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Blended morphologies of plasmonic nanofluids for direct absorption applications

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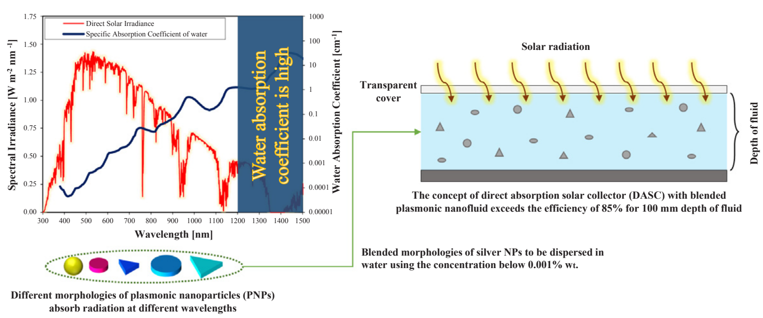
HIGHLIGHTS

- Comprehensive approach to develop plasmonic nanofluid for direct solar absorption.
- Blended plasmonic nanoparticles morphologies for broadband high absorptivity.
- Finite element method obtains the optical properties of plasmonic nanoparticles.
- Radiative transfer equation obtains the performance of direct solar collector.
- Very low concentrations of plasmonic nanoparticles can attain an efficiency of 85%.

GRAPHICAL ABSTRACT



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ABSTRACT

Direct absorption solar collectors were introduced to overcome the limitations of conventional surface absorber collectors. The advances in nanotechnology accompanied with phenomenological discoveries at the nanoscale have allowed the appearance of plasmonic nanofluids, which utilize localized surface plasmon resonance phenomenon that multiplies the extinction efficiency of the plasmonic nanoparticle several times at the resonance wavelength. Silver nanoparticles exhibit a high intensity of the localized surface plasmon, which can be fine-tuned within the broadband 350–1200 nm by tailoring their shape, size and aspect ratio. In this paper, we have numerically investigated the effects of silver nanoparticles' morphology on the localized surface plasmon resonance and on the extinction peaks. Numerical results allow determining the effective morphologies at every band of the solar spectrum. Thus, nanofluids composed of blended Ag nano-morphologies were designed, which can expand the absorbance over the entire solar spectrum. By means of the radiative transfer equation, we found that blended plasmonic nanofluids have the potential to raise the efficiency of the direct solar collector to more than 85% at a very low concentration below 0.001 wt%. Utilization of the blended plasmonic nanofluids are not limited to solar thermal and concentrated solar power applications, but also can be extended into the optical filters in PV/thermal applications.

1. Introduction

Solar energy is the cornerstone in building clean and sustainable energy models, where it can be harvested by means of photovoltaic and solar thermal technologies, artificial photosynthesis, and electricity generation. The use of solar thermal technologies in power generation

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Nomenclature

A_c	particle cross-sectional area, m^2
A_{DASC}	the surface area of the collector which is exposed to the solar irradiance, m^2
$\boldsymbol{B}$	total magnetic field vector (magnetic induction), $N \cdot A^{-1} \cdot m^{-1}$
$\boldsymbol{D}$	electric displacement vector, $C \cdot m^{-2}$
D_f	the depth of the fluid, m
$\boldsymbol{E}$, E_s	electric field vector, and the amplitude of the electric field in the direction s, $V \cdot m^{-1}$
G	mass flux, $kg \cdot s^{-1}\, m^{-2}$
I	radiation intensity, $W \cdot m^{-2}$
$I_{A,\lambda}$	spectral irradiance absorption intensity, $W \cdot m^{-2}$
$I_{b,\lambda}$	spectral intensity of the blackbody radiation, $W \cdot m^{-2}$
K	absorption coefficient m^{-1}
L	transmission length or depth of fluid, m
Q	optical efficiency, dimensionless
S, $\vec{S}$	pointing vector, $W \cdot m^{-2}$
T	temperature, K
V_m, $V_{dr,p}$	mass average velocity for the mixture, drift velocity of the nanoparticle, $m \cdot s^{-1}$
V_{NP}	volume of the nanoparticle, m^3
W	energy, W
c	the speed of light, $m \cdot s^{-1}$
c_p	specific heat capacity at constant pressure, $J \cdot kg^{-1} \cdot K^{-1}$
d	nanoparticle diameter, nm or m
f_v	volume fraction
h	convection heat transfer, $W \cdot m^{-2} \cdot K^{-1}$
l_∞	electron mean free path, m
$\dot{m}$	mass flow rate, $kg \cdot s^{-1}$
m_e	electron mass: $9.11e^{-31}$ kg
n_e	electron density, m^{-3}
n	refractive index, dimensionless
v_f	fermi velocity, $m \cdot s^{-1}$

Greek

Υ_∞	relaxation constant, s^{-1}
$\Phi_{(\vec{s},\vec{s}')}$	scattering phase function
ε	relative dielectric function (electric permittivity), dimensionless
η, η_{pt}	efficiency, photo-thermal energy conversion efficiency, dimensionless
λ	wavelength, μm
μ	magnetic permeability, $N \cdot s^2 \cdot C^{-2}$
ρ	density, $kg \cdot m^{-3}$
σ	optical coefficient, m^{-1}
τ	relaxation time, s
ϕ_k	the volume fraction of the phase k,
ω	angular frequency, $Rad \cdot s^{-1}$
ω_p	plasma frequency, $Rad \cdot s^{-1}$

Subscripts

0	vacuum
Abs	absorption
Sct	scattering
Ext	extinction
Inc.	incident
BF	base fluid
NP	nanoparticle

Abbreviations

wt%	weight fraction
DASC	direct absorption solar collector
DO	discrete ordinates
EM	electromagnetic
FEA	finite element analysis
LSPR	localized surface plasmon resonance
NIR	near-infrared
NP	nanoparticle
PNF	plasmonic nanofluid
PNP	plasmonic nanoparticle
UV	ultraviolet
VIS	visible

plants, manufacturing, and domestic applications has become more widespread with each passing year. Direct absorption solar collectors (DASCs) have been proposed recently to improve the efficiency and overcome the limitations of conventional solar collectors. With this concept, the working fluid directly absorbs solar radiation without any intermediary heat transfer processes. Various types of nanofluids have been studied using a wide variety of nanoparticles such as graphite [1], carbon nanotubes (CNTs) [2], and metal oxides such as aluminum oxide (Al_2O_3) [3,4], titanium oxide (TiO_2) [5], and copper oxide (CuO) [6].

The depth of fluid is one crucial parameter in the design of DASCs because it determines the extent to which the incident radiation passes through the fluid and becomes fully attenuated. In general, a high depth of fluid is desirable because it results in higher solar irradiance attenuation, which in turn, increases the photo-thermal conversion efficiency, but this is negated by the increase in size and weight of the collector. An alternative approach to boost the efficiency of DASCs without altering its size is to increase the concentration of nanoparticles dispersed in the base fluid. However, this should be approached with caution since the density and viscosity of the fluid will increase with an increase in nanoparticle concentration, which results in higher pumping power of the thermal system. In addition, nanoparticles are prone to sedimentation and aggregation, whereas the settlement velocity is proportional to the concentration of nanoparticles in the base fluid [7].

Plasmonic nanofluids (PNFs) are appealing alternatives to metal oxide and carbon-based nanofluids because of their unique features and favorable optical properties, which render these fluids ideal for solar energy harvesting. When a metallic nanoparticle is subjected to an electromagnetic field at wavelengths larger than the particle size, the free electron gas of the whole particle collectively starts to oscillate. Resonance occurs at a specific wavelength, at which the oscillating charges create an electromagnetic field much higher than the incident radiation and therefore, the absorption and extinction cross-sections of the particle are several or dozens of times the cross-section of the particle [8,9]. This phenomenon is known as localized surface plasmon resonance (LSPR). With the higher absorption cross-section, only a low concentration of particles is required for radiation attenuation. PNFs utilizes LSPR to attain high energy conversion efficiency while eliminating the need to increase the collector size or the concentration of particles. Recently, promising results have been obtained with very low concentrations ≤ 0.04 wt% of plasmonic nanoparticles (PNPs) such as gold and silver for photo-thermal conversion [10–15,1,16–18]. PNFs have also been proposed as optical filters in photovoltaic-thermal systems [19–22]. Among all metals, Ag has distinct LSPR properties within the visible-near infrared (VIS-NIR) spectrum with high plasmonic intensities [23,24]. In addition, Ag has high thermal conductivity, besides to that, Ag nanoparticles can be synthesized with various shapes and size with ease of size control [25–27,23]. For these reasons, Ag-based