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Evaluation of the effect of nanofluid-based absorbers on direct solar collector

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ABSTRACT

As conventional energy sources like fossil fuels are getting rare, cost of energy production has become higher as well as the concern of environmental pollution by burning of fossil fuels among the developed and developing nations. Solar energy is the most vastly available energy and very effective in terms of energy conversion. The most common solar thermal collector used is the black surface as radiant absorber but the thermal energy efficiency is low. In this study, the effect of nanofluid has been analyzed by using as working fluid for direct solar collector. The extinction coefficient of water based aluminum nanofluid has been investigated and evaluated by varying nanoparticle size and volume fraction. The particle size has minimal influence on the optical properties of nanofluid. On the other hand, the extinction coefficient is linearly proportionate to volume fraction. The improvement is promising within 1.0% volume fraction and the nanofluid is almost opaque to light wave.

1. Introduction

Sustainable energy generation is one of the most important challenges faced by our society today. Electricity consumption is increasing year by year and electricity generation has become a more major issue in the industry. Electricity supplies an increasing share of the world's total energy demand and is growing faster than liquid fuels, natural gas, and coal in all end-use sectors except transportation. Fossil fuels such as coal, petroleum and natural gas are used to steam generation in boilers of power plants and these plants stand a majority stack in the electricity power plant in the whole world. In addition, air pollution due to burning of fossil fuels has always been an issue for the governments, investors, environmentalists and researchers.

Solar thermal collectors are heat exchangers that are used to transform solar radiation energy to internal energy of the transport medium. Non-concentrating solar collectors can be used if a large amount of solar radiation is concentrated on a relatively small collecting area. Concentrating collectors exhibit certain advantages as compared with the non-concentrating collectors [1]. The most common system used in water heating system are the flat-plate, black-surface absorbers, which absorb solar energy through a solid surface [2]. The flat plate solar collector (FPC) has been built in a wide variety of designs with many different materials that are usually employed for low temperature applications up to 100 °C [3]. A theoretical method and novel computation algorithm were developed for the simulation of solar flat plate collectors with transparent insulation (TI) [4]. Another category of collectors is the uncovered or unglazed solar collector [5]. These collectors are usually the cheaper solution but still offer effective solar thermal energy in applications such as water preheating for domestic or industrial use, heating of swimming pools [6], space heating and air heating for industrial or agricultural applications. Conventional flat-plate solar collector is used in sunny and warm climates where the performance is greatly shrunk during cold, cloudy and windy days [3].

The idea of volumetric absorption using small particles has been proposed long before the ability to controllably synthesize nanoparticles was developed [7–10]. Tyagi et al. [11] investigated the feasibility of using a non-concentrating direct absorption solar collector (DAC) and compared its performance with a typical flat-plate collector. Aluminum nanofluids were used and it was observed that the absorption of incident radiation is increased by 9 times compared to pure water. The efficiency of DAC by using nanofluid has been found to be up to 10% higher than that of flat-plate collector.

Solar-weighted absorption coefficient for fluid's baseline capacity for absorbing solar energy has been investigated and it was found that water is the best absorber among the four tested liquids namely water, ethylene glycol, propylene glycol and therminol VP-1 [12]. However, it is still a weak absorber, only absorbing 13% of the energy. On the other hand, the addition of small particles causes scattering of the incident radiation allowing higher levels of absorption within the fluid, and hence an enhancement in

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Nomenclature

c_o	speed of light in vacuum, $c = 2.9979 \times 10^8$ m/s
d	diameter of the particle
E	energy content
ETC	evacuated tube solar collector
FPC	flat panel solar collector
f_v	volume fraction [%]
h	Planck's constant, $h = 6.62606957 \times 10^{-34}$ J.s or $4.135667516 \times 10^{-15}$ eV.s
h_c	convective heat transfer coefficient
I	transmitted light intensity
I_λ	total incident light intensity
k	absorption index of the particle
$K_{a\lambda}$	spectral absorption coefficient
k_B	Boltzmann constant, $k_B = 1.38 \times 10^{-23}$ J/K
$K_{e\lambda}$	spectral extinction coefficient
$K_{s\lambda}$	spectral scattering coefficient
m	normalized refractive index of the particle to the fluid
m_{particle}	complex refractive index of the particle
n	refractive index of the particle
q	heat transfer
$Q_{a\lambda}$	absorption coefficient
$Q_{e\lambda}$	extinction coefficient
$Q_{s\lambda}$	scattering coefficient
R	distance between the particle and the observer
T_{solar}	solar surface temperature, $T_{\mathrm{solar}} = 5800$ K
ΔT	temperature difference
v	frequency of photon associated electromagnetic wave
y	length of light path

Greek symbols

α	size parameter
θ	scattering angle
λ	wavelength [μm]

collector efficiency [13]. The optical properties of the effective fluid are highly dependent on the shape and size of the particle and the optical properties of the base fluid and particles themselves [14]. The radiation absorption characteristics of a Ni nanoparticle suspension were investigated by spectroscopic transmission measurement [15]. Recently, carbon nanohorns (CNHs), as the latest to be discovered in the family of carbon-based nanostructured materials [16] with large surface area and large number of cavities [17] have been used as nanoparticles to improve optical properties of direct solar absorbers. The studies showed promising improvement of absorption and scattering properties for carbon nanohorns-based nanofluid compared with water and glycol as base fluid [18,19]. The optical absorption of nanofluid also depends on the concentration or volume/weight fraction of nanoparticles added to the base fluid. The higher concentration nanofluid shifts the absorption spectra towards longer wavelength [20,21]. Carbon nanotubes, graphite, and silver were used as nanoparticles for absorption mechanism in solar thermal collectors where efficiency improvements of up to 5% were observed [22]. Taylor et al. [23] also used two models to obtain the optical properties of nanofluids. The authors claimed that by using nanofluid in an absorber near 95% of sunlight could be absorbed. Based on the model validated and presented by Lenert and Wang [24] when integrated with a power cycle, volumetric nanofluid receivers can cause the efficiency to go higher than 35%. They also outlined that optical thickness and solar concentration play substantial role in the performance. In another study by Lu et al. [25], it was stated that mass concentration can remarkably affect the performance and heat transfer in a solar collector (evaporating heat transfer coefficient was augmented up to 30%). PH values of the nanofluid has also been indicated to be effective by Yousefi et al [26]. They investigated the impact of using water with carbon nanotubes on the efficiency of a flat-plate solar collector and concluded that an increase on the difference between PH of the nanofluid and that of the isoelectric point causes the increase in the efficiency. The study by Yousefi et al. [27] also for flat-plate collectors showed an increase of 28.3% in the efficiency of the collector when operating with Al_2O_3/water nanofluid instead of pure water. The addition of nanoparticles to a base fluid has been shown to improve thermal conductivity. Studies suggested that the thermal conductivity is enhanced due to dispersion of nanoparticles [28,29], intensification of turbulence [29], Brownian motion [30,31] and thermophoresis [32]. The efficiency of a solar thermal collector relies on the effectiveness of absorbing solar radiant power and heat transfer from the absorber to the carrier, which is normally fluid. The conversion of highly concentrated sunlight into thermal energy suffers from relatively low efficiencies of 50% to 60% [33]. The application of nanofluids as a working medium for solar collectors is a relatively new concept. Further study to improve the physical properties for enhancing direct solar collectors has to be carried out. With the higher energy form and availability of solar power, researchers are interested in further developing the various aspects to make use of this energy.

The purpose of this study is:

(1) To investigate the suitability of nanofluid as a volumetric absorber.
(2) To explore the radioactive properties namely the base fluid and the nanoparticle.
(3) To find the effect of nanoparticle sizes and volume fractions for nanofluid as well as comparing its transmissivity of light.

2. Methodology

In this section the working principle, the incident solar intensity and transmissivity of Direct Absorption Collector (DAC), and finally the governing equations are used for nanofluid to develop its optical properties.

2.1. Direct absorption collector

Solar water heating technologies are becoming widespread and contribute significantly to hot water production in several countries. Solar collectors exhibit several shortcomings, such as limitations on incident flux density, relatively high losses, and corrosion effect. In order to overcome these drawbacks, the idea of using volumetric direct solar collectors is raised. DAC has few advantages compared to conventional surface absorption collector. Besides larger solar absorption area and actual installation surface area ratio due to the contribution of nanoparticle surface area, DAC can avoid surface heat losses due to excessive temperature on surface absorption collector. For a black body receiver, the radiative losses scale as the fourth power of the temperature. For surface solar absorber, the efficiency sharply drops with increasing temperature. The power losses from an ideal selective surface exhibit the same forth order dependence on the absorber temperature as a black body except the trend is shifted to higher temperature [34]. The convection losses to the ambient air also become significant as the temperature difference between the absorber surface and ambient air becomes larger. By using nanofluid as volumetric absorber, the drawbacks of surface emission and convection heat loss can be eliminated. The fluid is contained within the enclosed space of the DAC. The bottom wall is considered to be adiabatic, i.e. no heat flux is allowed to pass through, except for transmitted radiation. This assumption is based on the case when the bottom surface is highly insulated and transparent. The fluid is enclosed at the top by a glass surface which allows most of the incident solar flux to pass through. This top surface is assumed to be exposed to the ambient atmosphere and thus loses heat by convection. In order to model the heat transfer characteristics of this surface it is assumed that it loses heat to the ambient through convection. The incident radiation is considered to be the incoming solar radiation. For the study of the principal behavior of the nanofluid-based DAC, atmospheric absorption was neglected in these calculations. Hence, the incident solar intensity is calculated using the blackbody relation given by Eq. (1), where the value of T_{solar} is taken as 5800 K [11,13].

$$I_{b\lambda}(\lambda, T_{solar}) = \frac{2hc_o^2}{\lambda^5\left[\exp\left(\frac{hc_o}{\lambda k_B T_{solar}}\right) - 1\right]} \tag{1}$$

Using this relation the spectral intensity incident upon the solar collector was evaluated. The radiation intensity within the fluid was assumed to vary only in one dimension (along the y - direction). Eq. (2) is the radiative transport equation used in this model. The right side of the equation determines the attenuation in the intensity as the radiation travels through the fluid. Eq. (2) is integrated and expressed as:

$$\frac{\delta \boldsymbol{I}_\lambda}{\delta y} = -(\boldsymbol{K}_{a\lambda} + \boldsymbol{K}_{s\lambda})\boldsymbol{I}_\lambda = -\boldsymbol{K}_{e\lambda}\boldsymbol{I}_\lambda \tag{2}$$

$$\boldsymbol{I} = \boldsymbol{I}_\lambda e^{-\boldsymbol{K}_{e\lambda} y} \tag{3}$$

$$\frac{I}{\boldsymbol{I}_\lambda} = e^{-\boldsymbol{K}_{e\lambda} y} = \boldsymbol{T} \tag{4}$$

where $\mathbf{K_{a\lambda}}$ is the spectral absorption coefficient, and $\mathbf{K_{s\lambda}}$ the spectral scattering coefficient. Taken together they can also be represented as $\mathbf{K_{e\lambda}}$, the spectral extinction coefficient where **I**, denotes the transmitted light intensity. Eq. (3) confirms that the intensity of light transmitted is inverse to the length of light path, y and is further rearranged to turn into Eq. (4) to obtain transmissivity, T. This agrees with the Beer-Lambert Law. Since the temperatures in the solar collector are not expected to be very high, the emission term has not been included in Eq. (2). Also, in order to keep the model simple the effect of scattering has not been considered.

2.2. Radiative properties of nanofluid

The study of optical properties of nanofluid shows the need to study optical properties of the based fluid and nanoparticles separately. The brief theory and relation of light scattering and extinction for base fluid and nanoparticles are discussed below.

2.2.1. Radiative properties of base fluid

In order to fully understand the effects of suspending nanoparticles within a basefluid, the complete optical properties of the base fluid are needed. The bulk of the volumetric receiver is the fluid medium; therefore, the radiative properties of the fluid are influential on the efficiency of a volumetric design. An ideal fluid for a volumetric application would be completely transparent to the incoming solar radiation [34]. Base fluid normally used in direct solar collectors like water heater has to be non-toxic. A study of solar-weighted absorption coefficient for fluid's baseline capacity for absorbing solar energy found that water is the best absorber among the four tested liquids namely water, ethylene glycol, propylene glycol and therminol VP-1 [12]. However, it is still a weak absorber, only absorbing 13% of the energy. Mercatelli et al. [19] studied the absorption and scattering properties of carbon nanohorn-based nanofluids for DAC using glycol and water as base fluid also showed a more advantageous improvement than the water-based nanofluid. They also investigated the transmittance spectra of water and glycol-based nanofluids with the same Single Wall Carbon Nanohorn (SWCNH) concentrations and found improvement of the thermal stability properties of the nanofluid by optimization of SWCNH-surfactant concentration ratio. Despite the more superior performance of glycol-based nanofluid at high temperature, water is chosen to be the base fluid to study here as DAC is targeted to be used mainly in residential development and working temperature is estimated to be low. For pure fluids, scattering can be neglected and only the attenuation caused by absorption may be considered. For that case, the spectral absorption coefficient can be calculated using Eq. (5)

$$K_{a\lambda} = \frac{4\pi k}{\lambda} \tag{5}$$

where $\boldsymbol{k}$ is the index of absorption and λ is the wavelength of incident light. The absorption spectrum of pure water shows that water has low absorption coefficient at shorter wavelength that increases over the visible light spectrum until near infrared region [35]. Fig. 1 gives further illustration to the absorption coefficient of pure water with refractive index and extinction/absorption index plotted versus wavelength [12]. The graphs compare the data from previous works [12,36] and numerical calculations. The refractive index of pure water contributes almost constant values throughout the studied wavelength while the extinctive/absorptive index gives the major raise and is reflected in the absorption coefficient as shown in Fig. 1. Since the optical properties have long been studied and data are verified by many researchers [12,35,36], the spectrum of absorption coefficient used for calculation in this study will be based on the published data from previous work.

2.2.2. Radiative properties of nanoparticles

The nanoparticles are provided in a very small size and the volume fraction is only a small portion of the base fluid. Thus, the scattering effect of nanoparticles in nanofluid can be considered to be independent. Practical experiments most often employ a multitude of similar particles in a cloud or a solution. The simple proportionality to the number of particles holds only if the radiation to each particle is exposed which is essentially the light of the original beam. In actuality, each particle is also exposed to light scattered by the other particles, whereas the light of the original beam may have suffered extinction by other particles. In the study of nanofluids, the nanoparticles influence the nature of absorption as well as scattering. Rayleigh scattering can be applied. The particles are assumed to be spherical and the medium to be non-absorbing. In Rayleigh scattering $\alpha \ll 1$ and $|m|\alpha \ll 1$, where $\boldsymbol{\alpha}$ is defined as the size parameter and m is the normalized refractive index of the particles to the fluid [11,13,22]:

$$\alpha = \frac{\pi D}{\lambda} \tag{6}$$

$$m = \frac{m_{particles}}{n_{fluid}} \tag{7}$$

$$m_{particles} = n + ik \tag{8}$$

In physical terms, Rayleigh scattering can be understood as the regime in which the particle size is much smaller than the wavelength

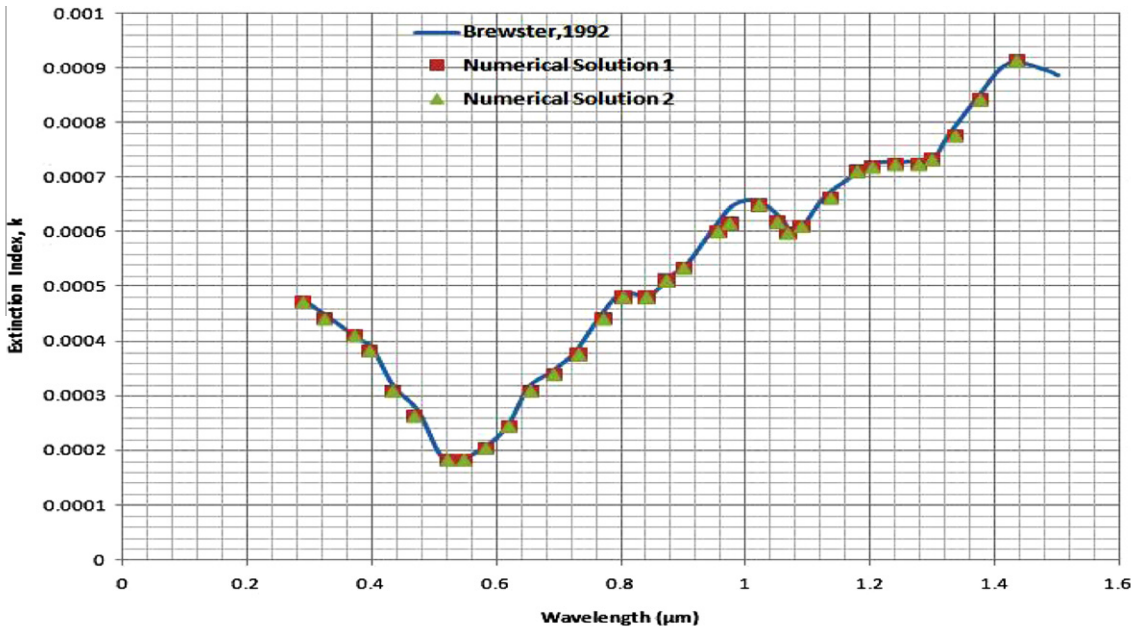

Fig. 1. Extinction index of water [12].

of the incident radiation. In general, the extinction coefficient can be given as:

$$K_{e\lambda} = \frac{3f_v Q_{e\lambda}(\alpha, m)}{D} \tag{10}$$

The extinction efficiency in the Rayleigh regime is given by the following relation [13,34]:

$$Q_{e\lambda} = 4\alpha \mathrm{Im}\left\{\frac{m^2-1}{m^2+2}\left[1+\frac{\alpha^2}{15}\left(\frac{m^2-1}{m^2+2}\right)\frac{m^4+27m^2+38}{2m^2+3}\right]\right\} + \frac{8}{3}\alpha^4 Re\left|\left(\frac{m^2-1}{m^2+2}\right)\right|^2 \tag{11}$$

where the extinction efficiency, $\mathbf{Q}_{e\lambda}$, term shown above contains two terms, including the absorption efficiency $\mathbf{Q}_{a\lambda}$ and scattering efficiency $\mathbf{Q}_{s\lambda}$, as shown below:

$$Q_{a\lambda} = 4\alpha Im\left\{\frac{m^2-1}{m^2+2}\left[1+\frac{\alpha^2}{15}\left(\frac{m^2-1}{m^2+2}\right)\frac{m^4+27m^2+38}{2m^2+3}\right]\right\} \tag{12}$$

$$\mathbf{Q}_{s\lambda} = \frac{8}{3}\alpha^4 Re\left|\left(\frac{m^2-1}{m^2+2}\right)\right|^2 \tag{13}$$

The scattering efficiency, $\mathbf{Q}_{s\lambda}$ varies as the fourth power of particle size. In addition, it is found that absorption efficiency, $\mathbf{Q}_{a\lambda}$ predominantly varies almost linearly with particle size. This is true even though there is a $\boldsymbol{\alpha}^2$ term inside the imaginary term because $\boldsymbol{\alpha}$<<1, the expression for $\mathbf{K}_{e\lambda}$ is obtained as follows:

$$K_{e\lambda} = \frac{12\pi f_v}{\lambda} Im\left\{\frac{m^2-1}{m^2+2}\left[1+\frac{\pi^2D^2}{15\lambda^2}\left(\frac{m^2-1}{m^2+2}\right)\frac{m^4+27m^2+38}{2m^2+3}\right]\right\} + \frac{8\pi^4D^3f_v}{\lambda^4} Re\left|\left(\frac{m^2-1}{m^2+2}\right)\right|^2 \tag{14}$$

where the extinction coefficient, $\mathbf{K}_{e\lambda}$ term shown above contains two terms, which are the absorption coefficient $K_{a\lambda}$ and scattering coefficient, $\mathbf{K}_{s\lambda}$.

$$K_{e\lambda} = \frac{12\pi f_v}{\lambda} Im\left\{\frac{m^2-1}{m^2+2}\left[1+\frac{\pi^2D^2}{15\lambda^2}\left(\frac{m^2-1}{m^2+2}\right)\frac{m^4+27m^2+38}{2m^2+3}\right]\right\} \tag{15}$$

$$K_{e\lambda} = \frac{8\pi^4D^3f_v}{\lambda^4} Re\left|\left(\frac{m^2-1}{m^2+2}\right)\right|^2 \tag{16}$$

Lenert [34] suggested that the two complex expressions can be greatly simplified if the terms with a higher order of the size parameter, $\boldsymbol{\alpha}$, are neglected because this parameter is small in the case of nanoparticles. It was assumed that the amount of incident radiation absorbed by the nanoparticle is dominated over the amount of scattering by the particle. Since scattering is neglected, the attenuated light is assumed to be absorbed; thus the extinction coefficient is merely just absorption coefficient [34].

$$K_{e\lambda} = \frac{6\pi f_v}{\lambda} \mathrm{Im}\left\{\frac{m^2-1}{m^2+2}\right\} \tag{17}$$

However, a small influence of the term $\boldsymbol{\alpha}^2$ has been seen in studies and is illustrated in Fig. 2 below [11,13]. It was found that, with all other parameters such as particle volume fraction, collector height, and collector length being constant, the collector efficiency increased slightly with an increase in the particle size.

The net extinction caused by the nanofluid was obtained for the individual contributions from the nanoparticles as well as the base fluid. The intensity distribution within the solar collector was obtained using:

$$\frac{\delta I_\lambda}{\delta y} = -K_{e\lambda,nanofluid} I_\lambda = -(K_{\alpha\lambda,water} + K_{e\lambda,nanoparticles}) I_\lambda \tag{18}$$

3. Results and discussion

Aluminum is used as nanoparticle in this research as it is one of the most common and vastly available metals. Besides, the thermal properties of aluminum based nanofluid have been studied extensively over the past decades and have shown promising improvement in thermal properties. The effects of nanoparticles in enhancing the optical properties are explored with nanoparticle

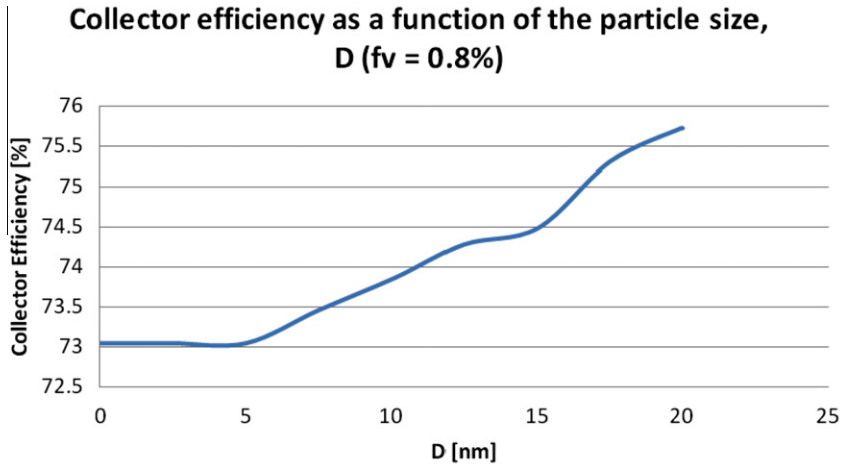

Fig. 2. Collector efficiency as a function of the particle size, D(f_v = 0.8%).

sizes and volume fraction as changing parameters. The volume fraction of nanoparticles in the nanofluid is also to be a smaller percentage to allow possibility of applying the results to ETC and to avoid shifting of the maximum absorption coefficient of nanofluid to the longer wavelength with less concentration.

3.1. Transmissivity of base fluid (pure water)

The transmissivity **T**, of the base fluid is first calculated to explore the effectiveness of light absorption for pure water. The transmissivity of pure water is shown in Fig. 3. From this figure pure water is almost transparent at the visible light region and does not absorb any of the light transmitted to it. The absorption of light only becomes noticeable when light wave goes into the near infrared region and reaches its maximum at 1.9 μm. After 1.9 μm, pure water again becomes non effective in absorbing light until the light wavelength exceeds 2.60 μm when the absorption coefficient increases sharply, transmissivity drops abruptly. In general, pure water is not an effective light absorber especially in the visible light region.

3.2. Optical properties of nanoparticles

The study on the effect of enhancing optical properties of nanofluid with aluminum nanoparticles starts with the selection of a suitable nanoparticle size. As mentioned earlier, the particle size is limited to below 20 nm. The absorption coefficient, $\mathbf{k}_{a\lambda}$, scattering coefficient, $\mathbf{k}_{s\lambda}$ and extinction coefficients, $\mathbf{k}_{e\lambda}$ of aluminum nanoparticle of few sizes namely 1 nm, 5 nm, 10 nm, 15 nm and 20 nm are calculated with the volume fraction of 2%. The results are presented in Figs. 4–6 to show the trend with increasing nanoparticle sizes.

Figs. 4–6 demonstrate the absorption coefficient, scattering coefficient and extinction coefficient of aluminum nanoparticles versus light wavelength with particle size as the varying parameter. From Fig. 4, it could be noted that there are five lines in the graph although the lines overlapped each other and only two very close lines are shown (blue line and brown line which denote particle sizes of 1 nm and 20 nm respectively). The data shows identical absorption coefficient for the different sizes after 0.6 μm. The particle size in nanometer becomes very insignificant to the overall. The further increase in wavelength will overshadow the effect of particle size and eventually leads to near-constant absorption coefficient. Fig. 5 illustrated a similar trend as the absorption coefficient graph. The effect of different particle sizes becomes almost unnoticeable after wavelength exceeds 0.6 μm. The particle size is in power of three while wavelength is in power of four. Near UV region, where wavelength is shorter, the effect of having larger particles is still obvious. As wavelength becomes longer and the scattering coefficient is inversely propor-

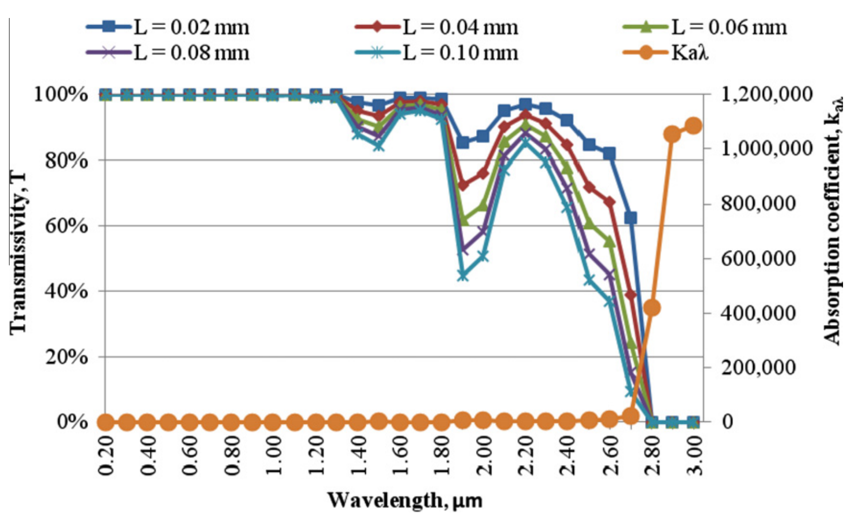

Fig. 3. Transmissivity and absorption coefficient, $k_{a\lambda}$ of base fluid (pure water) at various light path length.

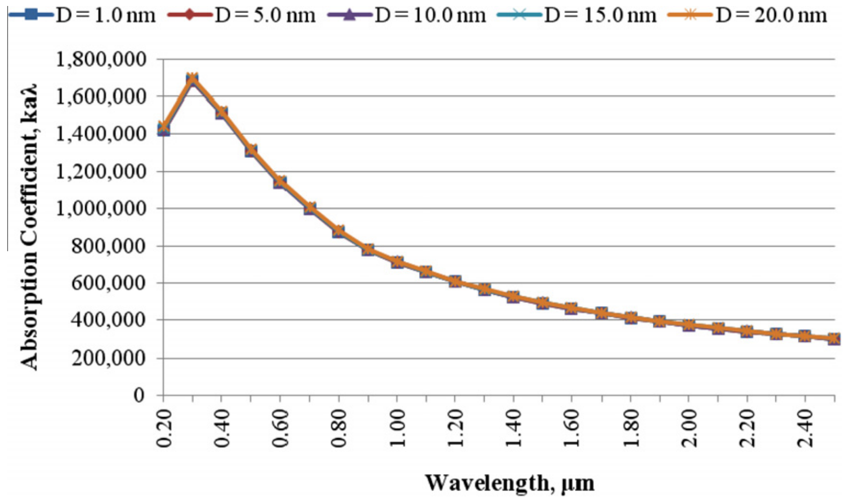

Fig. 4. Effect of nanoparticle sizes towards absorption coefficient, $k_{a\lambda}$.

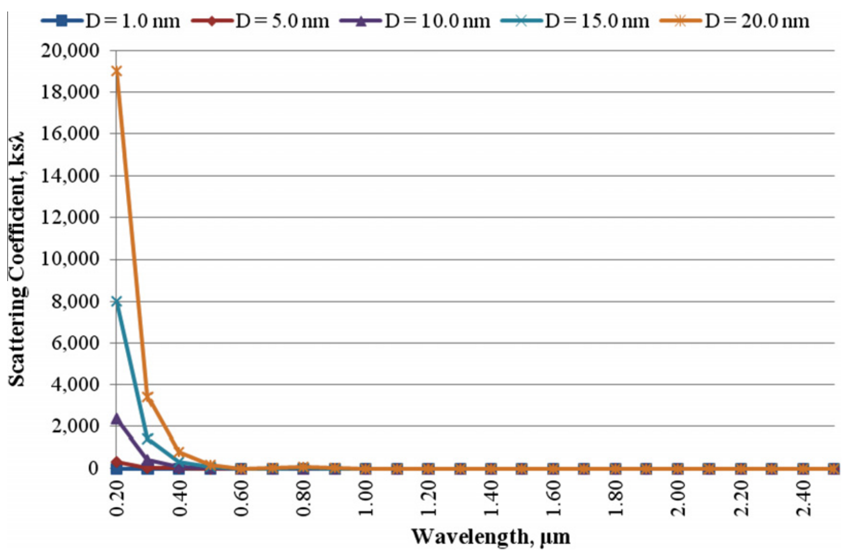

Fig. 5. Effect of nanoparticle sizes towards scattering coefficient, $k_{s\lambda}$.

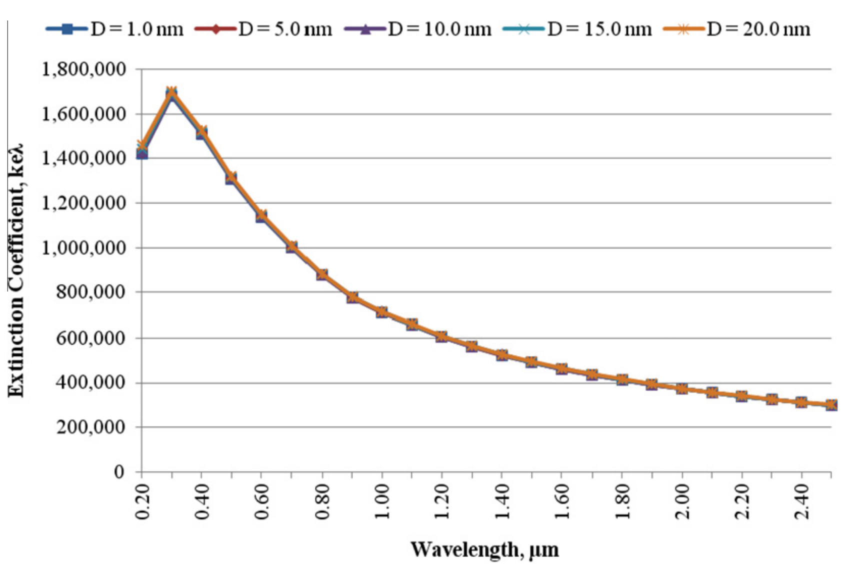

Fig. 6. Effect of nanoparticle sizes towards extinction coefficient, $k_{e\lambda}$.

tional to the wavelength with power of four, the effect is minimized. Fig. 6 is almost similar to Fig. 4. The extinction coefficient is the sum of scattering coefficient and absorption coefficient. The much smaller Scattering coefficient demonstrates no noteworthy influence to the overall extinction coefficient calculation. In short, particles used in nanofluid are extremely small and the terms D^2 and D^3 have very little impact to the Extinction coefficient. Lenert [34] suggested that the size of nanoparticle is not a majorly effective factor on the optical properties of nanofluid and the extinction coefficient is simply dependent on the optical properties in suspension and the total volume fraction. However, it is theoretically expected that the higher particle size should lead to higher extinction coefficient. However, for the Rayleigh scattering, the particle size has to be controlled within 20 nm.

By Fig. 7, it is shown that the absorption coefficient gains it weight sharply from wavelength of 0.2 μm to slightly before 0.3 μm and ease with almost the same pace along the visible light region. The absorption coefficient slowly comes to a constant decreasing gradient after wavelength of 0.9 μm and continues all the way through the studied wavelengths. This phenomenon happens to every volume fraction but larger volume fraction shows sharper rise and drop fashion. In general, absorption coefficient upsurges with the increase of volume fraction by the same rate. Absorption coefficient is linearly proportional to the volume fraction. Besides absorption coefficient; the scattering coefficient of aluminum nanoparticles is shown. Figs. 9 and 10, shows the trend of scattering coefficient along various light wavelengths.

Similar to the graphs plotted for absorption coefficient, the trend is shown in a graph to clarify the sensitivity of scattering coefficient towards volume fraction. Fig. 8 demonstrates the spectrum of scattering coefficient with interval of 0.5% increment of volume fraction. According to Fig. 8, aluminum nanoparticles only contribute to scattering coefficient at a very small region. The scattering coefficients are large and significant near UV section (0.2 μm) and they follow the abrupt descent to nil when entering the visible light section. The scattering coefficient of nanoparticle decreases to below 100 at wavelength of 0.3 μm and reach zero after wavelength of 0.5 μm. The increment of volume fraction gives larger scattering coefficient but it is also negligible after 0.3 μm of wavelength. The scattering coefficient can be neglected in most wavelengths as its effect is not perceptible when combined with absorption coefficient. The combined absorption coefficient and

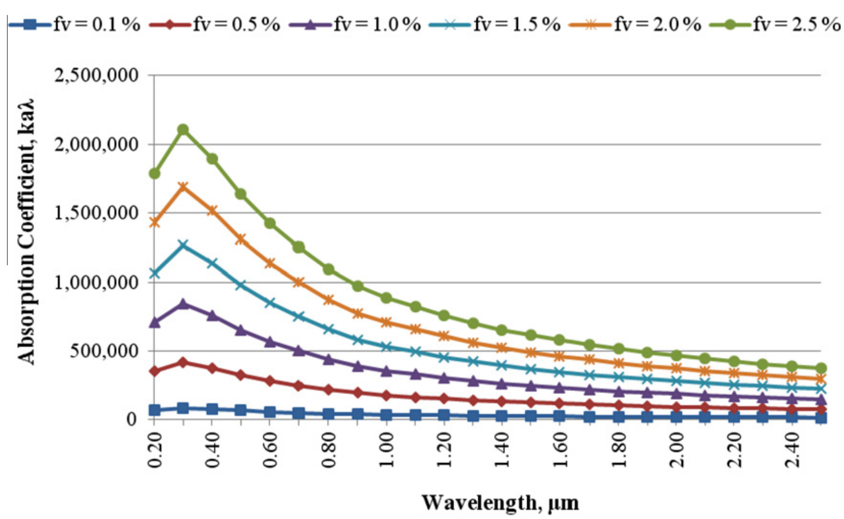

Fig. 7. Effect of nanoparticle volume fraction, f_v (0.1%–2.5%) towards absorption coefficient, $k_{a\lambda}$.

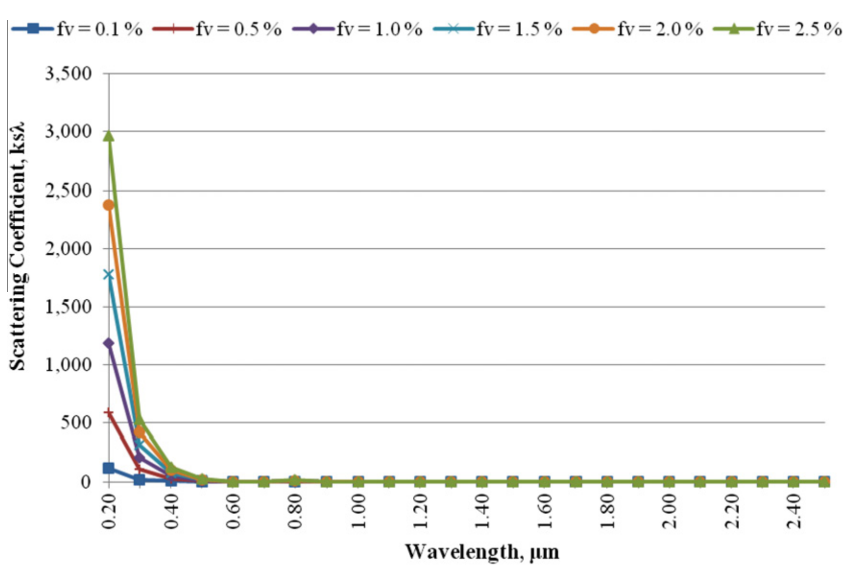

Fig. 8. Effect of nanoparticle volume fractions, f_v (0.1%–2.5%) towards scattering coefficient, $k_{s\lambda}$.

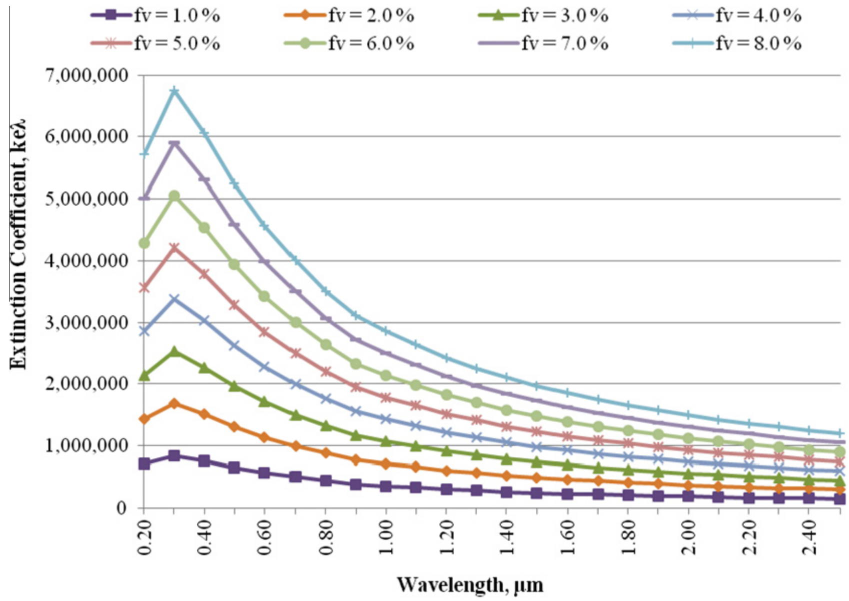

Fig. 9. Effect of nanoparticle volume fractions, f_v(1.0%–8.0%) towards extinction coefficient, $k_{e\lambda}$.

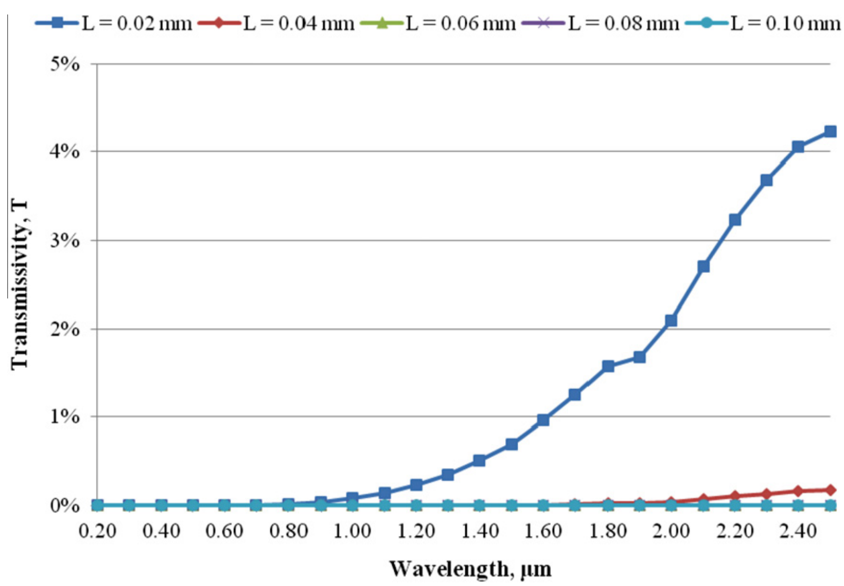

Fig. 10. Extinction coefficient and transmissivity of nanofluid (f_v = 1.0%).

scattering coefficient which gives the extinction coefficient of nanoparticles is shown in Fig. 9.

The spectrum of extinction coefficient is observed to be similar to that of absorption coefficient. This is true as the order of scattering coefficient is of thousands while the absorption coefficient in millions. Thus, the portion of scattering coefficient in the extinction coefficient is so minimal that the effect is inconspicuous. Besides, based on the trend in the extinction coefficient by increasing volume fraction of nanoparticles, it can be concluded that the more concentrated the nanoparticle in the nanofluid, the higher extinction coefficient can be expected. The influence of particle size on the optical properties of nanoparticle seems to be minimal. The extinction coefficient of nanoparticle is linearly proportional to the volume fraction. The optical properties possess more favorable trend with increasing the volume fraction nanoparticle. When augmenting the volume fraction of nanoparticles, the controlling factors such as possible clogging effect and stability of suspended nanoparticles in the base fluid are affected.

3.3. Transmissivity of nanofluid

The influence of light transmissivity of aluminum nanoparticle on the base fluid is studied and is shown in Fig. 10. The transmittance of light is significantly reduced by 60% in average throughout the visible light region. This is the region where pure water is most transparent and visible light passes through freely. The transmissivity gradually increases after wavelength of 0.3 µm where the nanoparticles have the most extinction coefficient. The extinction coefficient of nanoparticles, regardless of volume fraction, decline slowly and continuously towards near the infrared region which is shown in Fig. 9. This results in a greater transmissivity after visible light region and going towards the near infrared sector. The nanofluid becomes opaque to light from the values of near UV to about 0.5 µm wavelengths when light travels 0.1 mm or 100 µm into the nanofluid. The enhancement absorption is the result of having 0.1% of nanoparticle in the base fluid. When the concentration increases to 0.5%, the improvement becomes even more distinguished. The nanofluid extinct almost all the light when light path reaches 0.6 mm or 60 μm. When wavelength exceeds 1.60 μm, the light is able to be transmitted to a deeper layer of nanofluid. But light is totally prohibited from passing through when it reaches 0.8 mm light path. The transmissivity of light becomes almost impossible when 1.0% volume fraction of nanoparticle is used. Light can only barely pass through 0.02 mm or 20 μm of nanofluid and is being absorbed totally. This can be used to assume that the solar energy is completely harvested when light passes through about 0.03 mm into the nanofluid, which demonstrates a very promising improvement on the implementation of solar energy. However, with the projection of graph in Fig. 9 as well as the great absorption ability of pure water at that sector as illustrated in Fig. 3, the nanofluid is predicted to be relatively opaque to light wave for wavelengths exceeding 2.5 μm.

4. Conclusions

Solar energy is considered to be one of the best sources of renewable energy with the least environmental impact. Direct absorption solar collectors have been used for a variety of applications such as water heating; however the efficiency of these collectors is found to be limited by the absorption properties of the working fluid, which is very poor for typical fluids which are used in solar collectors. Direct solar collector uses nanofluids as volumetric absorber and is expected to provide excellent optical properties and enhanced thermal transfer. Pure water appears to be almost transparent to visible light but shows great absorption ability at longer wavelength of about 2.6 μm and onwards. Aluminum nanoparticle shows very strong extinction coefficient at shorter wavelength and peak at 0.3 μm. Despite a lower extinction coefficient at longer wavelength, aluminum nanoparticle can be used to enhance the light absorption ability of water at the visible and shorter wavelength region. The particle size shows minimal influence on the optical properties of nanofluid while the extinction coefficient is linearly proportionate to volume fraction. It is suggested that although the extinction coefficient of nanofluid is independent from the nanoparticle size, the size should be controlled to be below 20 nm in order for Rayleigh scattering to take place. On the other hand, the volume fraction should be minimal after obtaining the desired optical properties in order to avoid drawbacks like clogging and unstable suspension of nanoparticles. The transmissivity of light is compared between pure water (base fluid) and nanofluid. The improvement is promising and with only 1.0% volume fraction, the nanofluid is almost opaque to light wave. Since volume fraction of just 1.0% is showing satisfactory improvement to solar absorption, aluminum nanofluid is a good solution for direct solar collector compared to others.

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