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Analytical modeling and experimental investigation on optical properties of new class of nanofluids (Al_2O_3–CuO binary nanofluids) for direct absorption solar thermal energy

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ABSTRACT

Nanofluids play a major role in many modern engineering processes. Binary nanofluids are a new class of nanofluids that are prepared by dispersing simultaneously two dissimilar nanoparticles in a base fluid. They offer a good potential for use in direct absorption solar systems. The present study investigates both experimentally and analytically the optical properties of binary nanofluids for direct absorption in solar applications. For this purpose, two dissimilar nanoparticles, i.e. CuO and γ-Al_2O_3, are dispersed in water, ethylene glycol, and the ethylene glycol–water mixture to form binary nanofluids. In addition, a new method is developed for calculating the extinction coefficient of the binary nanofluids based on the classical electromagnetic theory. It will be shown that the extinction coefficients obtained from both analytical and experimental studies are in good agreement. Moreover, the extinction coefficient of the binary nanofluids is found to be approximately equal to the sum of the extinction coefficients of the constituent components, determined both analytically and experimentally. By increasing the nanoparticle volume fraction, improvements are observed in the extinction coefficient of the binary nanofluids prepared. Also, the analytical and experimental results of the study show that the extinction coefficient of the binary nanoparticles dispersed in water as the "base fluid" is greater than those of the binary nanoparticles dispersed in ethylene glycol or the mixture of ethylene glycol–water.

1. Introduction

Fossil energy resources are expensive and unstable in the long term. This gives way to the reliance of modern engineering on the application of renewable, especially solar, energy resources. For concentration the sunlight and conversion of solar energy into thermal energy, generally, solar thermal collectors are used. Due to the low absorption coefficient of working fluids used in solar thermal collectors, the efficiency of a solar thermal collector is usually low. A lot of research [1–11] has been dedicated over the years to finding ways of enhancing the optical efficiency of thermal solar collectors. These efforts have led to the finding that nanoparticles could be used to solve the problem due to their ability to change the thermal conductivity, convective and boiling heat transfer coefficients, and optical (absorption and scattering) properties of the solutions in which they are dissolved. More recently, a new class of solar thermal collectors known as "direct absorption solar thermal collectors" has been proposed as a novel solution in which the efficiency of the thermal collector is improved through direct absorption and scattering of solar irradiation by nanoparticles dispersed in the base fluid [12–21]. Otanicar et al. [15] introduced the nanofluid-based direct absorption solar collector. They conducted experiments to investigate the effects of a variety of nanoparticles such as carbon nanotubes, graphite, and silver on the efficiency of direct absorption solar collectors. Gupta et al. [16] investigated the effect of the flow rate of Al_2O_3–H_2O nanofluid on the efficiency of the direct absorption solar collector and showed that enhancements of about 8.1% and 4.2% could be achieved in collector efficiency with 1.5 and 2 (lpm) nanofluid flow rates, respectively. Luo et al. [17] studied the performance of a nanofluid solar collector based on direct absorption collection to show that the efficiency of the solar collector could be improved by up to about 2–25% as a result of the use of nanofluids. Tyagi et al. [18] estimated the efficiency of a direct absorption solar collector using aluminum nanoparticles in water and reported an improvement in efficiency by up to 10%.

The Mie theory is commonly used in analytical studies for modeling the striking of a light beam onto a particle in order to analyze

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Nomenclature

A	area (m^2)
a_n	coefficient obtained from Eq. (9)
b_n	coefficient obtained from Eq. (9)
d_p	particle diameter (nm)
E	electrical field
$\hat{e}_r$	unit vector
f_m	volume ratio of water to EG
f_v	volume fraction of nanoparticle to base fluid
H	magnetic field
I_i	intensity of incident irradiance
n_f	refractive index of base fluid
n_p	refractive index of nanoparticle
n	real refractive index
k	imaginary refractive index
m	normalized refractive index of the nanoparticles with respect to the base fluid
Q_{ext}	extinction efficiency
Q_{scat}	scattering efficiency
S	Poynting vector
σ_{ext}	extinction coefficient
σ_{sca}	scattering coefficient
ε	dielectric constant
ε'	real dielectric constant
ε''	imaginary dielectric constant
λ	wavelength (nm)
ζ	size parameter
index	
b	base fluid
i	incident
J	a type of nanoparticle
k	a type of nanoparticle
abs	absorption
eff	effective
ext	extinction
s or *scat*	scattering

and estimate the absorption, scattering, and extinction coefficients of nanoparticles in the base fluid [22].

The potential of Mie theory lies in its ability to calculate the optical properties of single or similar particles in solutions. Therefore, it is seen that there has been no investigation on the optical properties of binary nanofluids as a "new class of nanofluids". The present work investigates, both analytically and experimentally, the optical properties (extinction coefficient) of double nanoparticles, i.e., two dissimilar nanoparticles, dispersed in base fluids. Moreover, new analytical relations are proposed for the estimation of the extinction coefficients of binary nanofluids. Finally, the effect of the mixture of the base fluid (ethylene glycol and water) on the extinction coefficient of binary nanoparticles is investigated both analytically and experimentally.

2. Experimental

2.1. Materials and nanofluid preparation

The powder of γ-Al_2O_3 (TECACON Co., Spain) with a purity >99.99% and CuO powder (USA) with a purity >99.9% were used in this study. The average nominal sizes (outer diameter) of γ-Al_2O_3 and CuO nanoparticles were 40 nm and 100 nm, respectively. The specifications of the nanoparticles used are presented in Table 1.

The nanofluid was prepared using the two-step method. In this method, nanoparticles are procreated by chemical or physical methods as dry powders before they are dispersed in the base fluid using ultrasonic instigation (Hielscher UP-200S ultrasonic model, Germany) at a frequency of 24 kHz and an amplitude of 70%. The base fluids used were water, ethylene glycol (EG), and a mixture (50%) of EG and water. A scanning electron microscope (SEM) (Philips, SEM 430) was used to observe the dispersion and the size of the particles in the base fluid. The results are shown in Fig. 1. Clearly, the particles are generally spherical or quasi-spherical in shape and well-dispersed in the solution.

The SEM images of the particles suspended in the base fluid were obtained by sonication while the sample was placed on the sample holder and rapidly dried to obtain solid particles. To observe the dispersion, a thin layer of the nanofluid was poured into a clean dish and placed in a refrigerator before it was transferred to a vacuum chamber to solidify and remove any excess liquid from the nanofluid film. To achieve a well dispersed binary nanofluid, Sodium Hexa Meta Phosphate (SHMP) surfactant was used. The absorbency and extinction spectra of the binary nanofluids were measured by the UV–vis spectrophotometer (Jasco V-570, Jasco Corp., Japan) with a beam path length of 10 mm while the nanofluids were placed in quartz cuvettes. The uncertainty of the absorbency measurements was $\leqslant$2.84%.

Table 1
Nanoparticles' properties.

CuO		γ-Al_2O_3	
Average particles size	<100 nm	Average particles size	<40 nm
Specific surface area	<80 m^2/g	Specific surface area	<90–160 m^2/g
Purity	99.9+%	Purity	99.99+%
True density	6.4 g/cc	True density	3.65 g/cc

3. Theoretical

3.1. Extinction coefficient of the collection of similar nanoparticles in the base fluid

When light beam strikes a particle, such phenomena as absorption, scattering, and extinction (Fig. 2) occur at all points in the particle and at all points of the homogeneous medium in which the particle is embedded [22]. The combined effect of absorption and scattering is called extinction.

As shown in Fig. 2, (E_1, H_1), (E_i, H_i), (E_s, H_s) are the electromagnetic fields inside the particle, incident light, and that scattered in the medium surrounding the particle, respectively. The optical properties of the nanoparticles dispersed in the base fluid can be calculated using a polarized monochromatic wave [22]. The scattered fields may be obtained by taking advantage of the superposition of the incident light [22].

$$E_2 = E_i + E_s$$
$$H_2 = H_i + H_s \qquad (1)$$

where (E_2, H_2) is the electromagnetic field in the medium surrounding the particles. The time-averaged Poynting vector (S) at any point