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Analysis on the performance of a flat-plate volumetric solar collector using blended plasmonic nanofluid

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Abstract

In this paper, thermal performance of a flat-plate volumetric solar collector using a blended plasmonic nanofluid as its heat transfer fluid was investigated. The blended plasmonic nanofluid used in the experiment was manufactured based on three different aspect ratios of gold nanorods (AuNRs), and it was designed to have broad-band absorption over the visible and near-infrared spectrum. The conversion process of solar radiation to heat in the blended plasmonic nanofluid was verified experimentally by measuring the temperature distribution inside the nanofluid under illumination of a tungsten–halogen lamp and by comparing it with the simulation result. Through the theoretical investigation of a flat-plate volumetric solar collector, effects of channel depth, channel length, mass flow rate, and the magnitude absorption coefficient of the blended plasmonic nanofluid were characterized in order to establish a basic design. The results of this study will facilitate the development of highly efficient solar thermal collectors using plasmonic nanofluids.

Keywords: Volumetric solar collector; Blended plasmonic nanofluid; Gold nanorod; Localized surface plasmon

1. Introduction

Flat-plate solar collectors are the most popular system that converts solar radiation into heat by working fluids (Duffie and Beckman, 1980). It is a surface-based solar collector in which sunlight is first absorbed and converted to the heat by an absorbing plate. Heat generated in this step is then carried by the heat transfer fluid, which is water in most cases. During this process, large amount of heat is lost to the ambient by radiation and convection, and to the other components of the solar collector by conduction due to the imperfect heat transfer between absorbing plate and water. Therefore, minimizing heat loss to the environment is the key to improving the efficiency of a surface-based solar collector. In addition to thermal performance, polymeric materials have recently been employed in the solar collector for lower-weight and cost-effectiveness (Mintsa Do Ango et al., 2013; Chen et al., 2015; Gladen et al., 2015).

Volumetric solar collector converts sunlight into the heat that can be used for providing hot air or water in buildings, and it is a fascinating alternative to the surface-based solar collector (Tyagi et al., 2009). Because temperature of each component in a volumetric solar collector is lower than that of a surfaced-based solar collector as a results of the direct absorption and conversion of sunlight to the heat by black color working fluid (Minardi and Chuang, 1975; Al-Nimr et al., 2011; Missirlis et al., 2014), heat loss to the environment can be greatly reduced in a

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volumetric solar collector. Therefore, enhancing light absorption capability of the heat transfer fluid is crucial for improving the thermal performance of a volumetric solar collector, and nanofluids can be used for such purpose (Taylor et al., 2013) due to recent advancement of nanotechnology.

Nanofluid is a solution containing suspended nanoparticles (Das et al., 2007). Because suspended nanoparticles can interact with light by means of scattering and absorption (Bohren and Huffman, 2008), nanofluids can absorb light more efficiently than conventional fluid. As a matter of fact, advantage of using nanofluid in a volumetric solar collector was demonstrated in many research works. For instance, Tyagi et al. (2009) showed theoretically that Al nanofluid is capable of improving the performance of a flat-plate volumetric solar collector by 10% when compared to the case of using water. Al nanofluid was again tested theoretically by Khullar et al. (2012) for a concentrated volumetric solar collector, showing significant enhancement in thermal efficiency by reducing heat loss. On the other hand, Otanicar et al. (2010) manufactured graphite, carbon nanotube and Ag-nanoparticle based nanofluids in various volume fractions and experimentally showed the performance of volumetric solar collectors using each of the nanofluids. The possibility of other nanofluids based on Al_2O_3, ZnO and MgO (Gupta et al., 2015; Li et al., 2011) nanoparticles were also tested and each showed significantly improved light absorption capability.

Aforementioned research works did not make full use of the localized surface plasmon (LSP). LSP represents the collective oscillation of free electrons occurring at the surface of metallic particles, whose size is smaller than the wavelength of incident electromagnetic wave (Bohren and Huffman, 2008). In other words, LSP is an electric resonance between free electrons and electromagnetic wave, whose excitation condition depends on the material and geometry of the particle (Zayats et al., 2005). When LSP is excited, absorption efficiency of a metallic nanoparticle can be larger than unity, which implies that the particle is able to absorb light incident on the area larger than the particle itself (Bohren and Huffman, 2008). Therefore, with the excitation of LSP, temperature of the metallic nanoparticle and its surrounding medium can rise considerably even at extremely low particle concentration (Taylor et al., 2009).

A more efficient way of utilizing plasmonic nanofluid in collecting solar energy is by blending different types of nanoparticles to achieve broad-band absorption. Because the enhancement of absorption accompanied by LSP unavoidably has narrow bandwidth due to its resonance characteristic (Jain et al., 2006), mixing of different-type/-shape particles is necessary for achieving broad-band absorption and making full use of entire solar radiation from the visible to near-infrared spectrum. The concept of blended plasmonic nanofluid was first proposed by Lee et al. (2012) based on gold nanoshell nanoparticles of different core sizes and shell thicknesses, but fabrication of such gold nanoshells was not successful. Due to difficulty in manufacturing, core–shell type nanoparticle is not appropriate for further application in spite of its advantage in tunability of radiative properties (Hui Yu et al., 2014; Wu et al., 2015). In order to propose more practical solution, research performed by Jeon et al. (2014) replaced gold nanoshell with gold nanorod (AuNR) that is easy to manufacture and possess high adjustability in the geometry (Yu et al., 1997). Moreover, design scheme developed in Jeon et al. (2014) allows one to engineer optical property of a blended plasmonic nanofluid to achieve broad-band absorption with the desired absorption coefficient value.

The major accomplishment of previous works is the feasibility verification of the blended plasmonic nanofluid as a light absorbing and heat generating solution that can possibly enhance the performance of a volumetric solar collector. However, those works lack of investigating on more practical aspects arising when designing a volumetric solar collector, such as on which and how various system parameters affect its performance and its ability to provide sufficient heat used in practice. Therefore, present work aims to provide physical insight on system aspects of a flat-plate volumetric solar collector using blended plasmonic nanofluid as a working fluid. The theoretical model used in the simulation will be verified experimentally by measuring the temperature distribution inside the blended plasmonic nanofluid under illumination of a tungsten–halogen lamp and by comparing it with the simulation result of discrete dipole approximation (Draine and Flatau, 1994). Although performance analysis of a volumetric solar collector has already been done by several researchers previously (Otanicar et al., 2010; Al-Nimr et al., 2011; Lenert and Wang, 2012; Luo et al., 2014; Missirlis et al., 2014; Gorji and Ranjbar, 2015), this work is distinct from them in a way that it makes full use of the significant absorption enhancement and high tunability of LSP and that it clearly demonstrates the advantage of using blended plasmonic nanofluid in a volumetric solar collector.

2. Experiments

2.1. Preparation of the blended plasmonic nanofluid and optical property characterization

The blended plasmonic nanofluid used in the present research was prepared by mixing three AuNR-based plasmonic nanofluids in which different sized AuNRs are suspended in cetyltrimethylammonium bromide (CTAB) solution, whose extinction coefficient is essentially the same as that of water. The average diameter was measured to be 16 nm for all three AuNRs, and the average aspect ratio (i.e., ratio of the length to the diameter) was found to be 1.77, 2.73 and 4.17 for short, mid, and long AuNR, respectively, according to transmission electron microscopy