



Optical properties and transmittances of ZnO-containing nanofluids in spectral splitting photovoltaic/thermal systems

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ABSTRACT

As ZnO nanoparticles had the advantages of high thermal conductivity and low cost, the possibility of using ZnO nanoparticles in spectral splitting photovoltaic/thermal (PV/T) systems was initially studied from the perspective of optical properties. Water–ZnO and glycol–ZnO nanofluids were prepared via a two-step method and used for model validation and stability testing. The scheme employed to investigate the optical properties and radiative transfer of the nanofluids was developed using Mie scattering theory combined with the Monte Carlo ray tracing (MCRT) method. The overall effective spectral transmittance coefficients of PV cells were utilized for comprehensive evaluation of the spectral transmittances of the nanofluids in spectral splitting PV/T systems. The overall effective spectral transmittance of a PV cell water–ZnO nanofluids was 21.54% higher than that those of cells containing water–polypyrrole and water–Cu₂S nanofluids, respectively. The effects of the nanoparticle diameter, mass concentration and the optical length of the nanofluid on the spectral transmittance of glycol–ZnO nanofluid were also investigated.

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1. Introduction

Solar energy is the one of the most important types of renewable energy for human society [1,2]. Exploitation and utilization of solar energy can save conventional fossil energy, protect the natural environment, and mitigate climate change [3–5]. Opportunities and challenges related to solar energy development lie in substantially increasing the efficiency of solar energy conversion, leading to significant cost reduction of the entire solar energy business [6,7]. Meanwhile, researchers are aware that utilizing one method alone, for example, photothermal [8–11], photoelectric [12], or photochemical [13,14] conversion, cannot provide highly efficient solar energy utilization. Thus, several researchers have proposed simultaneous photoelectric and photothermal conversion in a single photovoltaic/thermal (PV/T) system, which has proven useful for increasing the efficiency of solar energy utilization [15,16]. For example: Colangelo et al. [17–19] had investigated the effects of water flow rate and PV configurations on the photoelectric and photo-thermal performance of this type of PV/T system.

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Thus far, two primary means of realizing the comprehensive utilization of photothermal and photoelectricity conversion have been employed [20]. In a conventional PV/T system, the waste heat from the photovoltaic cell is absorbed by a cooling system added to the back of the photovoltaic cell. Obviously, the shortcoming of this type of PV/T system is that the highest temperature to which the working fluid can be heated is limited by the working temperature of the photovoltaic cell, which is normally less than 60 °C [21]. Recently, some scholars have proposed adopting a spectral splitting technique to improve the overall solar energy conversion efficiencies of PV/T systems [22]. In this technique, the photons with energies below the band-gap energy of the PV cell are absorbed by the nanofluid and converted into thermal energy to heat the nanofluid, while those with energies higher than the band-gap energy pass through the nanofluid and are converted into electricity by the PV cell [23].

Karami et al. [24] had studied the effects of the optical properties of water–glycol–CuO nanofluids on the overall PV/T system efficiency. Their results indicated that the absorption coefficient of the nanofluid could be increased by four times when the volume fraction of CuO was 100 ppm and the optical path length was 10 mm, which led the effective thermal conductivity to increase from 5.6% to 13.7%. Milanese et al. [25,26] had initially used air-dispersed CuO nano-powders for solar parabolic trough collector

Nomenclature

a_n	Mie scattering coefficient	φ	scattering angle
b_n	Mie scattering coefficient	η	Riccati-Bessel function
c	clearance between particles	Φ	scattering phase function
D	diameter of the particle, nm	κ	absorption coefficient, m^{-1}
f_v	particle volume fraction	λ	wavelength, nm
$f_{v,B}$	basic particle volume fraction	σ	scattering coefficient
H	upper limit of integral	π_n	directional dependent function
I	radiative density	τ_n	transmittance
k	absorptive index	τ_λ	directional dependent function
L	lower limit of integral	Ω	solid angle, sr
m	complex index of refraction	ω	scattering albedo
N	number density of particles, m^{-3}	ξ	random number
S_2	amplitude function	ψ	Riccatie Bessel functions
P_n	Legendre polynomial		
Q_a	absorption efficiency factor	Subscripts	
Q_e	extinction efficiency factor	ext	extinction
Q_s	scattering efficiency factor	sca	scattering
S	amplitude function	abs	absorption
		f	fluid
Greek symbols		p	particle
β	extinction coefficient	rel	relative
χ	size parameter	T	monodispersed particles
δ	effective spectral transmittance coefficient	E	effective

with transparent tube receiver, and the maximum temperature of fluid can reach 180 °C. Ali et al. [27] had investigated the effects of water–SiC nanofluids on the photoelectric and photothermal efficiencies of a conventional PV/T system and found that these efficiencies increased by 24.1% and 100.19%, respectively, when 3 wt % SiC nanoparticles were added. Recently, An et al. [28,29] had designed and established an outdoor concentrating PV/T system using the spectral splitting technique. They had successfully adopted water–Cu₉S₅ nanofluids as spectral filters and firstly obtained nanofluids with temperatures higher than 100 °C with a total solar energy conversion system efficiency of up to 34.2%. In addition, they experimentally tested the effects of particle concentration on the total system efficiency to regulate the heat and electricity ratio of the PV/T system to meet the requirements of various applications.

For a spectral splitting PV/T system, the optical properties and spectral radiative transfer of the nanofluid need to be known exactly to regulate the heat and electricity ratio to achieve the maximum total system efficiency and meet the requirements of various applications [30]. Intrinsically, nanofluids are very complex colloids, and their nanoparticles usually have different shapes and exhibit agglomeration and precipitation. In fact, their nanoparticles are randomly oriented and rotate, so the probability of each particle being oriented in any direction is the same and the irregularly shaped nanoparticles can be simplified to spherical particles with homogeneous physical properties [30].

Rayleigh scattering theory is the most common framework used to calculate the optical properties of nanofluids. However, this theory can only be employed to calculate the optical properties of very small particles (usually smaller than 20 nm); otherwise, substantial errors would occur. For example, Zhang et al. [31] had adopted Rayleigh scattering theory to predict the extinction coefficients of nanofluids, and their results indicated that this theory was not appropriate to calculate extinction coefficients in the wavelength range below 1100 nm. The effects of the nanoparticle size and volume fraction on the optical properties of TiO₂ nanofluids were numerically and experimentally studied by Said et al. [32]. Their results indicated that nanoparticles smaller than 20 nm slightly

impacted the extinction coefficients of the nanofluids and that the volume fraction had a linear relationship with the extinction coefficient. They also found that the optical properties calculated using Rayleigh scattering theory deviated significantly from the experimental results due to nanoparticle aggregation and precipitation. Therefore, Said et al. [32] asserted that Rayleigh scattering theory should not be employed to calculate the optical properties of water–Al₂O₃ nanofluid in the ultraviolet (UV) region. There was growing consensus that nanoparticle aggregation and precipitation significantly affect the optical properties of nanofluids. Song et al. [30] had investigated the optical properties of Al nanofluids by performing numerical calculations and experimental tests. The optical properties of the nanofluids that they calculated using Rayleigh scattering theory were several orders of magnitude higher than those obtained in the experimental tests, while those calculated using Mie scattering theory agreed well with those obtained experimentally.

Although several researchers had experimentally studied spectral splitting PV/T systems [27–30,33–35], they mainly performed experimental tests with little theoretical guidance. In particular, they had focused on investigating the effects of the optical properties of nanofluids on the spectral transmittance, which can essentially be employed to regulate the heat and electricity ratios of PV/T systems to meet the requirements of various applications. Furthermore, most researchers had used Rayleigh scattering theory to calculate the optical properties of small nanoparticles ($\chi \ll 1$), which were severely deviated from those obtained experimentally.

In this study, the authors proposed that researches on the optical properties of nanofluids can provide theoretical guidance for nanoparticle type selection and size distribution optimization with the objective of maximizing the total efficiencies of spectral splitting PV/T systems. The possibility of using ZnO nanoparticles in such systems was addressed from the perspective of optical properties, in addition to their advantages of high thermal conductivity and low cost [36]. In this study, the optical properties and radiative transfer of ZnO nanofluids were investigated using Mie scattering theory combined with the MCRT method. Water–ZnO and glycol–ZnO nanofluids were prepared via a two-step method and used

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