Energy Conversion and Management 112 (2016) 21–30

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Enhancement of photo-thermal conversion using gold nanofluids with different particle sizes

Meijie Chen [a], Yurong He [a,*], Jiaqi Zhu [b], Dong Rip Kim [c]

[a] School of Energy Science & Engineering, Harbin Institute of Technology, Harbin 150001, China
[b] School of Astronautics, Harbin Institute of Technology, Harbin 150001, China
[c] School of Mechanical Engineering, Hanyang University, Seoul 133-791, South Korea

ARTICLE INFO

Article history:
Received 18 November 2015
Accepted 6 January 2016
Available online 13 January 2016

Keywords:
Gold nanofluids
Plasmonic nanoparticle
Solar energy
Photo-thermal conversion

ABSTRACT

This work describes an experimental study of the particle size dependence of gold nanofluids during photo-thermal conversion in a direct absorption solar collector (DASC). Au nanoparticles (NPs) with different sizes were synthesized using a seed mediated method. Au NPs play a significant role in enhancing the solar light absorption with respect to a pure base fluid at a very low concentration due to the localized surface plasmon resonance effect. Experimental results of the photo-thermal conversion showed that the photo-thermal conversion efficiency of Au nanofluids obtained an average enhancement of 19.9% and 21.3% for a cube shaped DASC and a flat shaped DASC, respectively, compared with H_2O at a relatively low mass fraction (∼0.000008% weight). Reducing the Au NP size led to the enhancement of the photo-thermal conversion efficiency under the present experimental conditions, which could be an effective way for the modification of optical properties and thermodynamic characteristics. However, the size of Au NPs did not significantly influence the efficiency for the cube shaped DASC. The cube shaped DASC model usually had the higher efficiency than the flat DASC model using the same working fluids since the heat loss percentage of the cube shaped DASC was lower.

1. Introduction

Fluids such as H_2O or oil are commonly used as energy carriers in solar collectors and heat exchangers due to their continuous flow and stability [1,2]. Many efforts have been devoted to find new types of fluids or solar collector models with improved thermal properties [3]. A nanofluid is a suspension of nano-sized particles (1–100 nm) in a conventional base fluid, which was first used by Choi in 1995 [4]. The characteristics of nanofluids such as, thermal conductivity [5], viscosity and interfacial properties [6] have been studied extensively in the last two decades. Xie et al. studied the thermal conductivities of various suspensions containing Al_2O_3 nanoparticles (NPs) using a transient hot-wire method. They had substantially higher thermal conductivity than the base fluid with the enhancement increase with an enlarged volume fraction of Al_2O_3 [7]. Researchers have found that nanofluids could be used to enhance a wide range of fluid properties [8], which made them suitable as a working medium for solar collectors [9,10], solar stills [11], photovoltaic thermal unit systems [12] and refrigerators [13]. The application of nanofluids was a new challenge in thermal science provided by nanotechnology [14]. Due to the large specific surface area and other physical properties, a comprehensive analysis of radiative heat transfer of nanofluids at high temperatures was inherently complex. Recently the number of studies on optical and radiative properties of nanofluids has been increasing. Results indicated that the radiative properties of nanofluids could be very different from those of the base fluids, suggesting that these properties could be tailored to satisfy specific applications. They also suggested that multiple and dependent scattering effects could be very dominant in nanofluids [15]. These properties made it possible for nanofluids to be the next generation of working medium for solar energy utilization.

Currently, flat-plate collectors, vacuum tube collectors and focusing collectors are commonly used as solar collectors [16,17]. Collector efficiency of vacuum tube collectors is usually higher than other types since the vacuum layer can reduce heat losses. These types of solar collectors absorbed solar energy by an efficient selective absorbing surface. High temperature can come out at the absorbing surface, increasing radiation heat losses, and the periodic high temperature can make the absorbing surface corrode seriously. In order to overcome these disadvantages of surface absorption collectors, Minardi and Chuang [18] studied the direct absorption solar collector (DASC) using working fluids as the

* Corresponding author. Tel.: +86 451 86413233.
E-mail address: rong@hit.edu.cn (Y. He).

http://dx.doi.org/10.1016/j.enconman.2016.01.009
0196-8904/

Nomenclature

A	area, m^2
c_p	specific heat, J/(kg K)
D	uniformity coefficient, °C
G	the input solar flux, W/m^2
h	heat transfer coefficient, $W/(m^2\ °C)$
m	mass, kg
q_r	radiative heat flux, W/m^2
Q	energy, J
t	time, s
T	temperature, K
y	vertical coordinate
Greek symbols	
η	photo-thermal efficiency
λ	thermal conductivity, W/(m °C)
ρ	density, kg/m^3
ζ	collector efficiency
Δ	difference
Subscripts	
amb	ambient environment
in	input
loss	heat loss
max	maximum
min	minimum
nf	nanofluid
top	top surface
Abbreviations	
AA	ascorbic acid
CTAC	Hexadecyltrimethylammonium chloride
DASC	direct absorption solar collector
NP	nanoparticle

absorbing medium. The concept of nanofluid based DASCs has recently been shown numerically and experimentally as an efficient method for harvesting and converting solar energy. The exact temperature profiles depend on the working medium characteristics in the collectors. For the same mean fluid temperature and solar heat flux, the temperature profiles in the DASC can be favorable because the temperature associated with heat loss is lower than the mean fluid temperature. This behavior is referred as "thermal trapping", which is physically similar to the "green house" effect [19]. Unfavorable temperature profile in the selective surface collector will lead to emissive losses. What is more, it can reduce the heat transfer resistance between absorbing surfaces and working fluids, and decrease heat losses during heat transfer processes. Therefore, the DASC such as a volumetric collector, despite being non-selective, can trap thermal energy more effectively, resulting in a higher collector efficiency.

The DASC was modeled numerically using a two-dimensional heat transfer analysis method [20]. It was observed that the presence of NPs increased the absorption of incident radiation by more than nine times than pure H_2O. Otanicar et al. [21] experimentally studied solar collectors based on nanofluids made from a variety of NPs (carbon nanotubes, graphite, and silver), demonstrating efficiency improvements up to 5% in solar thermal collectors by utilizing nanofluids in the absorption mechanism. The photo-thermal efficiency of a 0.01% graphite nanofluid was 122.7% of that of a coating absorbing collector, indicating that nanofluids, even with low-content had good absorption of solar radiation, thereby improving the system efficiencies [22].

In recent years, localized surface plasmon resonance (LSPR) in noble metal nanostructures has been applied to the field of optical property regulation [23] and has attracted the interest of many researchers [24]. It strongly enhanced the electric field intensity, scattering and absorption at the LSPR frequency, which lied in the visible region for Au, Ag and Cu. Eustis and Rycenga et al. [25,26] studied the differences among them. Results showed Au nanostructures were more attractive for optical applications since Cu was easily oxidized and Ag was unstable. Controlling the size, the shape, and the structure of metal NPs was technologically important because of the strong correlation between these parameters and optical, electrical, and catalytic properties. Thus, researchers have put much effort on the well-controlled synthesis of Au nanostructures. Silver cubes served as sacrificial templates to generate single-crystalline nanoboxes of gold in Xia's group [27]. The seed-mediated method was an effective way to control the NP's sizes and shapes. Gold nanorods were prepared via a seed-mediated sequential growth process involving the use of citrate stabilized seed crystals and their subsequent growth in a series of reaction solutions [28]. Monodisperse citrate-stabilized gold NPs with a uniform quasi-spherical shape of up to 200 nm and a narrow size distribution were synthesized following a kinetically controlled seeded growth strategy via the reduction of $HAuCl_4$ by sodium citrate [29]. Cole and Halas theoretically applied a straightforward optimization model to demonstrate the potential for the nano-engineering of light harvesting for solar energy applications using plasmonic NPs [30]. Xuan and co-workers [31,32] simulated the absorption properties of random Al/CdS and TiO_2/Ag nanoshell systems using the Finite Difference Time Domain (FDTD) method. Experimental results indicated that a TiO_2/Ag plasmonic nanofluid with good photo-thermal properties had potential applications in volumetric solar thermal receivers. Solar utilization based on plasmonic NPs could achieve great photo-thermal conversion performance at a low concentration [33,34], reducing NPs sedimentation and erosion–corrosion of pipelines.

An ideal working medium needs to be synthesized to fit the distribution of the solar spectral intensity for the application of plasmonic NPs in solar harvesting. There are many models theoretically analyzing the optical properties of nanofluids. The NPs material, size, shape and the dispersion medium affect the absorption of nanofluids. In this work, photo-thermal conversion characteristics of plasmonic Au nanofluids for the DASC were investigated. Firstly, Au NPs with different sizes were synthesized by a seed mediated method. Then, the optical properties of Au nanofluids were discussed. Finally, photo-thermal conversion experiments were conducted for both a flat shaped DASC model and a cube shaped DASC model, and the comparative photo-thermal characterization of nanofluids with different Au NPs sizes was presented.

2. Experiment section

2.1. Gold NPs synthesis and characterization

2.1.1. Reagents

Gold chloride hydrate ($HAuCl_4{\cdot}3H_2O$, Au $\geqslant$ 48%), sodium borohydride ($NaBH_4$, 99%), Hexadecyltrimethylammonium chloride (CTAC, 97%), sodium bromide (NaBr, 99%), ascorbic acid (AA, 99%) were supplied by Aladdin (http://www.aladdin-e.com/) and used as received. Deionized and redistilled H_2O was used in the experiments.