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Investigation of optical properties and radiative transfer of sea water-based nanofluids for photocatalysis with different salt concentrations

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ABSTRACT

Photocatalytic decomposition of sea water is an effective way to solve the future energy crisis. However, there is a great deal of controversy about seawater's effect on photocatalytic hydrogen production efficiency. In this paper, the catalyst particles are divided into large particles ($\chi > 1$) and small particles ($\chi < 1$). The Mie theory combined with Monte Carlo method are used to analyze the influence of sea water on radiative transfer in the sea water-based nanofluids. The effects of the optical constants of the base fluid (fresh water and sea water) on the spectral extinction and spectral transmittance of the TiO_2 nanofluids are calculated. Results indicate that, for sea water-based nanofluids with small particles ($\chi < 1$), the spectral extinction coefficient increases and spectral transmittance decreases with salt concentration increasing. For sea water-based nanofluids with large particles ($\chi > 1$), the spectral extinction coefficient and transmittance oscillate because of diffraction peaks.

Introduction

In the past centuries, fossil fuels have sustained the energy demands of human beings [1,2]. However, the world has been confronting an energy crisis due to depletion of non-renewable resources and increased environmental problems [3–6]. On account of this, it is necessary and important to develop renewable and clean energy sources [7,8]. Many regions and counties have been focused on vigorously searching for renewable and clean energy sources such as wind, solar, hydrogen, and tidal energy [9–16].

Hydrogen is likely to become an increasingly used energy source because it has many advantages [17–20]; for example, it has a high heating value and low emissions, and is environment-friendly, cleaner, and more sustainable [3]. In addition, the need for sustainable energy draws attention to hydrogen fuel [3], which is produced almost exclusively from

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Nomenclature

D	diameter of the particle, nm
m	complex index of refraction
n	refractive index
k	absorptive index
Q	efficiency factor
Q_{ext}	extinction factor
Q_{abs}	absorption factor
Q_{sca}	scattering factor
f_v	particle volume fraction
N	number density of particles, m^{-3}
I	radiative density
g	asymmetry factor
p	probability density function
P	cumulative distribution function
a_n	Mie scattering coefficient
b_n	Mie scattering coefficient
ψ_n, χ_n	Riccati–Bessel functions
π_n	directional dependent function
τ_n	directional dependent function
S_1, S_2	amplitude function
P_n	Legendre polynomial

Greek symbols

χ	size parameter
λ	Wavelength, nm
Φ	scattering phase function
Θ	scattering angle
σ	scattering coefficient, m-1
κ	absorption coefficient, m-1
β	extinction coefficient, m-1
ξ	random number
ω	scattering albedo
Ω'	solid angle, sr
ϕ	azimuth angle

Subscripts

ext	extinction
sca	scattering
abs	absorption
f	fluid
p	particle
rel	relative
T	monodispersed particles

fossil fuels through the steam reformation of methane [21]. Since the report by Fujishima and Honda on water splitting [22], hydrogen generation from water via solar energy using photocatalysts has been extensively studied [23–26]. Among all materials developed for photocatalytic applications, TiO_2 remains the benchmark photocatalyst for hydrogen generation [27,28] because it is environmentally friendly, corrosion resistant, cost-effective, and a suitable band gap semiconductor (3.2 eV) [29]. Now, more and more research [30,31] turns to photocatalytic hydrogen production from seawater because of the lack of fresh water resources and the fact that seawater accounts for 96.5% of all water.

However, the effect of seawater on photocatalysis is controversial, and a consensus on whether it has a positive or negative effect on the hydrogen production rate has not yet been reached. Several studies have been conducted to investigate the effect of seawater on photocatalysis. Peng et al. [32] studied the water-splitting property of the composite photocatalyst CdS–Pt/TiO_2 in visible light. The experimental results showed that the catalytic activity of the photocatalytic hydrolysis of seawater was 33% higher than that of photolysis with pure water under optimal conditions. Sang et al. [33] studied the effects of two kinds of catalysts, $La_2Ti_2O_7$ and CdS/TiO_2, on natural seawater and fresh water. The results showed that the hydrogen generation rate from seawater was about half as much as that from pure water. The main research objective of Simamora et al. [34] was to prepare effective photocatalysts for the splitting of seawater for hydrogen. They used CuO/nano TiO_2 to perform photocatalytic hydrogen production experiments on sea water and fresh water. The results were that the 2.5% CuO/nano TiO_2 has 9.9 and 7.8 times more activity than nano TiO_2 in the photocatalytic splitting of water and seawater, respectively, so the efficiency of seawater-based hydrogen production is still lower than that of fresh water.

In addition, nanofluids are the absorbing and scattering medium due to the presence of catalyst particles in the fluid phase. And just because of this, it is valuable for researchers to study the radiation field of the nanofluids [35,36]. The problem of liquid-solid two-phase radiation transmission in photocatalytic reaction vessels was studied by Pasquali et al. [37] using the Monte Carlo method. They analyzed the catalyst particles present in the liquid reaction solution according to the absorption and scattering of the participant. The numerical results indicated that the optical thickness of the reaction solution was thin, and catalyst particles with low absorption albedo could improve the efficiency of the photocatalytic process. They mentioned the effect of optical properties of the base fluids, but they did not study it further. With the same purpose, Said et al. [38] had studied the effects of the size and concentration of the TiO_2 nanoparticles on the extinction coefficient using the Rayleigh approach. Their results showed that a smaller particle size (<20 nm) has a nominal effect on the optical properties of nanofluids and the volume fraction is linearly proportional to the extinction coefficient. However, Said et al. [38] ignored the fact that the small particles would coalesce, and they did not research the influence of the large-scale particles on the optical properties of nanofluids. Additionally, Rayleigh scattering theory is not suitable for large particles. In order to improve the utilization of light in the biofuel photo bioreactor, Li et al. [39] used a combination of theory and experiment to measure the spectral transmittance of microalgae nanofluids with different species and concentrations. Their experimental results showed that there were significant differences in the UV–visible band, and the differences at long wavelengths were very small. However, they had not taken into account the effects of different media on the light utilization of microalgae nanofluids. The radiation characteristics of six different nanoTiO_2 particles were measured by Cabrera et al. [40]. Their results showed that the scattering extinction of nanoparticles plays a major role in radiative transfer, and the effects of particle scattering on