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Experimental investigation of a silver nanoparticle-based direct absorption solar thermal system

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ABSTRACT

A nanoparticle-based direct absorption system provides a promising alternative to conventional solar collectors. This work investigates experimentally the photothermal conversion characteristics of one of the plasmonic nanoparticles, i.e., silver, under realistic conditions. Stable silver nanofluids are formulated through a high-pressure homogenizer and the experiments are conducted under sunlight on a rooftop with tests running continuously for ~10 h. The results show that silver particles have excellent photothermal conversion capability even under very low concentrations. Up to 144% enhancement in the stored thermal energy can be obtained at the peak temperature for a particle concentration of 6.5 ppm. The photothermal conversion performance shows a transient behavior and is best achieved at the initial radiation period due to the low heat loss and strong surface plasmon resonance effect of silver nanofluids. Nearly constant initial specific absorption rate (SAR), ~0.6 kW/g, is obtained for nanoparticle concentrations up to 6.5 ppm, but it decreases significantly at higher concentrations, which is associated with increased particle–particle interactions.

1. Introduction

Solar thermal systems (STS) are widely used to harness solar energy for thermal energy (heat) applications. Depending on the applications, solar thermal collectors are classified as low-, medium- or high-temperature collectors. The collectors typically have low energy conversion efficiencies. The efficiency is limited not only by how effectively the absorber captures solar energy, but also how effectively the heat is transferred to the working fluid. For most of the solar collectors, the heat transfer process can be divided into three parts (i) radiation from the Sun onto the solar absorber, (ii) conduction from the solar absorber to the tube, and (iii) convection to the running fluids inside the tube. The absorber surfaces are typically black or spectrally selective such that high absorptivity in the solar spectrum is coupled with low emissivity in the infrared. Although surface absorbers are efficient at absorbing solar energy at the surface, they are not well suited for transferring heat into the carrying fluids. The heat transfer process is therefore surface-controlled where the highest temperature is on the absorber surface, and the lowest temperature is in the center of the fluids. The total solar energy that could be converted is limited by the surface area of the collection pipes.

Many methods have been proposed to address the problems associated with conventional solar thermal systems. The concept of direct absorption was originated in the 1970's as a simplification to the STS design and to potentially enhance the efficiency by absorbing solar energy within the fluid volume [2]. Seeding nanoparticles (NPs) that can absorb solar energy directly within the fluid volume is a recent development, i.e., direct absorption solar collector (DASC), which transfers surface controlled heat transfer model into a volumetric phenomenon. The solar energy is absorbed inside the fluid volume directly by radiation to the nanoparticles and to the base fluid. Comparing to conventional-sized particles, nanoparticles offer the additional benefits of increased surface-to-volume ratios and size-dependent radiation properties. Properly designed, it could simplify the conventional thermal systems, improve the photothermal conversion efficiencies, and reduce the sedimentation and wear issues.

The suspensions of nanoparticles in liquids, or termed as 'nanofluids', have been extensively studied for over a decade, and have shown promise to modify a wide range of liquid properties [3,21]. In the past a few years, the radiation properties of a number of nanofluids have been reported experimentally [16,15,18,17,5,11,6]

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and a few theories were proposed for maximizing the photothermal conversion efficiency under optimized particle concentrations [20,14,15]. It should be noted that many of these studies were based on optical properties and characterized by the extinction coefficient [16,17,13,18,14,26,4], which may not represent the bulk temperature increase that decides the photothermal conversion efficiency. Most of the studies were based on laboratory conditions using small volume of nanofluids, i.e., typically of a few milliliters [16,17,11,6]. The scale-up to a practical volume under realistic conditions (i.e., outdoor) only has limited reports [9]. Among these, Otanicar et al. [15] showed that by replacing water with nanofluids, the overall thermal efficiency of a solar collector could be improved by 5%. Sani et al. [17] and Mercatelli et al. [13] investigated the absorption properties of carbon nanohorn-based nanofluids with water and ethylene glycol as the base fluids. Comparing with both the base fluid and the carbon black nanofluids, the measured absorption coefficient showed a remarkable improvement over a wide spectrum range. He et al. [6] reported that under natural sunlight, the maximum bulk temperature can be increased by 25% by using copper nanofluid at 0.1% (in weight). Yousefi et al. [22] showed that the efficiency of a solar collector was increased by 28.3% by using a 0.2% (in weight) Al_2O_3 nanofluid. Liu et al. [12] reported that a solar collector using CuO nanofluid as the working fluid had much better thermal performance than the deionized water. Javadi et al. [8] suggested that the nanoparticle size could affect significantly the photothermal conversion efficiency of any nanofluid.

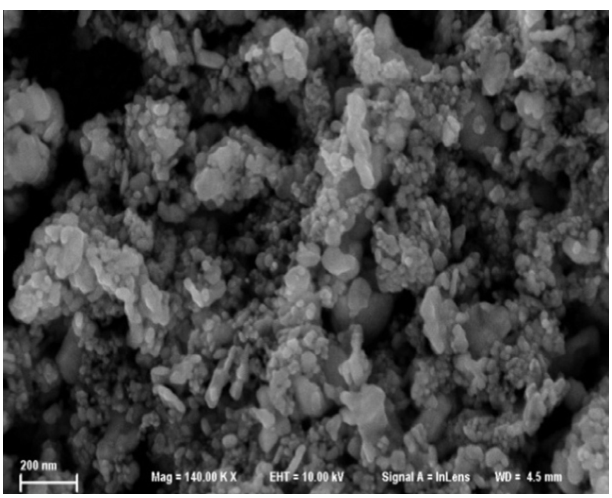

Fig. 1. SEM image of silver nanoparticles.

While many materials including metals, metallic oxides and carbon-based materials have been reported, the use of plasomonic nanoparticles to enhance the photothermal conversion efficiency has only received very limited attention. Surface plasmon resonance (SPR) is the collective oscillation of electrons stimulated by incident light, which is an effective way of converting light to thermal energy. The resonance condition is established when the frequency of light photons matches the natural frequency of surface electrons oscillating against the restoring force of positive nuclei. In addition to modify the bulk fluid's absorptivity, plasmonic particles can effectively convert light into heat. The numerical simulation by Lee et al. [10] showed that gold nanoparticle can enhance the solar collector efficiency by ~70% under a particle concentration of ~0.05% by volume. Experimentally Zhang et al. showed that gold nanoparticles achieved much higher specific absorption rates than other carbon-based nanoparticles [25]. It is well known in the physics that silver nanoparticle has strong surface plasmon resonance at the visible light spectrum [7], the use of silver will be complementary to the base water, which is a good absorber in the infrared region. It would be expected that silver nanoparticle could contribute significantly to the enhancement of solar thermal conversion efficiency.

This work will investigate the potentiality of silver nanoparticles as direct sunlight absorbers for solar thermal applications. The experiments will be conducted under realistic conditions that include (i) direct sunlight heating without focusing, (ii) long experiment duration lasting over 10 h , and (iii) large fluids volume in liters rather than milliliters. The influence of particle concentration on the photothermal conversion efficiency and the specific absorption rate (SAR) will be discussed. Such a work could act as an intermediate stage towards future industrial applications.

2. Experimental approach

2.1. Nanofluid formulation

Silver nanoparticles with primary particle size ~10 nm were bought from Nanostructured & Amorphous Materials, Fig. 1. The particles are in the form of large agglomerations that have to be

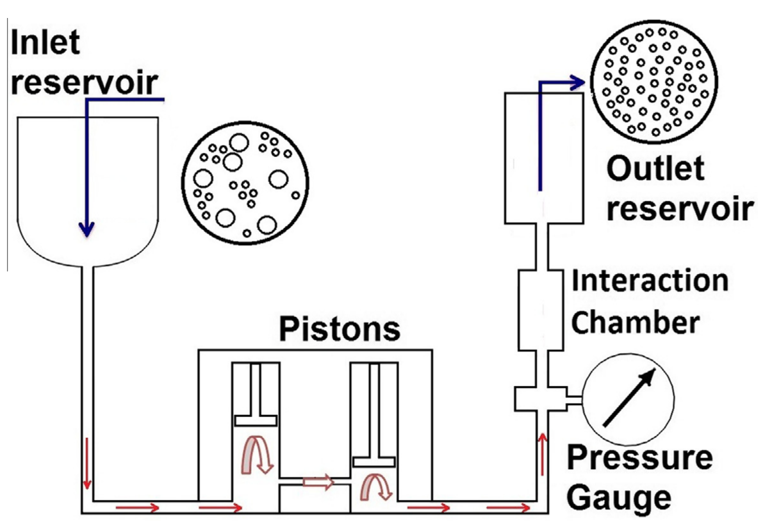

Fig. 2. A schematic view of the homogenizer system.