J Ther Eng, Vol. 7, No. 6, pp. 1366–1376, September 2021

Journal of Thermal Engineering
Web page info: https://jten.yildiz.edu.tr
DOI: 10.18186/thermal.990645

Research Article

Temperature-dependent particle stability behavior and its effect on radiative transfer in water/SiO_2 nanofluids

Layth AL-GEBORY[1,2,*]

[1]*Department of Materials Engineering, University of Technology, Baghdad, Iraq*
[2]*Department of Mechanical Engineering, Ozyegin University, Istanbul, Turkey*

ARTICLE INFO

Article history
Received: 27 October 2019
Accepted: 20 December 2019

Key words:
Nanofluids; Stability; Temperature; Radiative transfer

ABSTRACT

Radiative transfer is one of the methods of energy transport that includes in a wide range of applications and we feel it in our daily lives. Thermal radiation transfer plays an effective role in the utilization of renewable energy. The radiative and optical properties, as well as the nature of the radiative scattering, are the basic principles of the thermal radiation transfer. The unique properties of nanofluids offer the unmatched potential for use in energy utilization, the working temperature has a dominant effect on the stability and radiative properties of such type of suspensions. In this research, the radiative transfer (optical properties, the independent and dependent scattering, and radiative properties) in water/SiO_2 nanofluids are investigated; taking into consideration the effect of working temperature on the stability of the particles. The effect of the temperature on the stability ratio and particle agglomeration is determined by estimating the radius of gyration of particle agglomerates using the scaling law based on the stability (DLVO) method. The single-scattering approximation (SSA) is used to calculate the radiative properties in the case of independent scattering, while the quasi-crystalline approximation (QCA) is used for this purpose in the case of dependent scattering. The results show that the temperature has a significant effect on the stability of particles and radiative transfer in nanofluids. It was observed by comparing the results from the two approximation methods in the Rayleigh regime. Particle size affects the physical and scattering cross-sectional areas which give a general understanding of the scattering mechanism from small to large particles.

Cite this article as: Layth Al-Gebory. Temperature-dependent particle stability behavior and its effect on radiative transfer in water/sio_2 nanofluids J Ther Eng 2021;7(6):1366–1376.

INTRODUCTION

The suspension of particles with nano-size in base fluids, so named nanofluids, have shown significant enhancement in thermal behavior because of their unique radiative and thermophysical properties compared with regular fluids. Therefore, nanofluids are extensively used in different applications such as solar utilization systems, these applications are extremely depending on the principle of thermal

***Corresponding author.**
*E-mail address: 130006@uotechnology.edu.iq,
layth.ismael@ozu.edu.tr

This paper was recommended for publication in revised form by Regional Editor Jovana Radulovic

Published by Yıldız Technical University Press, İstanbul, Turkey

radiation transfer. On the other hand, there is still a concern about the stability of nanoparticles, which needs an extra investigation because obtaining long-term stable nanofluids under different conditions is the key to applications of such suspensions in different fields [1]. Particle collisions and agglomeration are common phenomena in nanofluids as a result of particle-particle adhesion due to the attractive forces, boundary conditions such as the working temperature. In any particulate suspension, particles initially are well dispersed and then particles begin to agglomerate to form different agglomerates. Particle stability means that collisions and agglomeration do not occur on a large scale. Therefore, as long as the particles remain unagglomerated or if particle agglomerates size can be controlled, it is possible to have stable nanofluids [2].

In solar thermal systems, conventional fluids can absorb about 15% of solar radiation within the infrared spectrum range, while a large amount of solar radiation is dissipated in the Ultraviolet and visible spectrum ranges. Nanoparticles are found as efficient media in the Ultraviolet and visible spectrum ranges because of their optical behavior and radiative properties. The optical and radiative properties of nanofluids are strongly affected by different parameters such as the radiation wavelength, particle size, particle volume fraction, and particle type. Also, they depend on the pressure and temperature of the media. All the possible applications of nanofluids are strongly connected to their thermal and radiative properties; for that, these properties should be investigated in more depth at different conditions. The flexibility of nanoparticle concentration, shape, and size offer the advantages of using nanofluids in thermal systems. To verify that nanoparticles can be used in a specific thermal application, the particle size before and after dispersion should be investigated carefully. A small change in these parameters can significantly affect the optical and radiative transfer such as absorption, scattering, and transmissivity [3,4].

Many studies have been conducted on nanofluids and their applications in recent years. Various investigations on the synthesis and stability of SiO_2 nanofluids have been done, many mechanisms of particle dispersion and different methods of stability enhancement have been used [5–7]. Many studies show that SiO_2 nanoparticle has good optical properties that have a significant impact on energy applications. The concept of using nanofluids in solar thermal collectors is conducted to enhance thermal efficiency [8–10]. Different techniques (ultrasonic disruptor, ultrasonic bath, and high-pressure homogenizer) were used to enhance the stability of nanofluids. Particle size was measured to observe the agglomeration process. It was observed that the best method to minimize the particle agglomerates size is the high-pressure homogenizer [11]. The stability of water/SiO_2 nanofluids was experimentally investigated, the dynamic light scattering (DLS) and the transmission electron microscopy (TEM) tests were conducted. The stability test indicated that the nanofluid samples had good stability for a long time even after six months. The measurements were done in the temperature range 25–55°C [12]. The agglomeration of particles and its impact on the radiative properties of nanofluids were investigated using the transmission electron microscopy, UV-visible spectroscopy, and the dynamic light scattering techniques. It was observed that the Dynamic Light Scattering techniques is the best method for particle agglomeration characterization [13]. It was observed that the thermal conductivity, dielectric constant, and refractive index of nanofluids were strongly affected by the increase in the size of the nanoparticles. Some of these properties were affected by individual particles and some affected by the different particle agglomerates [14]. The independent and dependent scattering in nanofluids was investigated in many studies, different nanofluids include closely packed systems of spherical nanoparticles were used in the investigations [15–17]. A comparison was carried out to investigate the scattering behavior in nanofluids. The quasi-crystalline approximation (QCA) and the Foldy's effective field approximation (FEA) were used in the Rayleigh scattering regime [18]. The thermo-physical and optical properties of nanofluids were investigated at different working temperatures (0–100°C) to study the potential of using nanofluids in solar thermal systems [19].

In the present study, the effects of temperature on the stability and radiative transfer in water/SiO_2 nanofluids are theoretically investigated. The DLVO theory is applied to observe the stability ratio of the nanoparticles by calculating the repulsive and attractive forces between suspended particles. Particle agglomeration is examined using the stability ratio and particle agglomeration time constant to calculate the radius of gyration of particle agglomerates using the scaling law. The study carried out an investigation on the effect of different agglomerate sizes at different working temperatures on the radiative properties. The nature of the scattering (independent and dependent) is also observed. The SSA and QCA approximations are used in the calculations.

THEORETICAL BACKGROUND

Stability of Nanoparticles

The interaction of particles in base fluids may cause the formation of particle agglomerates. There are different parameters that affect this interaction, the attractive (Van der Waals) and repulsive (electrostatic) forces between particles are among these parameters, these forces lead to form bonds between particles and produce various particle agglomerates. Particles with small size; particularly nano-size particles, increase the possibility of particle agglomeration. Decreasing the size of particles leads to decreasing the distance between particles, the attractive force is more important in this case [20]. According to

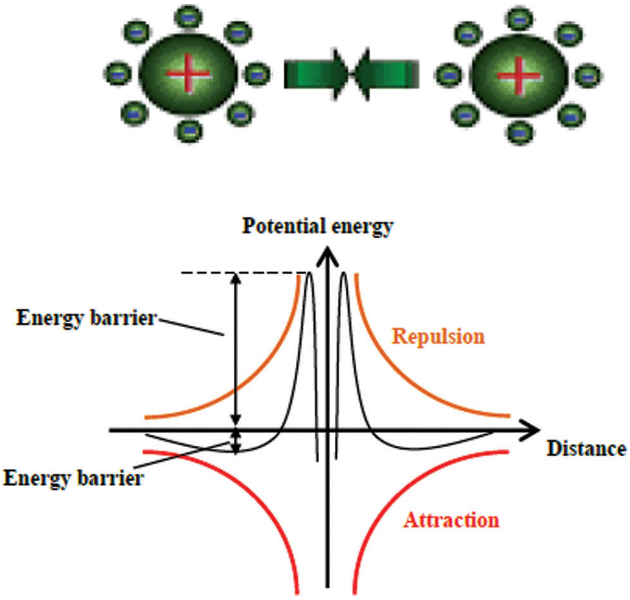

Figure 1. The forces act on particles based on the DLVO theory.

the DLVO theory, the overall potential is equal to the sum of repulsive and attractive forces between particles, as explained in Fig. 1 [21].

Radiative Transfer in NanoFluids

Different methods are considered to explain the radiative transfer in participating media (i.e. particulate suspensions). The radiation scattering can be described by the Lorenz-Mie and Rayleigh theories. The Rayleigh theory (after Lord Rayleigh) is applied to spherical and non-absorbing particles with a small size. In this theory, the hypotheses are based on the small size parameters ($x << 1$) of the particles where x represents the dimensionless ratio of particle size to the wavelength. The Lorenz-Mie scattering (after Gustav Mie) covers the absorbing or non-absorbing spherical particles of different sizes [22].

Radiation scattering becomes difficult in a cloud of particles. If the scattering by a particle is not influenced by neighboring particles, the scattering by each particle can be treated individually. This case is also known as the independent scattering, which is proposed when there is a considerable distance between the particles in particulate suspensions. On the other hand, radiation scattering is dependent when the particles are close to each other. The distance between the particles is considered taking into consideration the wavelength of radiations. Particle size and number have significant effects in the distance between the particles, which in turn affect the dependent and independent scattering [23]. To describe the radiative phenomenon inside a participating media, Fig. 2 shows the interaction of incident radiation with a particulate

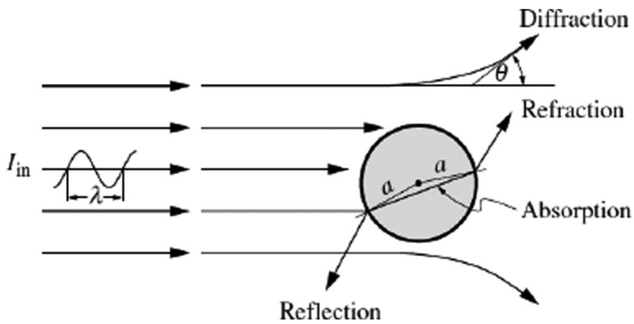

Figure 2. Incident radiations in a particulate media [23].

suspension. The incident radiations in the suspension are absorbed and scattered by the media (particles and base fluid), while some of the radiations are transmitted through this media.

MODEL OF CALCULATION

The nanofluids considered in this study are water-based SiO_2 nanoparticle. The original size of SiO_2 nanoparticle is $d_p = 50\ nm$ and with a concentration of $\phi = 0.5\%\ v/v$ in the base fluid, this concertation represents the average value of particle concentration in colloidal suspensions [24]. The thermal and optical properties of SiO_2 particle have a significant impact in thermal applications; therefore, SiO_2 nanoparticle has been chosen because it is widely used in solar thermal collectors. For that, an enhancement has been found in thermal systems which include water/SiO_2 nanofluids [25–27]. Therefore, the stability and its effect on the radiative transfer in water/SiO_2 nanofluids under different working temperatures should be investigated extensively.

The stability ratio and particle agglomeration time constant have been estimated at different working temperatures (T = 25, 50, 75, and 100°C). The temperature range from 25 to 100°C is the operating temperature range of low temperature solar thermal collectors such as the flat-plat and evacuated tube collectors [28]. The radius of gyration of particle agglomerates is obtained using the scaling law based on the stability ratio which is obtained from the DLVO theory.

The effects of the repulsive and attractive forces are included in the stability ratio which is determined by dividing the rate of diffusion by the rate of interaction between the particles in NPSs [29]:

$$W(u) = 2\int_0^{\infty} \frac{\beta(u)}{(u+2)^2} \exp\frac{V(u)}{k_b T}\, du \tag{1}$$

Where $u = \tau/r_p$ is the dimensionless distance between the spheres, $\tau = d_p\ ((\pi/6\phi_p)^{0.3}-1)$ is the particle-particle distance, r_p and d_p are the particle radius and diameter;

respectively, represents the factor of hydrodynamic interaction, β represents the factor of hydrodynamic interaction, k_b represents the Boltzmann Constant, ϕ_p is the volume fraction of particles, T is the working temperature, and V is the total potential between nanoparticles.

The attractive (Van der Waals) force due to the interaction between nanoparticles is calculated by [30]:

$$V_A = -\frac{A}{6}\left[\frac{2r_p^2}{\tau^2+4r_p\tau}+\frac{2r_p^2}{\tau^2+4r_p\tau+4r_p^2} + \text{In}\left(\frac{\tau^2+4r_p\tau}{\tau^2+4r_p\tau+4r_p^2}\right)\right] \tag{2}$$

where A represents the Hamaker constant.

The repulsive force is due to the interaction of the electric double layer around the nanoparticles and is given by [30]:

$$V_R = 2\pi r_p \varepsilon_r \varepsilon_0 \psi_s^2 \exp(-\tau\kappa) \tag{3}$$

where ε_r is the relative dielectric constant of base fluids, ε_0 is the dielectric constant of the free space, ψ_s is the surface charge, and κ is the Debye parameter which is the inverse of the Debye length [30]:

$$\kappa = 5.023\times10^{11}\sqrt{(I_s/\varepsilon_r T)} \tag{4}$$

where I_s is the ionic strength and is related to the pH of suspensions. For the water-based nanofluids, $I_s = 10^{-pH}$ for which pH ≤ 7 and $I_s = 10^{-(14-pH)}$ for which pH > 7. pH is a measure of the concentration of hydrogen ion in the solutions; a measure of the acidity and basicity of solutions. An acid solution is obtained when increasing the concentration of H^+ ions, while a base solution is obtained when increasing the concentration of OH^- ions. The surface charge ψ_s is a positive integer and increases with the decreasing pH below the isoelectric point (the point of zero charge where $\psi_s = 0$), which refers to acid solutions. Whereas, ψ_s is a negative integer and decreases with the increasing pH above the isoelectric point, which refers to base solutions. The isoelectric point of SiO_2 nanoparticle is $1.8 \leq pH_{iso} \geq 2.5$ [31].

The hydrodynamic interaction factor can be calculated by [30]:

$$\beta(u) = (6(u)^2+13u+2)/(6(u)^2+4u) \tag{5}$$

In the absence of a repulsive force, the stability ratio $W(u) = 1$ and hydrodynamic interactions occur between the particles. While $W(u) > 1$ in the case of high repulsive force. For diluted particulate suspensions that include high repulsion force between particles, the stability ratio $W \geq 10^5$ where the total forces between particles is $V_{total} \approx 15k_b T$ [20]. In this case, the low rate of particle agglomeration occurs and a compact shape of particle agglomerates which can be characterized by the radius of a large particle [21].

In colloidal suspensions, particle agglomerates can be characterized by the fractal theory, where the fractal calculations provide accurate details about particle agglomerates. The radius of gyration is used to describe particle agglomeration, the scaling law is used in the calculations [20]:

$$\alpha_c' I(t)_{rs} + q_{tl,bw-ci} = q_{cd,ci-co} \tag{6}$$

where R_a is the radius of the gyration of particle agglomerates, t is the suspension time of particles, and $t_p = (\pi\mu r_p^3 W)/(k_b T\phi_p)$ is the agglomeration time constant.

The calculations of the radiative transfer in water/SiO_2 nanofluids are carried starting from the different particle agglomerates which are obtained using the radius of gyration (Eq. 6). The scattering behavior (independent and dependent) is observed based on the distance between particles and the wavelength of radiations. The Lorenz-Mie theory is used to calculate the radiative properties of water/SiO_2 nanofluids, the two approximations SSA and QCA are applied based on the scattering behavior. The calculations of the radiative transfer are based on the scattering behavior (independent and dependent), where the radiative transfer in water/SiO_2 nanofluids occurs in or out of the Rayleigh regime.

The Lorenz-Mie theory describes the scattering from a spherical particle. Based on this theory, the differential cross-sections can be defined by the intensity functions i_1 and i_2 [32]:

$$\alpha_{VV} = \frac{\lambda^2}{4\pi^2} i_1 \quad \text{and} \quad \alpha_{HH} = \frac{\lambda^2}{4\pi^2} i_2 \tag{7}$$

The subscripts VV and HH refer to the state of the polarization of the incident and scattered radiation, respectively. Specifically, the subscripts VV represent the vertically polarized incident radiation and the vertically polarized scattered radiation with respect to the plane of the scattering Φ = 90°. The subscripts HH represent the horizontally polarized incident radiation and the horizontally polarized scattered radiation with respect to the plane of the scattering $\Phi = 0°$ [33].

The differential scattering cross-section is given by the average of Eq. 8 from which the following relationship is obtained [22]:

$$C_{scattering} = \frac{\lambda^2}{8\pi^2}(i_1 + i_2) \tag{8}$$

The efficiencies $Q_i = C_i/\pi r^2$ for the interaction of radiation with a particle are represented by the cross-sections C_i normalized to the particle cross-section πr_p^2, where i represents the scattering, absorption, and extinction of the radiation.

In dilute suspensions, suspensions with low particle volume fraction, the scattered intensity in nanofluids is equal to the scattered intensity from a single particle multiplied by the number of particles (linear summation rule) [23].

The scattering and absorption coefficients for a group of nanoparticles can be calculated as [30]:

$$\alpha_{scattering} = NQ_{scattering} \quad \text{and} \quad \alpha_{absorption} = NQ_{abs} \tag{9}$$

In these relations, N represents particles number in a unit volume of a media.

The sum of the scattering and absorption coefficients of particles, the extinction coefficient, is given as [22]:

$$\alpha_{extinction} = \alpha_{scattering} + \alpha_{absorption} \tag{10}$$

These relationships suggested that the nanosuspension includes dispersed particles, and the particle agglomeration is not considered. Therefore, for the particle agglomeration in the same nanosuspension with the same volume fraction, particle diameter d_p is replaced by the agglomerate diameter $2R_a$.

Thus far, the dependent scattering is not considered. In the Rayleigh regime, dependent scattering should be considered, specifically for particles with small sizes with respect to the wavelength. Therefore, the QCA approximation, which considers the dependent scattering, is applied in this regime [17, 34]:

$$\alpha_{scattering} = \frac{\left(\dfrac{2\bar{m}^2 x^4}{r_p}\right)\phi\left(1-\phi_p\right)^4}{\left(1+2\phi_p\right)^2(1-\phi\bar{m})\sqrt{1+\left(\dfrac{3\phi_p\bar{m}}{(1-\phi_p\bar{m})}\right)}} \tag{11}$$

where $\bar{m} = (m^2 - 1)/(m^2 + 2)$ and $m = n_{particle}/n_{media}$ is the complex refractive index, n is the refractive index.

Eq. 11 shows that size, concentration, and size parameter of particles have the dominant influences on the radiation scattering [35].

The ratio of the scattering to the extinction of incident radiations, the single-scattering albedo, which explains the scattering contribution in the radiative transfer in particulate suspensions [23]:

$$\omega = \alpha_{scattering}/\alpha_{exttinction} \tag{12}$$

RESULTS AND DISCUSSION

The results are obtained by considering water-SiO_2 nanofluids. The effects of temperature on the stability and agglomeration of suspended particles and the radiative transfer in nanofluids are theoretically investigated. Starting from the stability ratio modeling of the nanofluids based on DLVO theory, Fig. 3 shows the effect of the temperature on the agglomeration of SiO_2 nanoparticles dispersed in water with the concentration of particle (0.5% v/v), these results are obtained by applying Eq. 6. The radius of the gyration of the particle agglomerates for SiO_2 nanoparticles at a specified working temperature is shown in this figure. Each point in Fig. 3 represents a particle agglomerate and the particle agglomeration time constant is shown at each point. The agglomeration time constant is directly proportional to the temperature of the nanofluids and increasing particle agglomeration time constant leads to enhancing the agglomeration rate.

The optical behavior is shown in Fig. 4. The absorption and refractive indices are specified at the ultraviolet, visible, and infrared (UV-visible-NIR) wavelength ranges which represent the solar radiation spectrum [36]. Fig. 4-a shows that the SiO_2 nanoparticles and the medium have a considerable refractive index. In Fig. 4-b, the absorption index for the SiO_2 nanoparticle shows zero values in the UV-visible-NIR wavelengths; except the wavelength range 200–370 nm, where the SiO_2 nanoparticles show low values the absorption index in this range. On the other hand, water has a very low absorption index in the ultraviolet-visible spectrum range, while its absorption index enhanced in the near-infrared wavelengths.

The scattering coefficients of water-SiO_2 nanofluids are obtained using the SSA by applying the Lorenz-Mie theory, which is shown in Fig. 5. These results are obtained by applying Eq. 9. The scattering coefficient is inversely proportional to the wavelength. In addition, the scattering becomes important when particle agglomerate size increases to a limit, where particles with large size shows a high scattering coefficient. The relationship between the

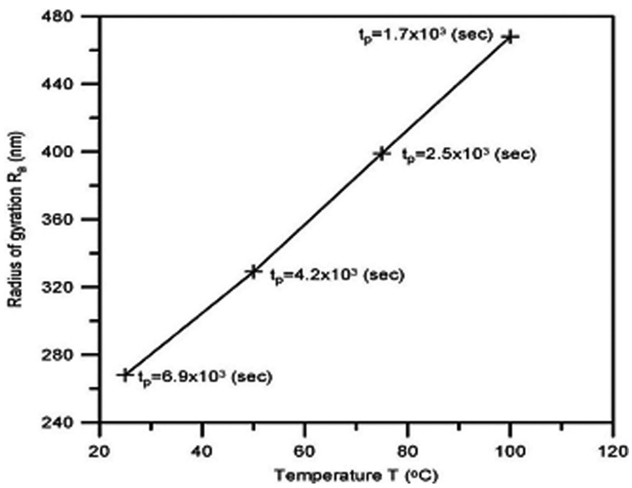

Figure 3. Particle agglomeration curve for water-SiO_2 nanofluids. The working temperatures are shown at each point which represent a type of nanofluid.

scattering efficiency and the particle size is quite important in such calculations, where scattering covers the reflection, refraction, and diffraction. And, each one of these phenomena shows different behavior at different particle sizes. For large particle size ($x \gg 1$), the scattering efficiency decreases. That is, large particles repel radiation more than can be interacted by its cross-sectional area. Indeed, the scattering becomes significant when there is a high difference between the refractive index of the medium and the particle, and when the wavelength and the particle size approach each other. The radiation scattering of nanofluids in this study is compared with other results from the literature based on experimental investigations, a good agreement was found between them [2,37]. The scattering behavior in these papers were obtained experimentally for different hydrodynamic particle size obtained from the dynamic light scattering technique.

Radiation scattering can enhance the absorption of particulate suspensions where the incident radiation passes-through the media. Two different phenomena occur (augmentation and attenuation). The augmentation of radiation comes from the emission (re-radiation) and the scattering comes in the direction of the optical path of the incident radiation (in-scattering). The attenuation of the incident radiation is a result of the absorption and deviation of radiation beams out of the optical path (out-scattering). These phenomena represent the principles of radiative transfer in photo-thermal energy conversion systems.

The extinction coefficient (scattering and absorption) of water-SiO_2 nanofluids is shown in Fig. 6. The impact of the different particle sizes at different working temperatures is explained, these results are obtained by applying Eq. 10. The extinction coefficient of the nanofluids includes the radiation scattering of nanoparticles and the absorption coefficient of the medium. The effect of the water absorption becomes important at a longer wavelength range $\lambda >$ 1000 *nm*, while the scattering becomes important in the shorter wavelengths. The shorter wavelength radiations carry high energy in comparison with a longer wavelength, thus enhancing the radiative properties within the short wavelength becomes quite important. Any enhancement in the radiative properties of different media improves the efficiency of thermal radiation systems such as solar thermal systems, where the photothermal energy conversion is improved by modifying the radiative properties. The optical and radiative properties results are compared with

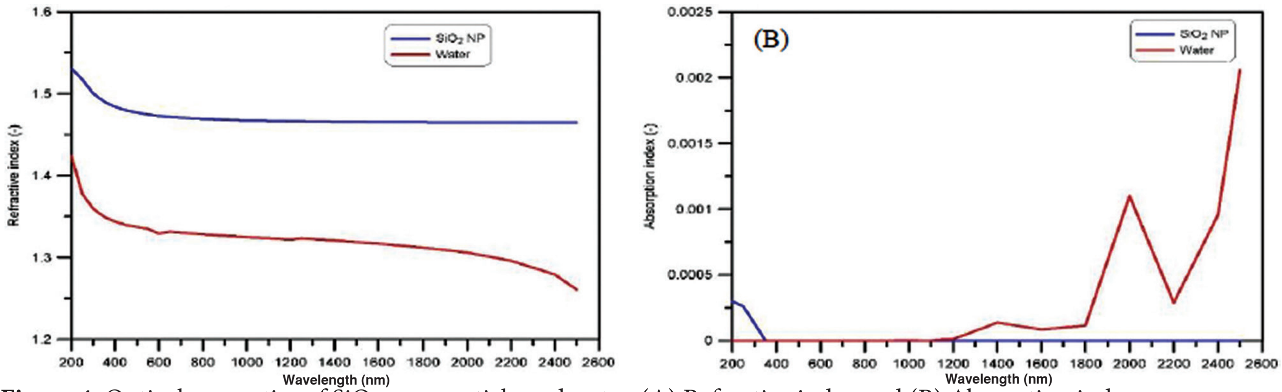

Figure 4. Optical properties of SiO_2 nanoparticle and water. (A) Refractive index and (B) Absorption index.

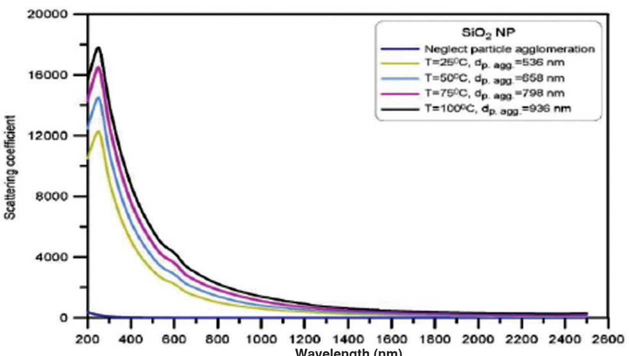

Figure 5. Scattering coefficient curves of water-SiO_2 nanofluids.

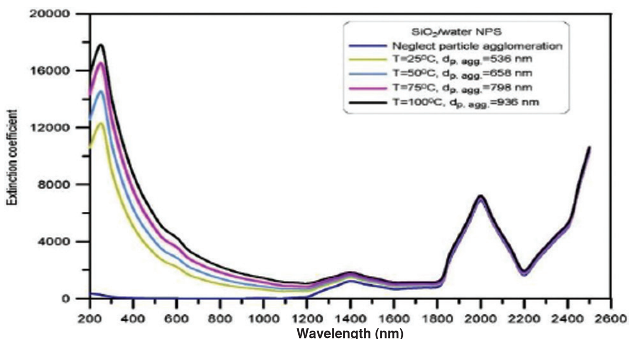

Figure 6. Extinction coefficient curves of water-SiO_2 nanofluids.

theoretical and experimental data from the literature. The comparison shows good agreement between these results.

Fig. 7 shows the independent and dependent scattering regimes for water-SiO_2 nanofluids. The effect of the particle agglomerates, which are produced under the effects of different temperatures on the independent and dependent scattering, is explored. The results of particle agglomerates are compared with another from the original particle size (d_p = 50 *nm*) regardless of the agglomeration effect, the comparison explains the effect of the particle agglomeration rate of the particles on such boundaries. Fig. 7 shows that particle agglomerates with small size approach the region of dependent scattering. Where, water-SiO_2 nanofluids with particle size (d_p = 50 *nm*) regardless of the particle agglomeration, undergo multiple and dependent scattering at a wavelength starting from 500 nm, where these nanosuspensions are located in the dependent boundary regime. The distance from the particle to particle surface is in relation with particle size and number, where particle size in a specified medium at fixed particle concentration leads to increasing the distance between the particles. The results in Fig. 7 explain this situation for the different particle agglomerates. Indeed, temperature affects particle agglomeration and the clearance between particles in a particulate suspension. The relationship between the two parameters (the distances between the particles and the wavelength) can demarcate the regimes of the independent and dependent scattering.

Based on the scattering, Fig. 8. shows the scattering coefficient of water-SiO_2 nanofluids with an original particle size (d_p = 50 nm), and with particle loading (0.5% v/v) from different theories (SSA using the Lorenz-Mie and QCA theories). These results are obtained by applying Eqs. 9 and 11. The difference in the scattering coefficient between the

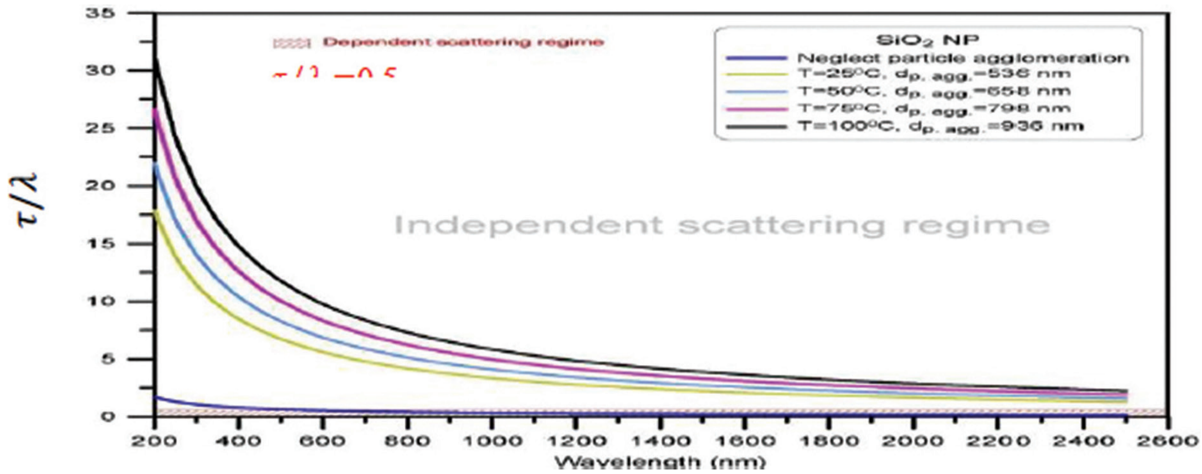

Figure 7. The independent and dependent scattering curves for water-SiO_2 nanofluids at different temperatures.

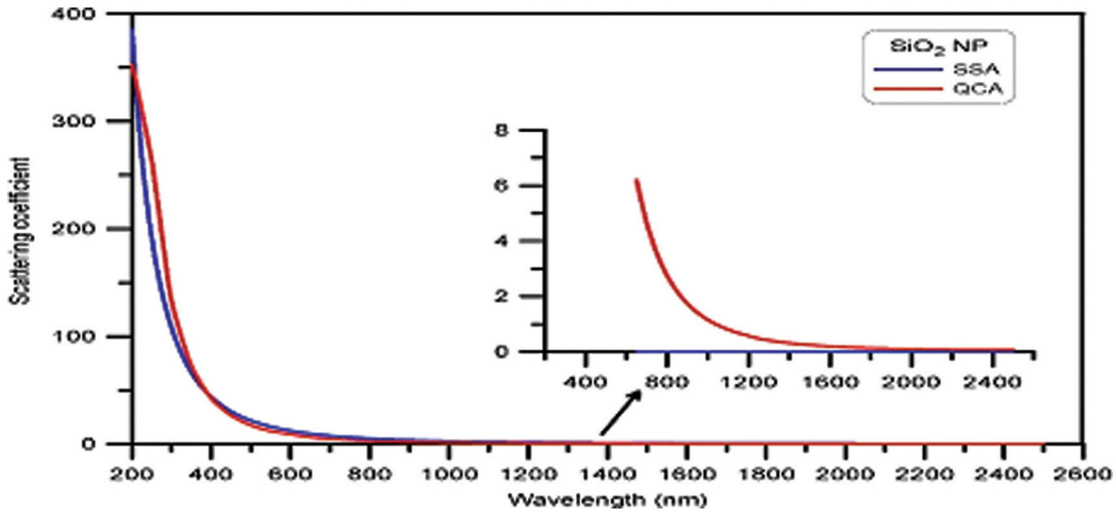

Figure 8. Scattering coefficient for water-SiO_2 nanofluids d_p = 50 *nm* from two theories. The SSA based on the LMT and the QCA.

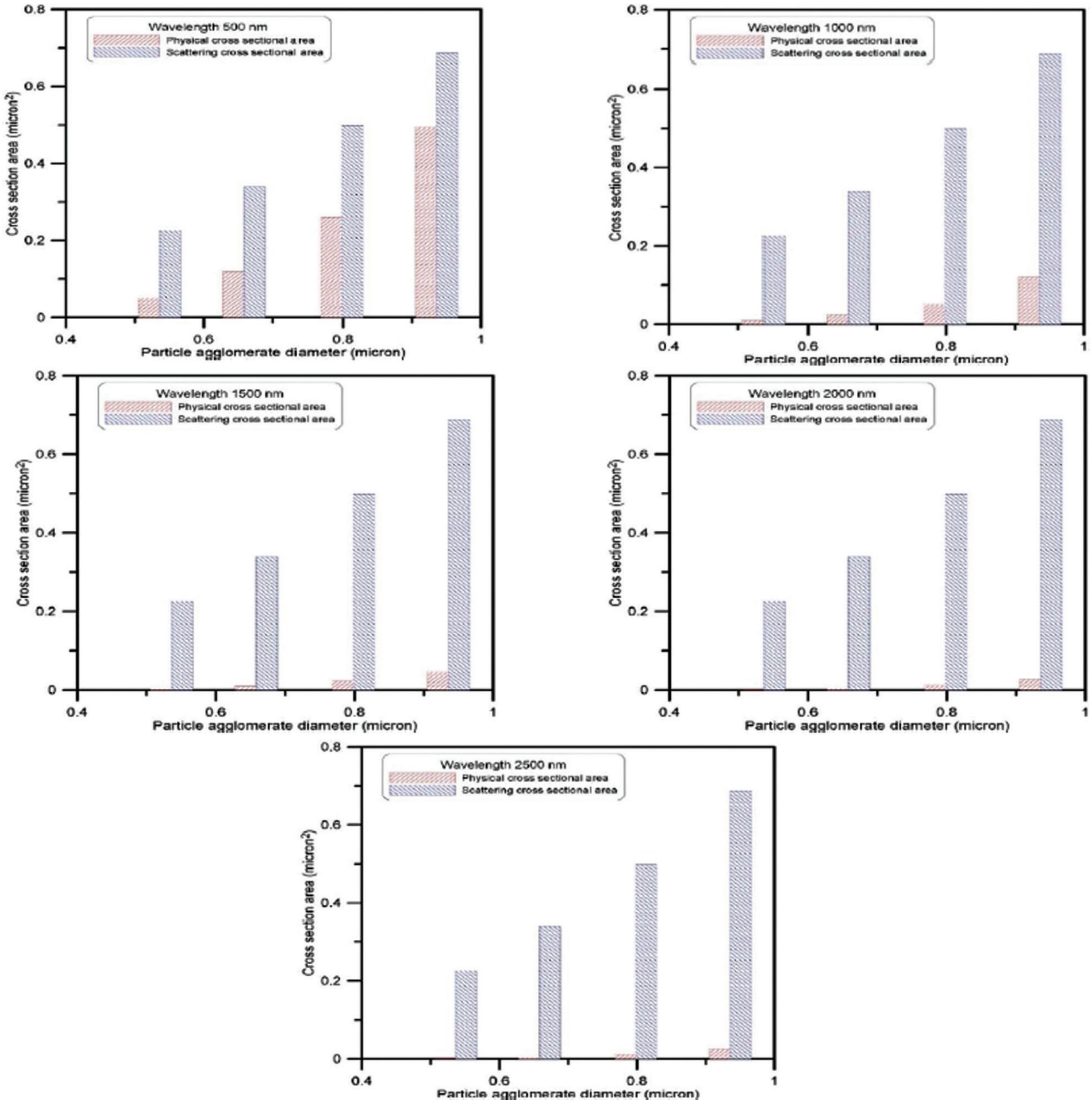

Figure 9. The physical and scattering cross sectional areas for different SiO_2 particle agglomerates each one of these figures at a specific wavelength.

QCA and the SSA results can be observed at a wavelength range λ > 600 nm. The dependent scattering becomes important in this wavelength range and the nanofluids located within the Rayleigh regime because of the effect of small size particles. The two optical theories (SSA based on the Lorenz-Mie and QCA theories) give precise information on the effect of the different sizes of particle agglomerates at different working temperatures on the scattering magnitude. Then, the dependent scattering can be explored using the quasi-crystalline approximation theory. The inset in Fig. 8 shows the difference in the scattering coefficients from the two theories at wavelengths $\lambda > 600$ *nm* which is not clear in the original figure. The inset shows clearly the effect of the dependent scattering which is observed using the QCA theory on the scattering coefficient calculations.

Fig. 9 shows the physical cross-sectional area and the scattering cross-sectional area of SiO_2 nanoparticle agglomerates, these results are obtained by applying Eq. 8. The scattering cross-sectional area depends strongly on the particle size, the refractive indices for medium and the particles, and the wavelength of the radiation. It is the area surrounding the particles in which the radiation scattering occurs, it

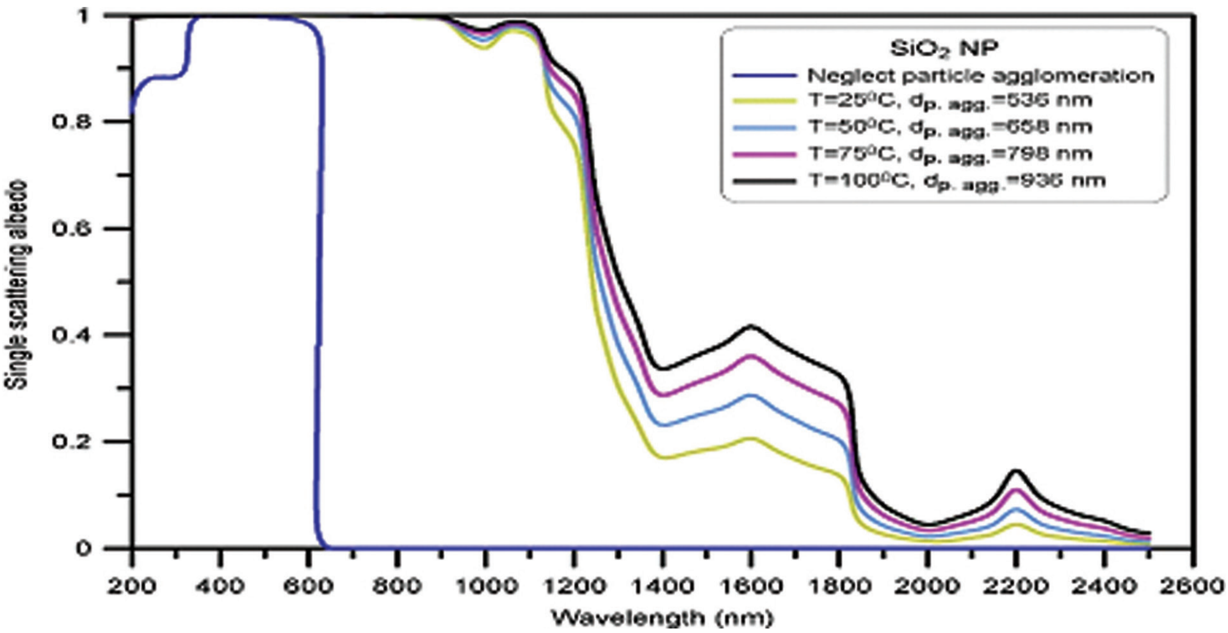

Figure 10. Single scattering albedo of water-SiO_2 nanofluids with different particle agglomerates size.

is also named as the scattering footprint. In this figure, the results completed for the wavelengths of 500, 1000, 1500, 2000, and 2500 nm which are representative values for thermal applications. These results provide a clear idea about the scattering of visible radiation in pigments and coatings, where the human eye is sensitive to the radiation at a wavelength of 550 nm. The results of the physical and scattering cross-sectional areas in this study are compared with experimental data from the literature. The experimental results were measured as a function of TiO_2 particle diameter with a refractive index of 2.73 in resin with a refractive index of 1.5 illuminated by radiation with a wavelength of 650 nm [38]. The comparison between these results show a good agreement for the physical and scattering cross-sectional areas behavior.

To quantify the importance of the scattering behavior in the extinction coefficient of water-SiO_2 nanofluids, the single scattering albedo of water-SiO_2 nanofluids is estimated considering the effect of particle agglomeration. Fig. 10 shows the single scattering albedo, these results are obtained by applying Eq. 12. It is clear that the scattering has a significant effect when the size of the particles increases. At shorter wavelengths, the scattering has an important contribution in the extinction coefficient, where the nanoparticles have an important effect on the radiative transfer at the ultraviolet-visible wavelengths.

CONCLUSIONS

This research shows the importance of the temperature on the stability of nanofluids, which in turn affects the radiative transfer. The different particle agglomerates under the effect of different working temperatures show a considerable change in the radiative properties of water-SiO_2 nanofluids. The radiative properties of particles have important impacts on different industrial and engineering applications; especially those occurring at high temperatures.

Particle stability and agglomeration are strongly affected by the temperature. Increasing the temperature leads to an increase in particle size and it affects the radiative properties of particles in addition to other properties. Nanofluids with ultrafine particles show a homogeneous system which means that the radiative properties of a particle are strongly affected by the other particles, where the distance between particle decreases with decreasing the particle size. The comparison between the SSA and QCA theories demonstrates the importance of the particle size on the radiative properties and the independent and dependent scattering. For a small particle size, the effects of dependent scattering cannot be ignored; especially in the boundaries of Rayleigh scattering, the size of the agglomerates in the same particle loading should be taken into consideration. The small size of particles shows an approach in the values of cross-sectional and scattering areas. While, the scattering cross-sectional area is larger than the physical-cross sectional area for large particles, which implies that the scattering has become of great importance. From the single scattering albedo, it can be observed that the scattering behavior of the nanoparticles is important spatially in the case of dielectric (non-absorbing) particles, where the attenuation of light is only by scattering. All these observations take into account the effect of radiation wavelength.

The radiative properties of nanofluids change with the properties of nanoparticles, some of these affect the group of particles and some of these affect individual particles. The different radiative properties for a specific type of nanofluids can be utilized when particular absorption and scattering are needed based on the type of application. Where different applications require different radiative properties based on the objectives of these applications.

DATA AVAILABILITY STATEMENT

No new data were created in this study. The published publication includes all graphics collected or developed during the study.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] Wahab A, Hassan A, Qasim MA, Ali HM, Babar H, Sajid MU. Solar energy systems–potential of nanofluids. Journal of Molecular Liquids 2019;289:111049. [CrossRef]

[2] Al-Gebory L, Mengüç MP. The effect of pH on particle agglomeration and optical properties of nanoparticle suspensions. Journal of Quantitative Spectroscopy and Radiative Transfer 2018;219:46–60. [CrossRef]

[3] Layth A-G. Participating media for volumetric heat generation. Journal of Thermal Engineering 2019;5:93–9. [CrossRef]

[4] Sobamowo M. Thermal performance analysis of convective-radiative fin with temperature-dependent thermal conductivity in the presence of uniform magnetic field using partial noether method. Journal of Thermal Engineering 2018;4:2287-302. [CrossRef]

[5] Haghtalab A, Mohammadi M, Fakhroueian Z. Absorption and solubility measurement of CO_2 in water-based ZnO and SiO_2 nanofluids. Fluid Phase Equilibria 2015;392:33–42. [CrossRef]

[6] Huang S, Li X, Yu B, Jiang Z, Huang H. Machining characteristics and mechanism of GO/SiO_2 nanoslurries in fixed abrasive lapping. Journal of Materials Processing Technology 2020;277:116444. [CrossRef]

[7] Ranjbarzadeh R, Moradikazerouni A, Bakhtiari R, Asadi A, Afrand M. An experimental study on stability and thermal conductivity of water/silica nanofluid: Eco-friendly production of nanoparticles. Journal of Cleaner Production 2019;206:1089–100. [CrossRef]

[8] Ahmadi MH, Ghazvini M, Sadeghzadeh M, Nazari MA, Ghalandari M. Utilization of hybrid nanofluids in solar energy applications: a review. Nano-Structures & Nano-Objects. 2019;20:100386. [CrossRef]

[9] Sahin AZ, Uddin MA, Yilbas BS, Al-Sharafi A. Performance enhancement of solar energy systems using nanofluids: An updated review. Renewable Energy 2020;145:1126–48. [CrossRef]

[10] Goel N, Taylor RA, Otanicar T. A review of nanofluid-based direct absorption solar collectors: Design considerations and experiments with hybrid PV/Thermal and direct steam generation collectors. Renewable Energy 2020;145:903–13. [CrossRef]

[11] Hwang Y, Lee J-K, Lee J-K, Jeong Y-M, Cheong S-i, Ahn Y-C, et al. Production and dispersion stability of nanoparticles in nanofluids. Powder Technology 2008;186:145–53. [CrossRef]

[12] Wang X-Q, Mujumdar AS. Heat transfer characteristics of nanofluids: a review. International Journal of Thermal Sciences 2007;46:1–19. [CrossRef]

[13] Murdock RC, Braydich-Stolle L, Schrand AM, Schlager JJ, Hussain SM. Characterization of nanomaterial dispersion in solution prior to in vitro exposure using dynamic light scattering technique. Toxicological Sciences 2008;101:239–53. [CrossRef]

[14] Wei W, Fedorov AG, Luo Z, Ni M. Radiative properties of dense nanofluids. Applied Optics 2012;51:6159–71. [CrossRef]

[15] Ivezic Z, Mengüç MP. An investigation of dependent/independent scattering regimes using a discrete dipole approximation. International Journal of Heat and Mass Transfer 1996;39:811–22. [CrossRef]

[16] Ivezic Ž, Mengüç MP, Knauer TG. A procedure to determine the onset of soot agglomeration from multi-wavelength experiments. Journal of Quantitative Spectroscopy and Radiative Transfer 1997;57:859–65. [CrossRef]

[17] Prasher R, Phelan P, editors. Modeling of radiative and optical behavior of nanofluids based on multiple and dependent scattering theories, Paper No. IMECE2005-80302. Orlando, Florida: ASME International Mechanical Engineering Congress & Exposition, November; 2005. [CrossRef]

[18] Prasher R, Phelan PE, Bhattacharya P. Effect of aggregation kinetics on the thermal conductivity of nanoscale colloidal solutions (nanofluid). Nano Letters 2006;6:1529–34. [CrossRef]

[19] Karami M, Akhavan-Behabadi M, Dehkordi MR, Delfani S. Thermo-optical properties of copper oxide nanofluids for direct absorption of solar radiation. Solar Energy Materials and Solar Cells 2016;144:136–42. [CrossRef]
[20] Babick F. Suspensions of colloidal particles and aggregates. Sevillia, Spain: Springer; 2016. [CrossRef]
[21] Ravisankar R. Application of nanotechnology to improve the performance of tractor radiator using cu-water nanofluid. Journal of Thermal Engineering 2018;4:2188-200. [CrossRef]
[22] Howell JR, Menguc MP, Siegel R. Thermal radiation heat transfer. 6th ed. Oxfordshire: Taylor and Francis; 2015. [CrossRef]
[23] Modest MF. Radiative heat transfer. Massachusetts, USA: Academic Press; 2013. [CrossRef]
[24] Lazarus G. Nanofluid heat transfer and applications. Journal of Thermal Engineering 2015;1:113–5. [CrossRef]
[25] Ferrouillat S, Bontemps A, Ribeiro J-P, Gruss J-A, Soriano O. Hydraulic and heat transfer study of SiO_2/water nanofluids in horizontal tubes with imposed wall temperature boundary conditions. International Journal of Heat and Fluid Flow 2011;32:424–39. [CrossRef]]
[26] Pourfayaz F, Sanjarian N, Kasaeian A, Astaraei FR, Sameti M, Nasirivatan S. An experimental comparison of SiO_2/water nanofluid heat transfer in square and circular cross-sectional channels. Journal of Thermal Analysis and Calorimetry 2018;131:1577–86. [CrossRef]
[27] Yan S, Zhang H, Wang F, Ma R, Wu Y, Tian R. Analysis of thermophysical characteristic of SiO_2/water nanofluid and heat transfer enhancement with field synergy principle. Journal of Renewable and Sustainable Energy 2018;10:063704. [CrossRef]
[28] Minkowycz W, Sparrow EM, Abraham JP. Nanoparticle heat transfer and fluid flow. Florida: CRC Press; 2016. [CrossRef]
[29] Al-Gebory L, Mengüç MP, Koşar A, Şendur K. Effect of electrostatic stabilization on thermal radiation transfer in nanosuspensions: Photo-thermal energy conversion applications. Renewable Energy 2018;119:625-40. [CrossRef]
[30] Mewis J, Wagner NJ. Colloidal suspension rheology. Cambridge: Cambridge University Press; 2012. [CrossRef]
[31] Naito M, Yokoyama T, Hosokawa K, Nogi K. Nanoparticle technology handbook. 3rd ed. Amsterdam, Netherlands: Elsevier; 2018.
[32] Mishchenko MI, Dlugach JM, Lock JA, Yurkin MA. Far-field Lorenz–Mie scattering in an absorbing host medium. II: Improved stability of the numerical algorithm. Journal of Quantitative Spectroscopy and Radiative Transfer 2018;217:274–7. [CrossRef]
[33] Lee BJ, Park K, Walsh T, Xu L. Radiative heat transfer analysis in plasmonic nanofluids for direct solar thermal absorption. Journal of Solar Energy Engineering 2012;134:021009. [CrossRef]
[34] Brewster M, Tien C. Radiative transfer in packed fluidized beds: dependent versus independent scattering. Journal of Heat Transfer 1982;104:573-9. [CrossRef]
[35] Drolen B, Tien C. Independent and dependent scattering in packed-sphere systems. Journal of Thermophysics and Heat Transfer 1987;1:63–8. [CrossRef]
[36] Gao L, Lemarchand F, Lequime M. Refractive index determination of SiO_2 layer in the UV/Vis/NIR range: spectrophotometric reverse engineering on single and bi-layer designs. Journal of the European Optical Society-Rapid Publications 2013;8:13010. [CrossRef]
[37] Yu H, Zhang H, Su C, Wang K, Jin L. The spectral radiative effect of Si/SiO2 substrate on monolayer aluminum porous microstructure. Thermal Science 2018;22(Suppl 2):629–38. [CrossRef]
[38] Diebold MP. Application of Light Scattering to Coatings: A User's Guide. Delaware, USA: Springer; 2014. [CrossRef]