Using nanofluids to enhance the operation of solar energy systems

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ABSTRACT

Nanofluids have garnered a lot of attention for their potential to modify thermal properties, particularly the thermal conductivity. While these modifications have been heavily investigated within the heat transfer and materials community, nanofluids additionally offer the potential for major modification to the radiative properties of the host fluid. Of particular interest here is how the modification of the radiative properties of fluids through nanoparticle dispersions can lead to enhanced energy conversion in systems dependent on radiative transport. By adjusting the size, shape, material, volume fraction and particle structure drastic modification can be achieved leading to enhanced efficiency within systems such as solar collectors, and night sky radiators. A summary review of the mechanisms that lead to enhanced efficiency are presented as well as new topics such as dynamic radiative property control with core-shell multifunctional nanoparticles.

Keywords: nanoparticles, energy, core-shell, radiative properties

1 INTRODUCTION

Nanofluids have garnered considerable interest in the heat transfer and materials community due their relatively straightforward creation and modification to thermal conductivity [1-2], mass transport [3], and radiative properties [4]. Because of the variety of modifications offered by dispersing nanoparticles into a host fluid proposed applications have varied widely from biomedical to electronics cooling [5] to energy harvesting [6-8]. A large portion of this research as applied to energy systems has focused on the potential improvements to thermal conductivity leading to enhanced heat transport and efficiency. While these improvements are significant a different approach can be taken that utilizes the modification of the fluid radiative properties due to nanoparticle dispersion. The radiative properties of small particles are of interest within a variety of fields ranging from interstellar optics to heat transfer within combustion chambers to solar thermal collectors due to their ability to absorb and scatter large amounts of radiation. Of relevance here is the use of nanofluids applied to solar energy collection systems.

Conventional solar thermal collectors typically harvest solar energy through the absorption of solar irradiance on a black metallic surface. These surfaces then exchange heat with the working fluid through convection with the overall goal of maximizing transfer to the working fluid and minimizing convective and radiative losses to ambient. While nanofluids could be potentially used in such a system purely for their enhancement to thermal conductivity the discussion here will focus primarily on the enhancement created by radiative property modification. Previous work [9-11] has noted the potential for radiative property enhancement through particle dispersion but these early systems were limited to micron size particles that were limited by particle settling and issues with pumping which are significantly mitigated by using nanoparticles. In addition to modifying the radiative properties for use in devices for solar energy harvesting, recent work [12] has also demonstrated the potential for using nanoparticles in radiative cooling schemes. A variety of mechanisms lead to benefits within energy devices and will be outlined below.

2 METALLIC NANOPARTICLES FOR SOLAR ENERGY CONVERSION

Due to limited resources and the desire to reduce greenhouse gas emissions the desire to enhance the efficiency of solar energy conversion has become increasingly important. One approach that looks to enhance the effciciency of solar thermal collectors is the so-called direct absorption, or volumectric, receiver. In solar thermal collectors the use of particle suspensions acting as a direct absorber [4, 7-12] is one such way to utilize the large levels of absorption and scattering created by small particles interacting with the solar irradiance. These direct absorption receivers serve as an alternative to conventional solar thermal collectors in which the sunlight is absorbed onto a surface which heats up, in turn transferring this heat through the back of the absorber to a flowing working fluid. This direct absorption, or volumetric, approach to energy harvesting can be shown to have several distinct advantages over conventional surface-based approaches when created with conventional metallic nanoparticles. The advantages experimentally observed and theoretically modeled from the use of volumetric absorption systems using metallic nanoparticles can be summarized in the following list:

1. Lower thermal resistance [8]: As noted in Taylor et al. the overall thermal resistance of direct absorption solar absorber has a lower thermal resistance due to eliminating the

resistance from convection from the hot absorbing surface to the working fluid.

2. Inherently selective absorption [13]: In the Rayleigh regime the absorption efficiency of a single nanoparticle decreases linearly with increasing wavelength.
3. Tunable absorption peaks [14-15]: By utilizing metallic nanoparticles, with sizes below the mean free path of the material the wavelength for peak absorption efficiency can be modified.
4. Reduced material demands [8, 16]: Through direct absorption the need for an absorbing surface is eliminated. Additionally very small volume fractions are necessary to create opaque fluids, see Figure 1.
5. Controllable temperature profile [17]: One of the more subtle benefits provided by volumetric absorption is the proposed control of the temperature profile within the fluid. By varying the volume fraction within the depth of the fluid and therefore the absorption within the depth the location of the highest temperatures can be shifted away from the lossy surfaces exposed to ambient temperatures.

While other potential benefits may be exhibited by a volumetric absorber these 5 benefits represent the largest contribution to the enhancements that have been observed in a variety of direct absorption solar thermal systems [7, 8, 15].

Figure 1: Silver nanoparticles dispersed in water and SDS surfactant solution

Not only can the drastic impacts on the radiative properties be utilized for absorption of energy, this impact can also be applied to systems where the emission is important. One such application is for night-sky radiators where the use of nanoparticles has been shown to enhance the radiative transfer to the night sky [12, 18]. Just like direct absorption receivers a volumetric emission based system has the benefits of increased emission over a similar surface, and reduced thermal resistance. Both of these applications reveal a strong functional dependence on the volume fraction of the dispersion.

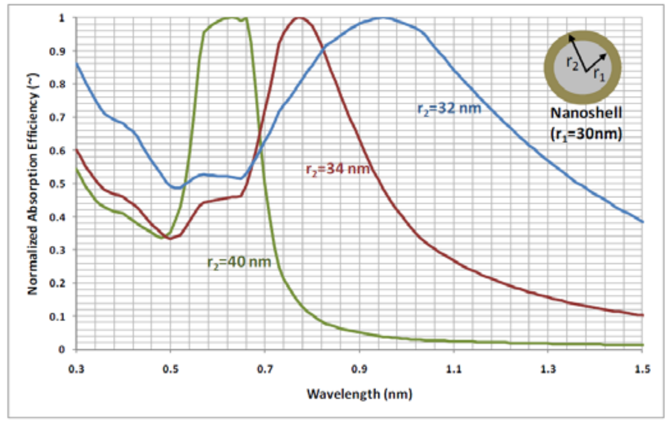

Figure 2: Peak absorption wavelength shift and spectral broadening achieved with silica-gold core-shell nanoparticles.

Effectively designing a system that's major thermal transport process is radiation requires careful consideration of the spectral properties of the system. In solar energy systems this is governed by the spectral properties of the sunlight while for night-sky radiation systems it's highly dependent on the temperature of the system as well as on minimizing absorbed downwelling radiation. For nanofluids the spectral properties can be affected in a few different ways. Two of the simplest methods are through careful choice of the particle material and particle shape [14-15] which directly impact the spectral response through the resonances of the material and interaction with the electromagnetic field respectively. Furthermore with the use of metallic particles with sizes that are smaller than the mean free path of the particular material the particles will exhibit spectral properties differing from the bulk material [7]. Asides from changes in the material one of the most promising methods for changing the spectral properties of a dispersion is through the use of core-shell nanoparticles, which combines different core and shell materials of differing sizes [14, 19-21].

3 CORE-SHELL NANOPARTICLES FOR SOLAR ENERGY CONVERSION

Core-shell nanoparticles are a very interesting nanostructure due to the relative ease of creation and most importantly for the ability to control the surface plasmon response of the core-shell nanoparticle by manipulating the size of the core and metallic shell [19-21]. Cole and Halas, in addition to the authors here, are one of the few investigators to propose the use of core-shell nanoparticle mixtures for solar energy harvesting. The key advantage gained by utilizing a nanofluid based of core-shell nanoparticles is the ability to "tune" the peak wavelength for energy absorption. In the small particle limit the extinction and scattering cross section of the core-shell nanoparticle can be calculated using the following relationship [20]:

$$\sigma_{sca} = \frac{8\pi^2 r_2^{\,3} \varepsilon_3^{1/2}}{\lambda} \mathrm{Im}\left[\frac{\varepsilon_2\varepsilon_a - \varepsilon_3\varepsilon_b}{\varepsilon_2\varepsilon_a + 2\varepsilon_3\varepsilon_b}\right] \quad (1)$$

$$\sigma_{abs} = \frac{128\pi^5 r_2^{\,6} \varepsilon_3^2}{3\lambda^4} \left|\frac{\varepsilon_2\varepsilon_a - \varepsilon_3\varepsilon_b}{\varepsilon_2\varepsilon_a + 2\varepsilon_3\varepsilon_b}\right|^2 \quad (2)$$

where:

$$\varepsilon_a = \varepsilon_1(3-2P) + 2\varepsilon_2 P \quad (3)$$

$$\varepsilon_b = \varepsilon_1 P + \varepsilon_2(3-P) \quad (4)$$

$$P = 1 - (r_1 / r_2)^3 \quad (5)$$

where r_1 is the core radius, r_2 the total radius, ε is the dielectric constant of the material with the subscripts *1*, *2*, and *3* are inner(core), metal(shell), and surrounding matrix respectively. Preliminary results for the design of fluid filters using core-shell nanoparticles indicate the strong control of the optical properties. One of the most important results is that by reducing the ratio of r_2 to r_1 the absorption peak created by the core-shell nanoparticle is shifted to longer wavelengths presented in Fig. 2. Figure 2 also demonstrates the impact of the electron scattering interface on the impact of the core-shell nanoparticle properties broadening the absorption band, demonstrating the importance of including the size-dependent effects of the material. Averritt et al., 1999 provides a mean to determine the location of the absorption peak based on the ratio of the size of the shell to the core.

While these effects are important from a static perspective of tuning your fluid for a single use the authors recognize an enormous potential for dynamic tuning of the radiative properties of nanofluids. Utilizing core-shell multifunctional nanoparticle based nanofluids opens up a new realm of dynamically controllable radiative properties for nanofluids. Figure 3 outlines the potential radiative property changes that can be achieved through relatively modest changes in particle geometry by capturing the shift in the wavelength where the peak absorption efficiency occurs.

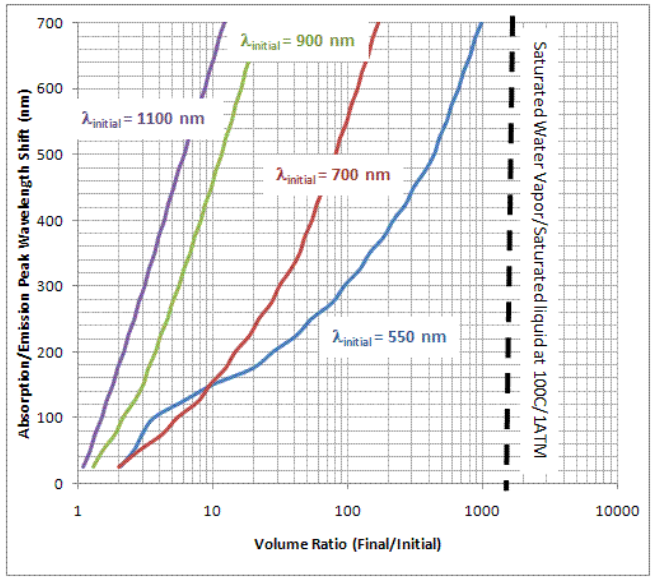

Figure 3: Core-Shell Nanoparticle Size Dependent Effects..

While designing particles capable of these dynamic shifts is challenging and interesting on it's own it is also important to consider the potential applications of such a system. On system that can be envisioned is a dual use solar thermal collector – night sky radiative cooler. A challenge with solar thermal collectors is the roof footprint that they consume, such a system could lead to an efficient daytime solar collector platform which at night transforms to a radiative cooler just by a simple change in the temperature of the bulk fluid.

4 CONCLUSIONS

The use of nanofluids in solar thermal collectors, and other energy systems depending on radiative transport, is an attractive concept for a variety of reasons afforded by the unique properties of nanoparticles. While the vast majority of the focus on nanofluids is in the realm of thermal conductivity the radiative properties of nanofluids are quite interesting and appealing for energy collection systems. Additionally by utilizing core-shell nanoparticles new levels of tuning of the radiative properties are created leading to the development of specialized fluid systems. Furthermore the unique size effects of core-shell nanoparticles can be used to create nanofluids with dynamic radiative properties through changes in the nanoparticle structure.

5 ACKNOWLEDGEMENTS

TO, PEP, LD and RS gratefully acknowledge the support of the National Science Foundation, through Grant No. CBET-1066705. PEP and RAT gratefully acknowledge the support of the National Science Foundation, through Grant No. CBET-0932720.

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