Sustainable Energy Technologies and Assessments 28 (2018) 14–21

Contents lists available at ScienceDirect

Sustainable Energy Technologies and Assessments

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

Original article

Empirical correlations for heat transfer in a silver nanofluid-based direct absorption solar collector

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ARTICLE INFO

Keywords:
Empirical correlation
Direct absorption solar collector
PVP-coated silver nanofluid
Dimensional analysis
Nusselt number

ABSTRACT

In this paper, the experimental results of the performance test of a direct absorption solar collector using PVP (polyvinylpyrrolidone) coated silver nanofluid as working fluid were obtained at different operating conditions such as different nanofluid volume fractions, different tilt angles, and different rate of flows. The dimensional analysis technique was utilized to develop an empirical correlation for collector efficiency. Also an empirical correlation is introduced for calculating Nusselt number in terms of Reynolds and Prandtl numbers to specify the amount of heat loss in direct absorption solar collector. Also, a comparison between experimental and correlated results was carried out. The results showed that the bias errors were 2.46% and 5.98% for Nusselt number and collector efficiency, respectively. Consequently, Average Standard Deviation (ASD) values reached 7.31% and 18.04% for both, respectively. The correlations presented can be used in calculating Nusselt number and collector efficiency for performance analysis of direct absorption solar collectors. It helps to enhance design calculations of this new type of solar collectors.

Introduction

Due to the global population increase and fossil fuels problems, using the energy of sun is necessary and inevitable in order to provide the heat needed for heating systems. In the meantime, using direct absorption solar collectors instead of conventional collectors, in order to increase the amount of energy absorbed, is of particular importance (is an important factor) [1]. Construction of solar collector aimed to absorb the energy by the working fluid, was first done in the mid. 1970s [2,3]. In direct absorption solar collectors (DASCs), compared to conventional collectors, due to the removal of absorber plate, thermal resistance is less in the path of energy absorption [4]. In recent years, numerous theoretical and experimental researches have been conducted on the use of nanofluids to improve heat transfer in engineering applications [5–7]. Therefore, by taking advantage of the potential of nanofluids in DASCs, solar system performance can be improved.

The first step of using nanofluid as a working fluid of DASC is investigation on the properties of the nanofluid. Stability, as well as thermal and optical properties is the feature that must be examined for each nanofluid. Therefore, remarkable attention has been given to the optical properties of various nanofluids in recent years [8–10]. Karami et al. [11–13] separately examined the properties of nanofluids containing carbon nanotubes, carbon nanoball and copper oxide. They found out that using nanoparticles can improve the thermal and optical properties of the base fluid. Chen et al. [14] investigated sunlight absorption characteristics of silver nanofluids experimentally. The results show that the efficiency of the silver nanofluid is 84.61% after 5 min irradiation with a mass concentration of 80.94 ppm, which was almost twice that of water and also much higher than that of ZnO nanofluid (mass concentration of 1.02%) and TiO_2 nanofluid (mass concentration of 0.7%). Vakili et al. [15] offer that the nanofluid containing graphene nanoplates can be used as the working fluid in direct absorption solar systems, because of increasing the absorption and the extinction coefficient of the base fluid.

Khosrojerdi et al. [16] studied photothermal specifications and stability of graphene oxide nanoplatelets nanofluid. The nanofluid with strong absorption band in the range of 280–350 nm was introduced and proposed as the appropriate working fluid for DASC. Photo-thermal characteristics of water-based $Fe_3O_4@SiO_2$ nanofluid for solar-thermal applications have been investigated by Khashan et al. [17]. They reported that the photo-thermal conversion efficiency has shown an enhancement at the bottom of the collector about 32.9% compared to the base fluid, at a concentration of 1 mg/1 ml of $Fe_3O_4@SiO_2/H_2O$, and with the utilization of kerosene into the solar collector, and radiation

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https://doi.org/10.1016/j.seta.2018.05.001
Received 1 November 2017; Received in revised form 17 March 2018; Accepted 2 May 2018
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Nomenclature

a_1	heat loss coefficient $\left(\frac{W}{m^2K}\right)$
a_2	temperature dependence of heat loss coefficient $\left(\frac{W}{m^2K^2}\right)$
A	area of collector (m^2)
C_p	specific heat $\left(\frac{J}{kgK}\right)$
G	incident solar radiation $\left(\frac{W}{m^2}\right)$
h	heat transfer coefficient $\left(\frac{W}{m^2K}\right)$
H	height of collector (m)
K	thermal conductivity $\left(\frac{W}{mK}\right)$
K_e	extinction coefficient $\left(\frac{1}{m}\right)$
$\dot{m}$	mass flow rate $\left(\frac{kg}{s}\right)$
T	temperature (K)
U	overall heat transfer coefficient $\left(\frac{W}{m^2K}\right)$

Greek symbols

α	absorptivity
β	tiltangle
ρ	density $\left(\frac{kg}{m^3}\right)$
τ	transmissivity
λ	wavelength (m)
ν	velocity $\left(\frac{m}{s}\right)$
η	efficiency
μ	viscosity $\left(\frac{kg}{ms}\right)$
φ	latitude

Subscripts

a	absorption
amb	ambient
e	extinction
f	fluid
h	hydro dynamic
i	inlet
o	outlet
nf	nanofluid

exposure for 5 min. Vakili et al. [18] investigated and modeled thermal radiative properties of f-CNTs nanofluid by artificial neural network with Levenberg–Marquardt algorithm using experimental data. The results from the indicators show a highly accurate and reliable model compared with the experimental results. Bhalla and Tyagi [19] tried to experimentally compare the effectiveness of surface absorption system and nanofluid absorption system. It is found that combination of 40 mg/L Al_2O_3 + 40 mg/L Co_3O_4 is an optimum mass fraction of the nanoparticles in the base fluid at which the average temperature rise (19.4 °C) of the fluid above the ambient temperature is maximum compared to other values of mass fractions.

Regarding the potential of nanofluids to absorb radiation energy, a new type of direct absorption solar collector, which its working fluid is nanofluid, firstly examined numerically by Tyagi et al. [20]. They increased the efficiency of Direct Absorption Solar Collector (DASC) 10% more than a conventional flat plate collector by using aluminum nanoparticle suspensions in water as the working fluid of collector.

According to Tyagi's work [20], Otanicar et al. [21] have assessed the function of low temperature DASC. They reported improvements of micro solar direct absorption collector efficiency up to 5% by utilizing nanofluids as the absorption mechanism.

Parvin et al. [22] numerically investigated heat transfer and entropy generation through nanofluid filled direct absorption solar collector. The results showed that by increasing the volume fraction of Cu nanoparticles and Reynolds number, Nusselt number and entropy generation increase. In another numerical study, Parvin et al. [23] showed that the higher absorption of solar radiation, results more collector efficiency.

Muhan et al. [24] used hybrid nanofluid of CeO_2/CuO-water as working fluid in DASC. They reported that collector efficiency enhancement was obtained by increasing the nanofluid volume concentration and mass flow rate. Kumar Das et al. [25] considered the pressure difference and heat transfer in TiO_2 nanofluid-based DASC using fluent software. The results showed that Nusselt number on the collector was increased by increasing Re number.

Gupta et al. [26] studied the effect of using aluminum oxide nanofluids on the performance of direct absorption solar collector. They built a sample collector with an area of 1.4 m^2 and observed the effect of the volume concentration of nanofluids and flow rate on the performance of the collector. Their test results showed that by using aluminum oxide nanofluid instead of base fluid at the volume rate of 1.5 L/min, the collector efficiency will increase by 8%. Karami et al. [27] studied the effect of copper oxide nanoparticles on the performance of direct absorption solar collector with the aim of applying it in the domestic water heaters. They chose water and ethylene glycol mixture (70%:30% in volume) as the base fluid and after stabilization of the nanofluids, they studied the effect of volume fraction of nanofluids and flow rate on the performance of the solar collector according to the EN12975-2 standard. In a similar research, Vakili et al. [28] managed to increase the direct absorption of solar collector efficiency by using graphene nanoplates up to 23% as the base fluid. According to their results, with nanofluid containing graphene nanoplates as working fluid, the efficiency of direct absorption solar collector reaches 93.2% at flowrate of 0.015 kg/s. Delfani et al. [29] examined the effect of applying MWCNT nanofluid as working fluid in DASCs. The results of this research showed that because of increasing the volume fraction of nanofluids, the efficiency of solar collector will increase, as long as the collector efficiency would be 89.3% at the flow rate of 0.025 kg/s.

Silver has unique properties, such as high thermal conductivity, significant thermal diffusivity, nontoxicity and compatibility with the environment. Otanicar et al. [21], investigated the effects of using silver nanofluid in micro collector. The results show that applying silver nanofluid can improve the micro collector performance. Lee et al. [30] investigated the efficiency of a DASC using Ag Nanofluids Synthesized by Chemical Reduction Method with mixing silver nitrate ($AgNO_3$) and sodium borohydride ($NaBH_4$) in an aqueous solution of polyvinylpyrrolidone (PVP). The results show that the extinction coefficient of water-based Ag nanofluids increases with the increase of nanoparticle volume concentrations. Chen et al. [31] developed a one-dimensional transient heat transfer analysis to analyze the effects of the Nanoparticle (NP) volume fraction, collector height, irradiation time, solar flux, and NP material on the collector efficiency. The results show that an optimum collector height (~10 mm) and particle volume concentration (~0.03%) achieving a collector efficiency of 90% as the maximum efficiency can be obtained under the conditions used in the simulation. Gorji and Ranjbar [32,33] performed a numerical and experimental investigation on the performance of a low-flux direct absorption solar collector (DASC) using graphite, magnetite and silver nanofluids. According to the results, nanofluids promoted the thermal and exergy efficiencies by 33–57% and 13–20%, respectively than the base fluid.

Based on the results of these researches, silver nanofluid has been chosen in the present study. In this study, the effects of using nanofluid containing PVP (Polyvinylpyrroledone) coated silver nanoparticles in

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