Solar Energy 150 (2017) 512–520

Contents lists available at ScienceDirect

Solar Energy

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

Optimization of a direct absorption solar collector with blended plasmonic nanofluids

Caiyan Qin, Kyeonghwan Kang, Ikjin Lee, Bong Jae Lee *

Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Daejeon 34141, South Korea

A R T I C L E I N F O

Article history:
Received 17 November 2016
Received in revised form 27 April 2017
Accepted 2 May 2017
Available online 22 May 2017

2016 MSC:
00-01
99-00

Keywords:
Direct absorption solar collector
Global optimization

A B S T R A C T

Recently, there have been grown interests in improving the performance of a direct absorption solar collector (DASC). The present work reports a systematic optimization to further improve the performance of a DASC, especially for a system using plasmonic nanofluids. Plasmonic nanofluids has adaptable absorption characteristics such that its absorption coefficient can be controlled to be nearly constant with respect to the wavelength by mixing different shapes (or sizes) of metallic nanoparticles. At the same time, the magnitude of the absorption coefficient can also be changed by varying the particle concentration. Therefore, the absorption coefficient of plasmonic nanofluids should be taken into account in the optimization processes; however, it has not drawn much attention in existing studies so far. In the present work, the collector geometry (i.e., depth and length of the channel), flow characteristics (i.e., flow rate), and fluid property (i.e., absorption coefficient) are taken as design variables in the optimization process. Effects of each variable on the temperature gain, thermal efficiency, and thermal loss parameter are theoretically analyzed. In order to reduce the cost of a DASC and avoid particle agglomeration when using plasmonic nanofluids, we also explore the configuration with the lowest possible absorption coefficient but with the reasonably high temperature gain as well as efficiency. The results of this study will facilitate the development of highly efficient solar thermal collectors using plasmonic nanofluids.

1. Introduction

Due to the increasing gap between energy demand and resources, it has been well recognized that the development of renewable energy is essential for meeting the global energy demand in the future. Solar energy, an important renewable energy, has been investigated intensively by researchers for several decades. Solar thermal system and photovoltaic system are the two ways for solar energy utilization (Leong et al., 2016). For a solar thermal system, a flat-plate collector has been frequently used such that solar energy is first absorbed by the absorbing plate on top of the collector and then transferred to the working fluid. The disadvantage of this collector is the large amount of heat loss in the heat transfer stage due to the large temperature difference between the absorbing plate and the low-temperature fluid, and also between the absorbing plate and the ambient, which can be up to 40% of the incident solar energy (Tyagi et al., 2009; Gupta et al., 2015a). The second type of the collector in a solar thermal system is a direct absorption solar collector (DASC), in which no absorbing plate is applied on top of the collector, instead the nanoparticles are added in the base fluid to enhance the absorption of solar radiation (Tyagi et al., 2009; Otanicar et al., 2010; Lee et al., 2012; Jeon et al., 2014; Gorji and Ranjbar, 2015). This mixture of base fluid with the suspended nanoparticles is called nanofluids (Tyagi et al., 2009; Sarsam et al., 2015). In a DASC, solar energy is absorbed directly by the nanofluids so that the temperature difference is smaller than that of the flat-plat collector, thus the heat loss can be reduced (Tyagi et al., 2009; Otanicar et al., 2010).

For the DASC system using nanofluids, nanoparicles ranging from carbon and graphite to metallic and metallic oxide nanoparticles, as well as from a single kind of nanoparticle to mixtures of various kinds of nanoparticles have been investigated. For example, the DASC with carbon nanohorn, carbon nanotube, and graphite nanofluids was studied by a group of researchers either theoretically or experimentally (Otanicar et al., 2010; Sani et al., 2010; Sani et al., 2011; Ladjevardi et al., 2013; Karami et al., 2015). It was found that the efficiency of a DASC with nanofluids was higher than that with only base fluid. Similar research was also done for metallic and metallic oxide nanofluids, such as gold, silver, aluminium oxide, titania oxide, and copper oxide nanofluids (Lee et al., 2012; Polvongsri and Kiatsiriroat, 2014; Rativa and

* Corresponding author.
E-mail address: bongjae.lee@kaist.ac.kr (B.J. Lee).

http://dx.doi.org/10.1016/j.solener.2017.05.007
0038-092X/

Nomenclature

c_p	specific heat capacity (J/kg-K)	T_∞	ambient temperature (K)
F_R	collector heat removal factor	$\overline{T}_{out}$	average temperature at the outlet (K)
G_T	incident solar flux (W/m^2)	ΔT	temperature gain, $\overline{T}_{out} - T_0$ (K)
h_{conv}	convection heat transfer coefficient (W/m^2-K)		
h_{rad}	radiation heat transfer coefficient (W/m^2-K)	*Greek symbol*	
H	depth of collector (cm)	α	absorption coefficient of nanofluids (cm^{-1})
k	thermal conductivity of nanofluids (W/m-K)	η	thermal efficiency of the collector
L	length of collector (m)	ρ	density of nanofluids (kg/m^3)
$\dot{m}$	mass flow rate per unit width (kg/m-s)	σ	Stefan-Boltzmann constant (W/m^2-K^4)
$\dot{Q}$	heat generation in the collector (W/m^3)	τ	transmissivity of glass cover
T_0	inlet temperature (K)		

Gómez-Malagón, 2015; Chen et al., 2015; Gupta et al., 2015b; Chen et al., 2016; Karami et al., 2016). An advantage of metallic nanofluids over carbon or graphite nanofluids lies in that the former has higher absorption coefficient due to the plasmonic resonance of free electrons inside the metallic nanoparticles. The nanofluids with metallic suspension that can support localized surface plasmon was named as plasmonic nanofluids (Lee et al., 2012; Xuan et al., 2014). However, the high absorption coefficient of plasmonic nanofluids only occurs at certain wavelength; thus, it is not suitable for broad-band absorption. The easiest method for overcoming the resonance characteristics of localized surface plasmon is to combine different types of nanoparticles with different resonance frequencies to realize broad-band absorption (Lee et al., 2012). For instance, Jeon et al. (2014) mixed three kinds of gold nanorods of different aspect ratios, and the resulting extinction coefficient turned to be relatively uniform in the solar spectrum. Du and Tang (2016) also designed nanofluids made up of gold nanoparticles with three different shapes to obtain optimal broad-band solar absorption. Besides, a hybrid of nanoparticles with different materials was studied, including gold, copper, aluminum, graphite, and silicon dioxide, to achieve optimal solar energy absorption (Tullius and Bayazitoglu, 2016).

In addition to the investigation of the absorption coefficient of nanofluids, parametric studies were also done in order to examine the effect of different variables on the performance of a DASC (Polvongsri and Kiatsiriroat, 2014; Kasaeian et al., 2015; Liu et al., 2015; Rativa and Gómez-Malagón, 2015; Sarsam et al., 2015). In these studies, considered variables include the concentration of nanoparticles, the flow velocity, and the collector geometry. In addition, geometry optimization was also performed to obtain the optimum collector configuration with fixed flow rate and concentration of nanoparticles, such as in Lenert and Wang (2012), Veeraragavan et al. (2012), Gorji and Ranjbar (2015) and Jeon et al. (2016). However, there still exist several limitations in the previous research on DASC with plasmonic nanofluids. First, the efficiency of the collector was often stressed and evaluated, while the temperature gain of the nanofluids was not paid much attention to. In reality, however, the temperature gain of the working fluid through the solar collector is also important. For instance, in the water heating system of a building, hot water with 55–60 °C is needed to satisfy the residents' needs (Bagh et al., 2004). Second, previous work on optimization was done by only focusing on the geometry aspects, while in fact, many more variables can affect the performance of the collector, such as the flow property and the nanofluids characteristics. An important characteristic of nanofluids is that its absorption coefficient can be tuned by changing particle size, shape, and concentration. Thus, the absorption coefficient of plasmonic nanofluids should be taken into account in the optimization processes; however, it has not drawn much attention in the existing studies so far.

In the present work, the collector geometry (i.e., depth H and length L of the channel), flow characteristics (i.e., flow rate $\dot{m}$), and fluid property (i.e., absorption coefficient α) will be taken as design variables in the optimization process. In the present work, two global optimization algorithms, the genetic algorithm (Rao, 2009; Messac, 2015; Singh et al., 2015) and the pattern search method (Zhao et al., 2006; Rao, 2009; Messac, 2015), are employed. Various optimizations will be performed for cases with different constraints and objectives, including optimization of the thermal efficiency (or the temperature gain) with the constraint on the temperature gain (or the thermal efficiency), and optimization of an objective function combining both the temperature gain and the collector efficiency without any constraint. In addition, the lowest absorption coefficient will be explored without substantially sacrificing the system performance. Furthermore, effects of each design variable on the collector performance (i.e., the temperature gain, the thermal efficiency, and the thermal loss parameter) will be investigated through the sensitivity analysis.

2. Theoretical model of the direct absorption solar collector

A two-dimensional (2-D) simulation model of a DASC with plasmonic nanofluids is built with COMSOL Multiphysics. The schematic of the computational domain is illustrated in Fig. 1. Solar radiation is normally incident. Nanoparticles suspended in the base fluid absorb solar energy efficiently through plasmonic resonance, leading to the volumetric heat generation inside the collector channel. Although the nanoparticle size is not concern of the present work, it is usually within the range of 10–100 nm (Sarsam et al., 2015; Verma and Tiwari, 2015). Heat is lost from the solar collector through convection and radiation. A quartz cover (with transmissivity $\tau = 0.95$) is placed at $y = 0$ to contain the working fluid (i.e., preventing evaporation) as well as to reduce the heat loss by convective heat transfer. The solar collector with the length L and the depth H is placed horizontally; thus, the buoyancy effect can be neglected. This is because the solar radiation will be absorbed by the working fluid from the top and the resulting temperature distribution would also be higher at the top.

In evaluation of the extinction of incident light, scattering is ignored. As a matter of fact, in several studies about DASC (Tyagi et al., 2009; Otanicar et al., 2010; Veeraragavan et al., 2012; Rativa and Gómez-Malagón, 2015; Cregan and Myers, 2015), particle scattering was often neglected due to the fact that suspended nanoparticles are in several tens of nanometers and the particle scattering can be described by the Rayleigh scattering theory. Because the scattering efficiency is proportional to the fourth power of particle size parameter in Rayleigh scattering regime, the assumption of ignoring scattering is reasonable towards longer wavelengths. Recently, Jeon et al. (2014) experimentally showed that as far as the visible spectrum is considered, for the blended