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A novel liquid optical filter based on magnetic electrolyte nanofluids for hybrid photovoltaic/thermal solar collector application

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ABSTRACT

Different from solid optical filters, the nanofluid filters display various optical properties and can also be easily pumped at low cost. However, finding a proper nanofluid meeting the standard of practical application is a great challenge. In the present study, we propose a novel magnetic electrolyte nanofluid (ENF) for the first time which can be potentially used as liquid optical filters for hybrid photovoltaic/thermal (PV/T) application. By dispersing optimized amount of magnetic iron oxide (Fe_3O_4) nanoparticles in 50% water/50% EG solutions containing methylene blue (MB) or copper sulfate (CS), we obtained two stable ENF filters satisfactorily meeting the optical absorption of two typical PV cells, Si and InGaP, respectively. Due to its magnetism, ENF can be considered as a smart liquid optical filter controllable by external magnetic field. The root-mean-square errors (RMSE) of the absorptance between the ENF filters and the corresponding ideal filters are both smaller than that of water-based nanofluid filters containing typical core/shell nanoparticles while their thickness is much smaller. The stability, particle size distribution and thermal conductivity of the optimized ENF filters were investigated. It was found that both ENF filters have good stability and higher thermal conductivities than their base fluids. Performance of ENF filters in PV/T system was evaluated based on a reported theoretical model. The results showed that the values of merit function (MF) for the two types of ENF based PV/T systems are both higher than that of typical core/shell nanoparticle nanofluid filters. Overall, our study demonstrates that ENF represents an efficient, low-cost and smart liquid optical filter for the application in PV/T system.

1. Introduction

Solar energy is one of the most promising renewable resources for future energy consumption due to the high availability and the low atmospheric emissions (Akorede et al., 2010; Sims, 2004). To be competitive with conventional systems, it is required that solar energy devices/systems have high efficiency at low costs (Concepts, 2008). Common PV modules convert 4–17% of the incident solar irradiation into electrical energy, depending on the type of solar cells and the working conditions. In other words, more than 50% of the incoming solar energy is converted to heat, not electricity (Kandilli, 2013). One proposed approach is to combine a photovoltaic (PV) cell with a solar thermal collector, often referred to as hybrid photovoltaic/thermal (PV/T) system. PV/T systems are designed to produce electrical and thermal energy simultaneously which can enhance the overall solar conversion efficiency and make economic use of the space.

In common PV/T systems, where the working fluid is directly in contact with the PV module and to remove the excess heat, significant challenges result from the conflict between the drop in efficiency with temperature for PV cells and the value of higher output temperatures from the thermal system. It is therefore desirable to have the thermal and PV components of the PV/T system working completely separately (Otanicar et al., 2013). This leads to PV/T system designs with optical filters (Chendo et al., 1987; Otanicar et al., 2011; Sabry et al., 2002) or beam splitting (Imenes and Mills, 2004; Mojiri et al., 2013) to minimize the unwanted solar flux on the PV cell. The theory and application of this method have been reviewed by Imenes and Mills (2004) and Mojiri et al. (2013). In this design, a spectral beam splitter is used to separate sunlight into different wavelength bands. Each band can then be directed to the most efficient receiver for that spectral range. Chendo et al. (1987) originally proposed the concept of selective absorption by heat transfer liquids for hybrid solar collector. They found that cobalt sulfate or copper nitrate in solution, or some specific organic-based high-temperature oils could be used as liquid filter. Recently, Looser et al. (2014) studied the optical transmittance of various commercial heat transfer fluids. Results

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showed that the optimum fluid for direct-absorption filter is the industrial grade propylene glycol adapted with a chemically-inert red dye. Mojiri et al. (2015) developed a novel spectrally splitting hybrid solar receiver by combining a simple dichroic filter and a liquid channel as a selective absorbing medium. They also introduced a semiconductor doped glass combined with propylene glycol to act simultaneously as the heat transfer fluid and a band pass filter for the optimized light transmittance as required by Si PV cell (Mojiri et al., 2016).

A major challenge of such system is the lack of available liquid with suitable optical properties (Mojiri et al., 2013). However, nanofluid based heat transfer liquids which incorporate nanoparticles to achieve tuneable optical properties have shown potential in addressing this issue (Jing et al., 2015; Mu et al., 2009; Taylor et al., 2011; Taylor et al., 2013a). Taylor et al. (2012) theoretically analyzed the applicability of nanofluid-based optical filters for spectral beam splitting indicating that they have considerable potential for this application. The work by Mu et al. (2009) shows that the water solutions of some nanoparticles, such as SiO_2, TiO_2, ZrC, AlN and TiN, can be chosen as the nanofluid-based spectral splitting filter. Recently, An et al. (2016) verified the application potential of a novel kind of polypyrrole nanofluid in spectral splitting hybrid PV/T system. For the design of nanofluid-based optical filters for PV/T system, the most important consideration is apparently the choice of materials. Up to now, noble metals and core/shell nanoparticles are the two main feasible materials based on analysis of the optical properties of all potential candidates (Taylor et al., 2013b). Core/shell nanoparticles, with dielectric cores and noble metal shells, have even more pronounced plasmon absorption peaks than pure noble metals. Moreover, by controlling the ratio of shell-to-core radius, the resonance peak can be shifted considerably (Halas et al., 2011). Based on this concept, an optimization study on the core/shell nanoparticle based optical filters for PV/T systems has been conducted by Taylor et al. (2012). Studies on the use of nanofluids containing core/shell nanoparticles as optical filters for PV/T systems have been attempted but a few of them are successful (Crisostomo et al., 2017; Hjerrild et al., 2016). This is mainly due to many fabrication difficulties of core/shell nanoparticles, e.g., tight size distribution tolerances and small and uniform nanoshells (Taylor et al., 2013b).

In spite of relatively large number of studies introduced above, research with respect to efficient nanofluid optical filter for practical application is still very limited. Finding a proper nanofluid satisfying the application criterion is therefore a great challenge. Electrolyte nanofluid (ENF) which is colloidal suspensions of nanoparticles in electrolyte solution, is the expansion of the nanofluid concept to investigate the influence of nanoparticles on the mass transfer process (Beiki et al., 2013a,b). Due to the different light-absorbing characteristics of nanoparticles and colored electrolyte solutions, ENF may also have interesting optical properties resulting from the combination of its components. However, to the best of our knowledge, we are the first to investigate the optical properties of ENF.

In this study, we reported a facile design of ENF as optical filters for hybrid PV/T solar collector. Firstly, we selected the suitable component materials from various candidates based on the optical properties of the objective PV cells options. By dispersing Fe_3O_4 nanoparticles in methylene blue (MB) solution and copper sulfate (CS) solution, we were able to prepare two stable ENFs, that is Fe_3O_4/MB and Fe_3O_4/CS, corresponding to Si and InGaP PV cells respectively. In order to effectively match the spectral response of the PV cells, optimization conducted through adjusting the particle volume fraction and electrolyte molar concentration. The various parameters of the optimized ENF filters, i.e., spectral absorptance, components and thickness, were compared with that of water-based nanofluid filters containing typical core/shell nanoparticles. Besides, the stability, particle size distribution and thermal conductivity of the optimized ENF filters were also investigated. With the optimized ENF served as optical filter for PV/T system, a theoretical model was then employed to further investigate the performance of our proposed ENFs in practical application. The obtained results are expected to be helpful for the development of an efficient PV/T system with ENF as working fluid.

2. Materials and methods

2.1. Materials selection

It is known that the photovoltaic conversion can be initiated when the wavelength of incident light, λ, is shorter than λ_g, which corresponds to the band gap of the PV. Unfortunately, PV can only utilize and convert the part of incident energy corresponding to its band gap and additional energy arriving to PV surface will often lead to undesired heat. This will inevitably give rise to a decreased overall energy conversion efficiency. Based on this consideration, our design of the hybrid PV/T solar collector aims to improve the overall conversion efficiency of incident sunlight by harvesting different spectral bands of the solar radiation with different receivers for thermal and PV, respectively (Imenes et al., 2006; Crisostomo et al., 2013), as also shown in Fig. 1. Basically, the desired wavelength band (λ_1–λ_2) for incident light is to achieve an optimized conversion efficiency of solar spectrum reaching the PV surface. The rest of the spectrum is absorbed by the thermal receiver as it can generate heat with relatively wavelength independent conversion efficiency.

Depending on the type of PV cells, suitable materials were selected firstly. Since PV designs can be quite variable, this study was 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 751 nm and those longer than 1126 nm (Taylor et al., 2012). Table 1 shows the assumptions made for the two selected PV cells, Si and InGaP, used in this study.

In order to design optical filters applicable under all temperature conditions especially in winter, 50:50 mixture of water and ethylene glycol (50% water/50% EG) was utilized as the base fluid throughout our study due to its relatively low freezing point (Peyghambarzadeh et al., 2011). In search of ENF with optical properties corresponding to the spectral response of selected PV cell,

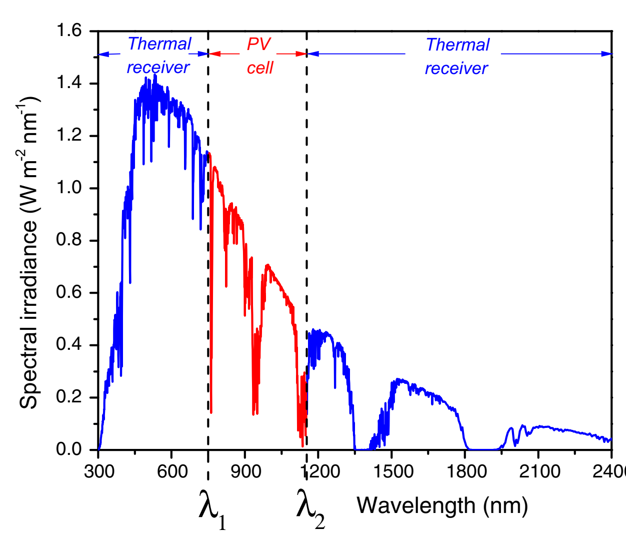

Fig. 1. Schematic of beam splitting for hybrid PV/T solar collector.