OPTIMIZATION OF OPTICAL NOZLLE OF NANOFLUIDS FOR PHOTOVOLTAIC AND THERMAL SYSTEMS

Iskandarov A.A. (Republic of Uzbekistan)
Email: Iskandarov327@scientifictext.ru

Iskandarov Asilbek Akrom ugli – Bachelor,
DEPARTMENT OF THERMAL ENGINEERING,
TASHKENT STATE TECHNICAL UNIVERSITY NAMED AFTER ISLAM KARIMOV,
TASHKENT, REPUBLIC OF UZBEKISTAN

Abstract: *optical filters are essential in a wide range of applications, including optical communications, electronics, lighting, optical sensors and photography. This article presents recent work which indicates that optical filters can be created from specialized nanoparticle suspensions. The nanofluid filters described in this work compare favorably with conventional optical filters for five photovoltaic (PV) cell alternatives: InGaP, CdTe, InGaAs, Si, and Ge. This study demonstrates that nanofluids make efficient, compact and potentially low-cost, spectrally selective optical filters.*
Keywords: *hybrid; nanofluid; optical filter; photovoltaic; solar energy; solar thermal.*

ОПТИМИЗАЦИЯ ОПТИЧЕСКОЙ ДЛИНЫ НАНОЖИДКОСТЕЙ ДЛЯ ФОТОЭЛЕКТРИЧЕСКИХ И ТЕПЛОВЫХ СИСТЕМ

Искандаров А.А. (Республика Узбекистан)

Искандаров Асилбек Акром угли – бакалавр,
кафедра теплотехники,
Ташкентский государственный технический университет им. Ислама Каримова,
г. Ташкент, Республика Узбекистан

Аннотация: *оптические фильтры необходимы в широком спектре применений, в том числе в оптической связи, электронике, освещении, оптических датчиках и фотографии. В этой статье представлена недавняя работа, которая показывает, что оптические фильтры могут быть созданы из специализированных суспензий наночастиц. Нанофлюидные фильтры, описанные в этой работе, выгодно отличаются от обычных оптических фильтров для пяти вариантов фотоэлектрических (PV) элементов: InGaP, CdTe, InGaAs, Si и Ge. Это исследование демонстрирует, что наножидкости делают эффективные, компактные и потенциально недорогие спектрально-селективные оптические фильтры.*
Ключевые слова: *гибрид; наножидкость; оптический фильтр; фотоэлектрические; солнечная энергия; солнечное тепловое оборудование.*

Optical filters are traditionally made of thin films or solid materials. These filters have been designed for a myriad of applications including optical communications, optical sensors, electronics, lighting, photography and energy harvesting. With recent advances in nanofabrication and thin film manufacturing techniques, optical filters have seen a step-change in the number of available production methods and materials. Techniques which provide control on the nanoscale have been successfully deployed to achieve finely tuned spectral properties of thin films [1]. However, fluid-based filters remain relatively underdeveloped.

Hybrid photovoltaic/thermal (PV/T) solar collectors can theoretically be designed to operate at near 80% in combined efficiency. This represents almost double the efficiency of the best photovoltaic (PV) only systems, for which the record test efficiency for PV cells in 2012 was 43.5% $\pm$ 2.6% (multijunction cells). If designed well, PV/T systems can also provide significant financial savings for residential and industrial applications where demands for both electrical and thermal energy are presented. Several PV/T concepts have been proposed. Most commonly PV/T systems put the working fluid directly in contact with the PV system, thereby removing excess heat. This type of design necessitates a compromise between the drop in efficiency with temperature for PV cells and the value of higher output temperatures from the thermal system. While straightforward, an integrated system forces operation temperatures to be moderate, in the range of 30 – 100^{0}C [2]. In concentrating PV/T (or CPV/T) solar systems, irradiance on the receiver is high causing the compromise in performance to be even more pronounced.

This article suggests that nanofluids—nanoparticles suspended in conventional base fluids—provide one possible solution to the challenges discussed above. Several studies have investigated the capacity for nanoparticles and nanofluids to achieve tunable optical properties. Additionally, previous work of the co-authors has shown that nanofluid mixtures can improve the performance of solar thermal systems. Other studies have shown that pure fluids (water and organic liquids) can be applied to solar systems as optical filters.

Modification of bulk properties based on particle characteristics

The next step was to modify the bulk properties based on particle size, addition of dopants, and whether or not the materials were incorporated into a core/shell nanoparticle. The Drude–Lorentz model was the starting point for each of these modifications. The model assumes that electrons are harmonically bound to the nucleus.

Table 1. Design parameters for nanofluid-based filters

Parameter	Minimum	Maximum
Particle size	20 nm diameter	50 nm diameter
Volume fraction (%)	0	0.1
Filter depth (mm)	0.1	100

Size effect modification. When the nanoparticle diameter nears the mean free path of the bulk material, boundary effects can become important. This effect has been demonstrated numerically, and confirmed experimentally for metallic nanoparticles. To account for this, the bulk properties were modified through the damping coefficient in the Drude– Lorentz model. As such, the Drude–Lorentz model can be transformed into the following expression:[3,4]

$$\varepsilon(\omega) = \varepsilon(\omega)_{\text{exp}} + \omega_{\text{P}}^2 \frac{1}{\omega^2 + i\omega\gamma_{\text{bulk}}} - \omega_{\text{P}}^2 \frac{1}{\omega^2 + i\omega\gamma(l_{\text{eff}})} \qquad (1)$$

Where $\varepsilon(\omega)_{\text{exp}}$ is the bulk complex dielectric constant (from handbook data), $\omega_{\text{P}}$is the bulk plasmon frequency, ω is the variable electromagnetic wave frequency and γ_{bulk} is the relaxation frequency of bulk metal. The small particle modification term, $\gamma(l_{\text{eff}})$ is defined as the following [5]:

$$\gamma(l_{\text{eff}}) = \frac{1}{\tau_0} + \frac{AV_{\text{f}}}{D} \qquad (2)$$

In this equation, τ_0 is the bulk metal free electron scattering time, A is a geometric parameter assumed to be 1, V_{f} is the Fermi velocity (where an experimental values on the order of $V_{\text{f}} \approx 10^6$ m/s), and D is the particle diameter which is used as the effective mean free path. For example, copper and silver have mean free paths around 50 nm. Thus, Equations (1) and (2) are used when the particles are less than or equal to the mean free path. When this is the case, the mean free path is assumed to be restricted to the particle diameter.

Addition of dopants. Semiconductor materials are viable for use in a nanofluid band-pass filter since they have complementary optical properties to PV cells. To calculate the optical properties, the effect of added dopants must be included. For high absorption in the selected regions, significant dopant concentrations are necessary. With heavy doping, it is possible to exceed the Mott critical density, n_c. The parameter ranges from ,$\sim 6 \cdot 10^{13}$ cm^{-3} for InSb to $\sim 3 \cdot 10^{18}$ cm^{-3} for Si and were calculated by the following:[6]

$$n_c = \left(\frac{1}{4a_0}\right)^3 \qquad (3)$$

where the Bohr orbit radius is denoted as a_0. Thus, Equations (1) and (2) also apply to semiconductor nanoparticles. In this case, however, the bulk plasmon frequency, ω_{P}, was modified based on the carrier density [7]:

$$\omega_{\text{P}}^2 = \frac{n_e e^2}{m_e \varepsilon_o} \qquad (4)$$

where n_e is the electron density, e is the electronic charge, m_e is the effective electron mass and ε_o is the permittivity of free space. Thus, Equation (4) was used in Equation (1) to determine the optical properties of semiconductor nanoparticles.

Core/shell nanoparticles. Metallic shell/dielectric (silica) core particles were chosen because their plasmon resonance is very pronounced. That is, under specific wavelength, polarization and incident angle conditions, free electrons (plasma) at the surface of the nanoparticle strongly absorb incident photons. Therefore, a narrow band of wavelengths is converted into plasmon waves which spread across the surface. The wavelengths at which this occurs are determined by the particle's size, shape, shell thickness and the bulk optical properties of the materials involved. As was shown in a seminal study by Oldenburg *et al.*, controlling the ratio of the shell radius to the core radius can allow for strong plasmon resonance tuning.

The modeling assumption used for core/shell nanoparticles was the quasi-static approximation. This assumption is valid if particles are much smaller than the wavelength of light and if the incident light does not vary over the particle diameter. Both of these assumptions were applicable to the nanofluids of this study. To find the properties of an individual nanoparticle, the approach of Lv *et al* [4] was used.

Particle mixture selection

Depending on the PV cell, various nanoparticles were selected. Since PV designs can be quite variable, this study optimizes based on an 'ideal' approximations of PV material response curves. For example, the 'ideal' filter for a silicon PV cell was assumed to absorb wavelengths shorter than 0.75 μm and those longer than 1.125 μm.

The base fluid will also absorb light. Water and Therminol VP-1 are effectively transparent for wavelengths shorter than 1.5 μm, but highly absorbing beyond 1.5 μm. To keep the resulting nanofluid suspensions and optimization somewhat straightforward, only two- and threeparticle liquid filters were modeled in this study. In general, any number of particles could be chosen to meet the specifications of the application.

The highest solar weighted efficiency achieved in this study, η, is found to be 76.1% for CdTe using a conventional filter with H_2O. As compared with conventional filters, two- and three-particle nanofluid filters are generally not as good in terms of solar weighted efficiency, η. The exception is the Ge cell where the conventional filter has an η=63.9%, but a nanofluid filter can achieve η=67.1%. The optimized nanofluid filter is thinner (9–20 mm) as compared to pure fluids and conventional filters—shown in Table 2. This indicates a more compact CPV/T design may be possible with nanofluid-based optical filters. Table 2 summarizes the particle volume fractions used to achieve each filter and the associated filter efficiency values calculated from the objective function of Equation (8). It should be pointed out that in these optimized designs, the highest particle volume fraction, f_V, is $<10^{-4}$ (i.e., <0.01% by volume). Importantly, this means that very few particles are needed to create these filters. Overall, these results indicate that nanofluid optical filters can potentially be employed in any number of CPV/T systems.

This study presented innovative designs of nanofluid-based optical filters for PV/T systems. Nanofluid-based filters provide superior solar-weighted efficiency to pure fluids and comparable efficiency to conventional optical filters over the solar wavelengths—ultraviolet to near infrared. In addition, the resulting nanofluid filters are considerably more compact than a pure fluid filter or a conventional filter surrounded by a pure fluid. Another advantage of liquid filters is that they can potentially be controlled—dynamically—with pumps, magnetic/electric fields and temperature changes. The optimization results of this study reveal that, at most, a volume fraction of 0.0011% is required to achieve optimum filters for CPV/T applications. A big advantage of core/shell nanoparticles is that only a small fraction of each particle is metal, while the majority is silica. This results in an inexpensive nanofluid since little metal material is required to create highly absorbing particles. This indicates excellent potential for very low-cost liquid filters with comparable performance to conventional filters.

Table 2. Comparison table of nanofluid optical filters

Design option	Best efficiency pure fluid	Best efficiency conv. filter (w/Fluid)	Particle 1 (f_{V_1})	Particle 2 (f_{V_2})	Particle 3 (f_{V_3})	Best efficiency (*nanofluid filter)
InGaP	61.9% H_2O [192mm]	69.5% GC435+H_2O [200mm]	4nm Au, 30 nm SiO_2 ($2.1\cdot10^{-8}$)	4nm Au, 40 nm SiO_2 ($6.8\cdot10^{-7}$)	None	*65.0% H_2O [20mm]
CdTe	55.6% H_2O [90mm]	76.1% GC495+H_2O [200mm]	4nm Au, 30 nm SiO_2 ($5.0\cdot10^{-7}$)	2nm Au, 40 nm SiO_2 ($2.2\cdot10^{-6}$)	4nm Au, 40 nm SiO_2 ($8.8\cdot10^{-7}$)	*61.1% H_2O [9mm]
InGaAs	55.6% Brayco 888F [81mm]	75.5% GC570+H_2O [200mm]	2nm Au, 40 nm SiO_2 ($8.7\cdot10^{-10}$)	8nm Al, 30 nm SiO_2 ($4.1\cdot10^{-10}$)	30nm pure Ag ($2.1\cdot10^{-6}$)	*63.6% H_2O [52mm]
Si	49.5% Valvoline [19mm]	65% RG715+VP-1 [200mm]	2nm Au, 50 nm SiO_2 ($7.3\cdot10^{-7}$)	30nm pure Ag ($2.5\cdot10^{-5}$)	None	*55% VP-1 [18.5mm]
Ge	0% VP-1 [1mm]	63.9% RG1000+VP-1 [1mm]	4nm Au, 40 nm SiO_2 ($1.1\cdot10^{-5}$)	8nm Ag, 40 nm SiO_2 ($4.7\cdot10^{-5}$)	8nm Al, 30 nm SiO_2 ($7.6\cdot10^{-6}$)	*67.1% VP-1 [0.5mm]

The efficiencies (denoted by a % sign) in the table are calculated from Equation (8). Values in brackets represent filter thickness while values in parenthesis represent particle volume fraction. *H_2O and Therminol VP-1 were chosen as the base fluids for all nanofluid and conventional filters.

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