Sustainable Energy Technologies and Assessments xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Sustainable Energy Technologies and Assessments

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

Original article

Solar energy harvesting by cobalt oxide nanoparticles, a nanofluid absorption based system

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ARTICLE INFO

Article history:
Received 26 October 2016
Revised 26 January 2017
Accepted 26 January 2017
Available online xxxx

Keywords:
Nanofluid
Nanoparticles
Solar energy
Heat transfer
Surface absorption
Direct absorption
Optical properties

ABSTRACT

The improvement in the conversion of solar energy to thermal energy has been taking place over the last several years due to the growing demand of efficient solar powered systems. In recent times, nanofluid has emerged as an efficient heat transfer fluid due to its inherent capability to increase the solar-thermal performance. The present study comprises of a detailed experimental work to compare the effectiveness of two different types of system, viz. surface absorption system and nanofluid absorption system. The effectiveness of these systems have been evaluated based on the ability to raise the average temperature of the working fluid above the ambient temperature. The comparative study revealed an optimum range of cobalt oxide nanoparticle's mass fraction (i.e. 40 mg/l), which leads to a rise in average temperature of about 23.3 °C while using nanofluid absorption system. This value is almost 9.3 °C higher as compared to the surface absorption system under similar conditions which give a corresponding rise of about 14 °C. The study pointed out that the direct absorption of solar energy by the nanofluid is an important factor for overall increase in temperature (and consequently will lead to higher collector efficiencies). The work also highlights the use of cobalt oxide (Co_3O_4) based nanofluid for enhanced heat transfer events.

Introduction

Solar energy is a large, clean and freely available source of energy. As per current environmental scenario [1], it is recommended to use solar energy over fossil fuels [2]. Presently, solar energy can be harness by two main methods (a) solar photovoltaic and (b) solar thermal [3]. The solar photovoltaic device works by directly converting the solar energy to the electrical energy [4]. However to run a power generation cycle from solar energy, solar thermal collectors are used [5,6]. These solar thermal collectors typically comprise of a receiver, heat transfer fluid, and power generation cycle, where receiver is considered as the main component in which the solar energy is converted into thermal gain of the working fluid [7].

Most commercially available solar thermal collectors consist of receivers that are constructed from a metallic absorber plate (usually employing selective coatings), which absorb the irradiation, convert that into thermal energy and transfer that energy to the working fluid either by conduction or convection heat transfer mechanism [8] (such systems are referred as surface absorption system and are abbreviated as 'SAS' in this paper). The performance of the solar thermal collector and the overall system is directly dependent on the temperature rise of the fluid in the receiver, because of which the solar thermal collectors are targeted to operate at high temperature. To achieve high temperature, the solar radiation are usually highly concentrated (using line or point concentration geometry), and that leads to the overheating of the material. Such cyclic variations of high temperatures may eventually damage the material. However, the efficiency of the solar collector does not depend on the absorption efficiency only, but also on how the thermal and re-radiating losses to the surroundings can be minimized [9]. When the temperature of the fluid in the receiver increases, it starts re-radiating to the environment and these radiative losses are proportional to the fourth power of the temperature [10]. Therefore, the efficiency of solar thermal collector can be improved by reducing these radiative emission losses. One of the ways to achieve this is to allow the solar radiation to be directly absorbed by heat transfer fluid.

In recent time, the researchers have explored such type of solar collectors in which the solar irradiation has been directly absorbed by the heat transfer fluid not by any absorbing surface. It is observed that most of the heat transfer fluids (distilled water, ethylene glycol, silicone oil, Therminol VP-1, molten salts etc.) are transparent with the spectral range of 0.2–1.5 μm, so these fluids are not good absorber of solar irradiation by themselves [12]. Some dopant (nanoparticles) need to be added in these fluids, which can

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http://dx.doi.org/10.1016/j.seta.2017.01.011
2213-1388/

Nomenclature

D	diameter
f_v	mass fraction
H	height
I	flux
I_o	incident flux
K	optical coefficient
m	complex refractive index, $m = n + i\kappa$
T	temperature
y	thickness of fluid layer

Greek Symbols

α	absorptivity
β	size parameter
ε	emissivity
n	index of refraction
κ	index of absorption

Subscripts

a	absorption
e	extinction
s	scattering
λ	spectral

Abbreviations:

Co_3O_4	cobalt oxide
CMC	critical micelle concentration
DAQ	data Acquisition
NAS	nanofluid absorption system
NCPCS	nanofluid based concentrating parabolic solar collector
SAS	surface Absorption System
Stag	stagnation
SWF	short wave filter

absorb the irradiation and in turn transfer the heat to the fluid (such systems are referred as nanofluid absorption system and are abbreviated as 'NAS' in this paper) [13–19]. These types of solar thermal collectors have many advantages over the SAS, like (a) low surface temperature (i.e. low radiative and convective losses) (b) prevention of thermal stress (c) decreased problem of hot spot caused by high heat flux concentration (d) low weight and (e) cost [11]. The nanoparticles have very high heat transfer coefficient in the order of 10^8 (Wm^{-2} K) so they are very efficient to transfer the heat to the fluid in immediate contact [20,21]. The optical properties of the nanoparticles are dependent on shape, size, constituent material and the surrounding dielectric medium. So for solar thermal energy applications, the nanoparticles can be optically tuned accordingly [22].

During recent years, various kinds of nanoparticles have been used by the researchers to harness the solar energy. For instance, Tyagi et al. [23] carried out numerical study with aluminium/water nanofluid for low temperature direct absorption solar collector and concluded that the absorption of irradiation has increased by nine times over pure water. Moreover, under similar working conditions, the direct absorption solar collector has 10% higher efficiency than conventional flat plate solar collector.

Otanicar et al. [24] carried out numerical and experimental study with various types of nanoparticles (carbon nanotubes, graphite, and silver) on flat plate collector and suggested that there has 5% improvement in the efficiency of the solar collector by using nanoparticles. Taylor et al. [25] suggested through the numerical and experimental study on the parabolic dish collector with graphite/Therminol VP-1 nanofluid that 10% enhancement in efficiency can be achieved relative to surface absorption based receivers when the concentration ratios are in the range of 100–1000. Further graphite nanofluid with volume fraction on the order of 0.001% are suitable for 10–100 MWe power plants. Lee et al. [26] carried out numerical study with the Gold-nanoshell nanoparticles on flat plate collector and concluded that the use of blended nanofluid can increase the solar collector efficiency with an very low particle concentration (e.g. approximately 70% for 0.05% particle volume fraction) Lenert and Wang [27] prototyped a nanofluid based cylindrical receiver which has been optimized with carbon coated nanoparticles suspended in Therminol VP-1. They suggested that the receiver efficiency is directly proportional to nanofluid height and incident solar flux. Khullar et al. [28] performed numerical analysis of nanofluid based concentrating parabolic solar collector (NCPSC) with Aluminium/Therminol VP-1, and suggested that by maintaining same external conditions the NCPCS has about 5–10% higher efficiency as compared to the conventional parabolic solar collector. He et al. [29] performed experiments with Cu/H_2O nanofluid and they observed that with Cu/H_2O nanofluid (0.1 wt%) the temperature can be increased up to 23.5% as compared with deionized water. Khullar et al. [30] experimentally compare the performance of amorphous carbon nanoparticles and multi-walled carbon nanotubes suspended in ethylene glycol with the commercially available selective coating in cylindrical container. They suggested that the performance of the nanofluid based system is sensitive to the amount of the nanoparticles dispersed. Liu et al. [31] performed numerical and experimental study with graphene/ionic liquid based nanofluid. The numerical model showed that the receiver efficiency is directly proportional to solar concentration and the receiver height, but conversely with graphene concentration under concentrated solar intensity. Karami et al. [32] and Menbari et al. [18] performed experimental studies with CuO/water + ethylene glycol and CuO/water nanofluid respectively and showed that with the use of CuO nanoparticles there has an increase in the efficiency of the direct absorption solar collector. Verma et al. [19] performed experimental study on flat plate collector with MgO/H_2O nanofluid under 8×500 W Infrared lamp and experimentally found that there is about 9% thermal efficiency enhancement for 0.75% volume fraction at flow rate of 1.5 lpm.

The review of previous studies indicates that no study has been conducted with the cobalt oxide nanoparticles. The present experimental study attempts to do a careful thermal analysis in the absence of convective heat transfer for nanofluid absorption system (NAS) and surface absorption system (SAS). For NAS, cobalt nanoparticles (Co_3O_4, Nanostructured and Amorphous Materials, Inc., 10–30 nm Average particle size, 99.8% purity) have been used to harness the incident radiation. Further to access the potential of these particles as an efficient solar energy harvester, these nanoparticles have been compared with commercially available solar selective surface (TiNOX®, thickness 0.2 mm, $\alpha = 95\%$, $\varepsilon = 4\%$) [33]. TiNOX® is a composite coating of multiple layers like protective layer, antireflective layer, absorber layer, bonding layer and substrate. Each layer has a different role to play e.g. antireflective layer ensures maximum transmissivity so that most of the incident solar irradiance reaches the absorber layer. The absorber layer material is selected in such a way that it can absorb maximum irradiation. Substrate should be IR reflective for low radiative losses. The entire layers work together to ensure high solar absorptivity and low IR emissivity.

Different mass fractions of the nanofluid have been irradiated to predict the optimum mass fraction where the temperature rise is