Particle size effects of solar absorbing dispersions in water and convergence of Mie solutions

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Introduction

Nano particle dispersions have been extensively studied in terms of solar collector applications to increase the absorption capability of the fluid. In addition, they can be tailored to suit specific requirements. Recently, they have also been studied to enhance the surface evaporation process and boiling applications for solar desalination purpose

Dispersion systems

Dispersions floating on water help absorbing the incoming solar radiation. Specific uses in solar collectors have been studied by [1-2]. They have also been identified for use in solar water evaporation process [3]. The particles can be tuned to meet specific radiation properties: either to act as an absorber or a strong reflector [1].

These dispersions can be metallic plasmons or non-metallic particles. The radiative properties depend explicitly on the size of the suspension and the complex index of refraction.

Radiation model consideration

The radiation properties are firstly calculated by determining the scattering and absorption efficiency. They are calculated by using three different models to account for size variations. The models considered are [4]:

1. Rayleigh scattering theory (X<<0);
2. Mie Theory (X≈1); and
3. Geometric Optics (X>>1)

The size parameter 'X' quantifies the radiation model form to be used. It is given as

$$X = \frac{2\,\pi\, n_w\, r}{\lambda}$$

Where n_w is the refractive index of water.

Activated Carbon is selected as the absorbing material. For simplicity, and use of the radiation models described above, three different values for radius are considered: 40nm, 4μm and 4mm. The complex index of refraction are taken from [5].

Formulation

The input for the computations: 1. Wavelength (λ); 2. radius (r); 3. complex index of refraction: m = n+ik;

1. Efficiency

Based on the size (parameter) of the dispersion, the respective radiation model is selected and the absorption and scattering efficiency are firstly determined. They are given as

Mie Theory

Determining the scattering and absorption efficiency requires computation of Mie coefficients which are a combination of spherical Bessel functions (1st and 2nd kind) and the Henkel function

$$a_n = \frac{m^2\, j_n(mx)[x\, j_n(x)]' - j_n(x)[m\, j_n(mx)]'}{m^2\, j_n(mx)[x\, h_n(x)]' - h_n(x)(mx\, j_n(mx))'}$$

$$b_n = \frac{j_n(mx)[x\, j_n(x)]' - j_n(x)[m\, j_n(mx)]'}{j_n(mx)[x\, h_n(x)]' - h_n(x)(mx\, j_n(mx))'}$$

For

$$h_n(z) = j_n(z) + i y_n(z) \qquad j_n(z) = \sqrt{\frac{\pi}{2z}}J_{n+0.5}(z) \qquad y_n(z) = \sqrt{\frac{\pi}{2z}}Y_{n+0.5}(z)$$

and $[zj_n(z)]' = zj_{n-1}(z) - nj_n(z)$ $\qquad [zh_n(z)]' = zh_{n-1}(z) - nh_n(z)$

$$Q_{sca} = \left(\frac{2}{x^2}\right)\sum_{0}^{\infty}(2n+1)(|a_n|^2 + |b_n|^2)$$

$$Q_{abs} = \left(\frac{2}{x^2}\right)\sum_{0}^{\infty}(2n+1)Re_n(a_n + b_n)$$

To reduce the complexity of summation of infinite series, a maximum limit to accuracy can be given by

$$n_{max} = 2 + X + 4X^{1/3}$$

Rayleigh Scattering Theory

For extremely small particles, the scattering efficiency and absorption efficiency can be given as

$$Q_{sca} = \frac{8}{3}X^4\left|\frac{m^2-1}{m^2+1}\right|^2$$

$$Q_{abs} = 4X\, Im\left\{\frac{m^2-1}{m^2+1}\left[1+\frac{X^2}{15}\left[\frac{m^2-1}{m^2+1}\right]\frac{(m^4+27m^2+38)}{2m^2+3}\right]\right\} + \frac{8}{3}X^4\mathrm{Re}\left\{\frac{m^2-1}{m^2+1}\right\}^2$$

Geometric Optics

The absorption efficiency and scattering efficiency are given in terms of hemispherical absorptivity and reflectivity of the particle as

$$Q_{sca} = \rho$$

$$Q_{abs} = 1 - \rho = \alpha$$

The hemispherical reflectivity is given as $\rho = \frac{(n_p - n_w)^2 + k_p^2}{(n_p + n_w)^2 + k_p^2}$

The extinction efficiency is given as $Q_{ext} = Q_{abs} + Q_{sca}$

For large particles (X>>1), the extinction efficiency $Q_{ext} = 2$

2. Coefficients

The coefficients are then calculated from the determined efficiencies as

$$\kappa_p = 1.5\frac{Q_{abs} f_v}{d_p} \qquad \sigma_p = 1.5\frac{Q_{sca} f_v}{d_p} \qquad \kappa_w = \frac{4\pi k_w}{\lambda}$$

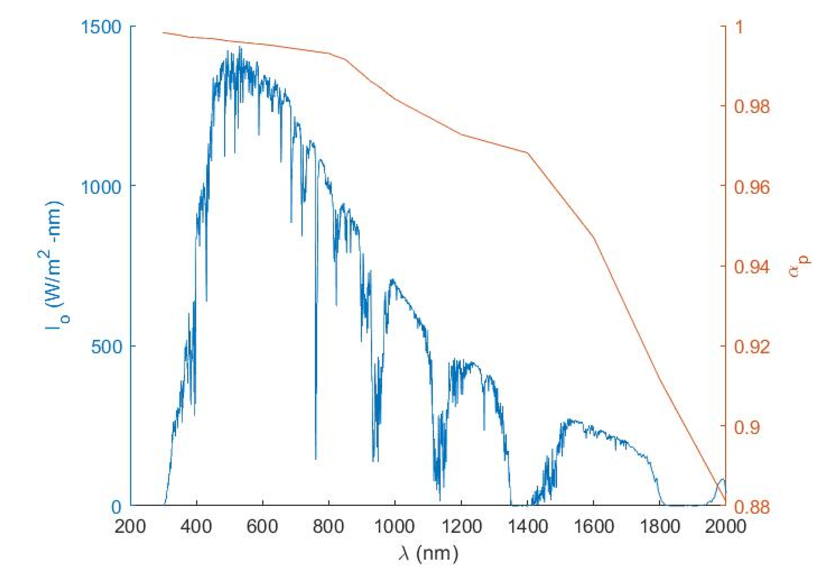
Extinction coefficient is given as

$$\beta_{ext} = \kappa_p + \sigma_p + \kappa_w$$

and transmissivity of the system is

$$\tau = \frac{I}{I_o} = \exp(-\beta_{ext} S)$$

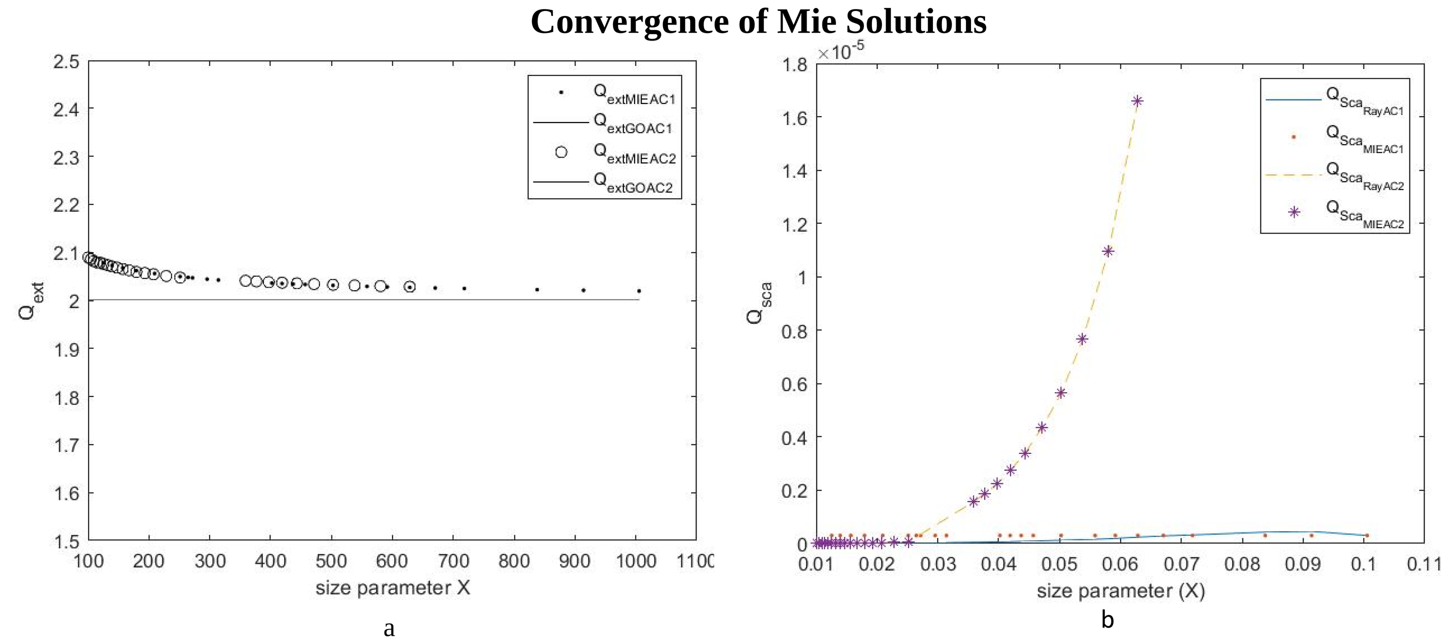
Utilizing large sized Activated Carbon as a dispersion in solar collector or water evaporation systems



Large sized (4000μm) Activated Carbon is a potential dispersion material for good solar absorption as shown in the figure above.

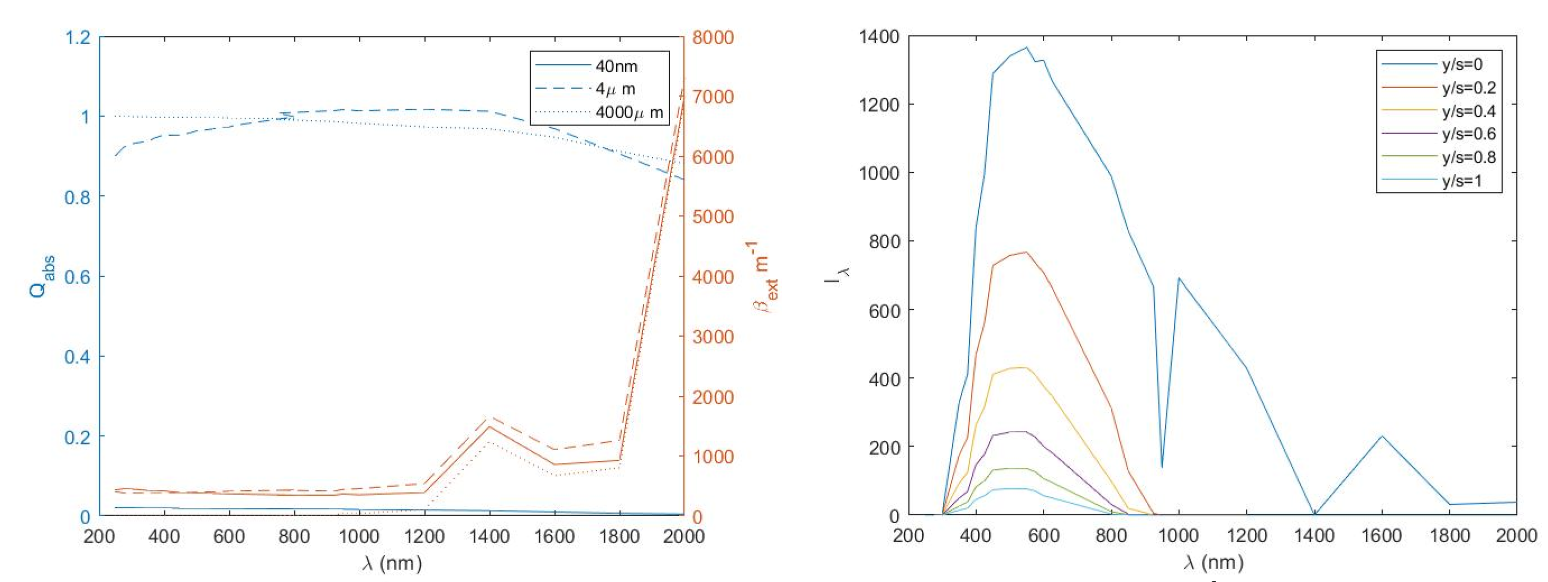
Results

Convergence of Mie Solutions



Convergence of Mie solutions to a. Geometric Optics and b. Rayleigh scattering theory for Activated Carbon (AC1) and Amorphous Carbon (AC2) for large sizes at 40μm and small particle at 4nm.

Size effects of Radiation Properties and Intensity attenuation for large particles



a. Size effects of Activated Carbon on absorption efficiency and extinction coefficient; b. Intensity attenuation with depth for Activated Caron of 4000μm size for a total depth of 1.5m

Activated carbon is a good low cost substitute for many commonly used nano-fluid dispersions for good solar absorptivity. Its inherent advantage is that, even at large scale, it tends to have higher efficiency than most of the other dispersion candidates in use. The other advantage comes from the fact that, the material doesn't need to be grinded or pulverized to extremely small scales. It can be used as is from the commercially available scale with no or very simple grinding to a few hundred micrometers.

References

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Acknowledgements

This work is partially supported by UC Solar. The authors also acknowledge the constructive help of Dr. Michael F. Modest.

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