^2)
$\mathbf{s}$	vector of location
T	temperature (°C)
t	time (s)
$\mathbf{\Omega}$	direction of radiative transfer
Φ_λ	spectrum scattering phase function

Greek symbols

α	size parameter
η	photo-thermal efficiency
κ	absorption coefficient
λ	wavelength (nm)
ρ	density (kg/m^3)
ϕ	solid angle (sr)

Subscripts

b	blackbody
v	volume

has been shown that the addition of NPs has a dramatic effect on the base fluid's thermophysical properties such as the thermal conductivity, mass diffusivity, and viscosity [15–20]. Compared with the base fluid, the enhanced optical and thermophysical properties of a nanofluid allow it to be a working medium applied in different solar collectors [21,22]. Tyagi et al. [14] revealed that under similar operating conditions, the efficiency of a DASC using nanofluids as the working fluid was up to 10% higher than that of a flat-plate collector. In addition, they also observed that the presence of NPs increased the absorption of solar energy by more than nine times compared to that of pure water. Many recent studies have indicated that the selection of the nanofluid is very important to obtain a performance enhancement in a DASC. A carbon nanotube/water nanofluid was applied as a working fluid in low-temperature DASCs by Karami et al. [23]. The extinction coefficient and thermal conductivity of the functionalized carbon nanotube nanofluid showed remarkable improvement compared to the base fluid, even at low particle loadings. Its promising optical and thermal properties, together with the appropriate stability, make it very interesting for increasing the overall efficiency of low-temperature DASCs. The extinction coefficient of a water-based aluminum nanofluid with a varying NP size and volume fraction was investigated and evaluated by Saidur et al. [24]. The particle size had a minimal influence on the optical properties of the nanofluid. Moreover, a promising improvement was achieved within a volume fraction of 1.0%, and the nanofluid was almost opaque to light. The optical properties of a titanium dioxide nanofluid for a DASC was studied by Said et al. [25]. Promising results were observed for NP volume fractions less than 0.1%. Despite having a very high extinction coefficient at shorter wavelengths, the addition of particles to water could also improve the light absorption ability in the visible- and shorter-wavelength regions. He et al. [26] experimentally investigated the photothermal properties of copper/water nanofluids. The results showed that the temperature of the copper/water nanofluids (0.1 wt.%) can be increased up to 25.3% compared with that of deionized water when the solar irradiation time was ~1200 s under natural sunlight. As stated above, different NP materials, NP volume fractions, and collector styles have significant impacts on the solar utilization efficiency. The selection of the working fluid is very important to obtain a performance enhancement in a DASC.

In recent years, the applications of plasmonic NPs for solar absorption have attracted significant interest [27–29]. Research has showed that silver NPs exhibit an excellent photothermal conversion capability, even at very low NP volume fractions since the Localized Surface Plasmon Resonance (LSPR) in the nanostructures enhance the electric-field intensity, resulting in enhanced scattering and absorption coefficients at the LSPR frequency [30]. For the applications of plasmonic NPs, silver is the most attractive metal owing to its high surface plasmon strength, which allows silver nanofluids with very low concentrations to exhibit considerable absorption and scattering properties at the resonance frequency [31]. Further, many works have focused on the experimental determination or simulation of the optical properties of NPs for the application of plasmonic NPs to DASCs [27,28,32]. It should be noted that in addition to the properties of the working fluids, the parameters of a DASC also have strong impacts on the efficiency, which is a factor that has received little attention. A systemic simulation of the optical properties of the working medium and the collector parameters is significant for the application of plasmonic NPs to DASCs. To achieve an optimized collector efficiency, it is desirable to systematically investigate the photothermal conversion characteristics of plasmonic nanofluids under different conditions both experimentally and numerically, including different collector designs.

In this work, the photothermal conversion characteristics of plasmonic silver nanofluids for DASCs are investigated. Silver NPs are synthesized by using ascorbic acid as a reductant and citrate as a stabilizer. A one-dimensional transient heat transfer analysis is carried to analyze the effects of the NP volume fraction, collector height, irradiation time, solar flux, and NP material on the collector performance, leading to optimized collector and fluid parameters.

2. Numerical calculation

A one-dimensional (1-D) numerical analysis is developed to study a DASC undergoing transient heat conduction in the presence of natural convection on the top surface, as shown in Fig. 1. The nanofluid is contained within the enclosure of the collector. The length of the collector along the horizontal direction is assumed to be sufficiently large compared to the height h in the vertical direction. The bottom, left, and right side walls are considered to be adiabatic, i.e., no heat flux is allowed to pass through except for the transmitted radiation. The top surface consists of selective glass that allows most of the incident solar flux to pass through it. As the temperature of nanofluid is low, the heat loss