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Investigations into nanofluids as direct solar radiation collectors

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ABSTRACT

Nanofluids that directly absorb solar radiation have been proposed as an alternative to selectively coated metallic receivers in solar thermal collectors. Given the expense of characterising a potential nanofluid experimentally methods for comparing nanofluids virtually are needed. This paper develops a computational wave optics model using COMSOL to simulate the absorption of nanoparticles suspended in a fluid for solar radiation (380–800 nm) and compares it to experimental results using reflectance and transmission spectrometry. It was concluded that while both yielded data with matching trends, the exact absorption of some fluids differed by up to 1 AU. Optical characteristics of nanofluids comprising ethylene glycol (melting point −12.99 °C and boiling point range 195–198 °C at 1013 h Pa) and graphene oxide (sheets size 5 nm × 19 nm × 19 nm, volume fraction 0.004–0.016%) have been experimentally measured. An optimum volume fraction of 0.012% of graphene oxide has been identified achieving a minimum reflectance and highest absorbance over the visible spectral range.

1. Introduction

Nanofluids, suspensions of nanoparticles in liquids, have been the focus of recent interest for use as directly absorbing working fluids, due to their reported stability in suspension and the availability of materials from which they can be synthesised (Romasanta et al., 2011). Directly absorbing nanofluids offer many advantages over traditional surface absorbers: reduced thermal and radiative losses, potential for miniaturisation of solar concentrators and lower material costs (Toppin-Hector and Singh, 2013). The amount of solar radiation that a solar concentrator working fluid will directly absorb depends primarily on the type of fluid used and its solar absorption characteristics and the dimensions of the receiver tube (Gorji and Ranjbar, 2015; Toppin-Hector and Singh, 2013).

Extinction describes the reduction in the amount of radiation that is observed when any medium (gas or liquid or solid or a combination) is placed between a light source and a detector (Otanicar et al., 2009).

The attenuation of light intensity ($-dI_x$) as light passes through a layer of an absorbing medium is proportional to the intensity of light at the entrance of the medium layer (I_x) and the differential thickness of the layer (dx). Mathematically this relation can be expressed as (Maikala, 2010):

$$-dI_x = aI_x dx \tag{1}$$

where

a is the wavelength dependent absorption or extinction coefficient

Eq. (1) is popularly known as Bouguer-Lambert's law and in this equation '–' sign indicates a definite decrease in the intensity as light passes through any absorbing medium.

Previous studies have focussed on the scattering component using an adaptation of the Rayleigh approximation (Ladjevardi et al., 2013). However, the Rayleigh approximation only holds for particles that are spherical, are close in refractive index to the medium they are in, and are small in size relative to the wavelength (λ) such that $\ll \lambda/10$ (Kerker et al., 1978). Models based on the Rayleigh approximation will not be able to predict the optical properties of non-spherical particles such as graphene nanoparticles.

Taylor et al. (2011) took a Maxwell-Garnett effective medium approach to model the optical properties of nanofluids based on the optical properties of the fluid and the bulk materials of the nanoparticles (NPs). Their study has a serious drawback in that they did not consider any difference in the electrical permittivity between a nano scale particle and a macro scale sample of the same metal. They concluded that the Maxwell-Garnett effective

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medium approach did not correctly predict the extinction caused by nanoparticles in a fluid but did not expand on the reason nor suggest alternative methods.

Beer-Lambert's law relates the reduction in the intensity of light with the depth of medium layer as it passes through an absorbing medium of a specific concentration (C). Thus Eq. (1) can be expressed as Eq. (2) as follows:

$$-dI_x = aI_xCdx \tag{2}$$

Eq. (2) can be integrated over the thickness of the medium layer varying from $x = 0$ to $x = L$ to yield Beer's law (Maikala, 2010):

$$A = \log_{10}\frac{I_o}{I} \tag{3}$$

where

A is the absorbance of the absorbing medium
I_0 is the intensity of light that enters the medium
I is the intensity of light that leaves the medium layer of thickness L

Absorbance therefore can be easily linked with the depth of a medium. Beer-Lamberts law allows the absorbance for any path length through a medium to be calculated. This principle can be interpreted so that it is only necessary for a model to simulate the optical properties of a small volume of fluid to be useful for predicting the absorption of any volume. Currently the optical properties of each different fluid and particle combination must be measured experimentally to identify the ideal working fluid for a direct solar absorption application. If a computer model could be developed that is capable of identifying the most likely nanoparticle-fluid combinations, the process of designing a directly absorbing solar thermal concentrator would be greatly simplified.

1.1. Modelling approach

1.1.1. Raytracing

One of the simplest ways to model light absorption by objects is ray tracing. Ray tracing models light as being composed of several (how many depends on the precision of the model) infinitely narrow straight rays. A nanofluid would be simulated by a ray trace model as a series of opaque objects randomly distributed throughout a transparent medium (the population density and size of the objects is analogous to the volume fraction and size of nanoparticles). Rays are then passed through the virtual nanofluid and when they are incident on a nanoparticle they are considered to have been absorbed and propagate no further by simpler models. Once every incident ray has encountered a sphere and been absorbed, the distance travelled by the last ray to be absorbed and the number of rays used in the simulation can be used to estimate the depth of the fluid layer to cause full absorption of the solar radiation.

Ray trace models have the advantage of requiring relatively little information about the nanofluids and are based on simple geometric calculations to produce a result. However, they cannot accurately simulate the absorption of solar radiation by nanofluids as nanoparticles are significantly smaller than the wavelength of solar radiation.

The uncertainty in the position of a photon makes it difficult to determine if a photon will be absorbed by a nanoparticle using a ray trace model. For a photon, it can be derived from the uncertainty principle expressed in Eq. (4).

$$\Delta x \geqslant \frac{\lambda}{4\pi} \tag{4}$$

where (Δx) is the uncertainty in position and (λ) is the wavelength.

For a photon of visible light uncertainty in the position is always greater than ~40 nm which is larger than the size of many nanoparticles considered for direct absorption (size ~15 to 30 nm). As such modelling light as rays at scales less than this is not a meaningful analogy (Novotny and Hecht, 2006). The wavelength of visible light could easily be around 10–25 times greater than the size of NPs. Thus, model assumption that light travels in straight lines and is only absorbed by particles on which it is directly incident is not valid (Bohren and Huffman, 1983).

As a result of these two shortcomings, a purely ray tracing based model only considers the interaction between particles and light directly incident on it. Such a model would either under- or over-estimate the optical absorption by a nanofluid. An alternative would therefore be to simulate the process using ray tracing only at scales where its assumptions are sensible and an alternative model to simulate the fluid properties at smaller scales.

1.1.2. Wave optics

While the Rayleigh approximation was originally derived geometrically it has been shown to be consistent with wave optics (Bohren and Huffman, 1983).

The interaction of electric and magnetic fields is described physically by Maxwell's, Eqs. (5)–(8).

$$\nabla \times \boldsymbol{E}(\boldsymbol{r},t) = -\frac{\partial \boldsymbol{B}(\boldsymbol{r},t)}{\partial t} \tag{5}$$

$$\nabla \times \boldsymbol{H}(\boldsymbol{r},t) = \frac{\partial \boldsymbol{D}(\boldsymbol{r},t)}{\partial t} + \boldsymbol{j}(\boldsymbol{r},t) \tag{6}$$

$$\nabla \cdot \boldsymbol{D}(\boldsymbol{r},t) = \rho(\boldsymbol{r},t) \tag{7}$$

$$\nabla \cdot \boldsymbol{B}(\boldsymbol{r},t) = 0 \tag{8}$$

where (E) is the electric field; (D) is the electric displacement; (H) is the magnetic field; (B) is the magnetic induction; (j) is the current density, (ρ) is the charge density, ($\nabla\times$) represents the curl of a vector and ($\nabla\cdot$) represents the divergence of the vector.

Light is therefore described by wave optics as an electromagnetic wave comprised of varying electric and magnetic fields orthogonal to each other and the direction of wave propagation.

In vacuum electromagnetic waves will continue to propagate indefinitely whereas in other mediums charges will be affected by the varying electrical and magnetic field which will diminish energy content of the wave as it passes through. In this way the electromagnetic wave is absorbed and its energy is transferred to the medium.

A medium's resistance to a change in electric field and magnetic field is given by the electrical permittivity (ε) and magnetic permeability (μ) respectively. These properties are more commonly represented in terms of the refractive index (n) (9).

$$n = \sqrt{\frac{\varepsilon}{\varepsilon_0}\frac{\mu}{\mu_0}} \tag{9}$$

where (ε_0) is the electrical permittivity of free space and (μ_0) is the magnetic permeability of free space.

In most circumstances, at speeds much less than the speed of light or intensities less than 10^{18} W/m^2, only the electric field and electrical permittivity need be considered (Peatross and Ware, 2011). The wave equation for the electric field in a medium with a refractive index (n) can be written as shown in Eq. (10).

$$\nabla^2 E - \frac{n^2}{c^2}\frac{\partial^2 E}{\partial t^2} = 0 \tag{10}$$

where (c) is the speed of light.