International Journal of Heat and Mass Transfer 80 (2015) 58–71

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Efficiency of a volumetric receiver using aqueous suspensions of multi-walled carbon nanotubes for absorbing solar thermal energy

Seung-Hyun Lee, Seok Pil Jang *

School of Aerospace and Mechanical Engineering, Korea Aerospace University, Goyang, Gyeonggi-do 412-791, Republic of Korea

ARTICLE INFO

Article history:
Received 9 April 2014
Received in revised form 28 August 2014
Accepted 28 August 2014
Available online 27 September 2014

Keywords:
Nanofluid volumetric receiver (NVR)
Nanofluids
Solar thermal energy
Multi-walled carbon nanotube (MWCNT)
Extinction coefficient
Wavelength

ABSTRACT

This paper analytically investigates the efficiency of a nanofluid volumetric receiver (NVR) for absorbing solar thermal energy considering the experimentally measured extinction coefficient of aqueous suspensions of multi-walled carbon nanotubes (MWCNT) according to the wavelength from 200 to 2000 nm. For this purpose, considering the spectral behavior of nanofluids, we obtained analytical solutions of temperature fields as well as the efficiency of the NVR based on the condition of fully developed flow between the two plates. The aqueous MWCNT nanofluids were prepared using the two-step method, and their extinction coefficients were experimentally measured by the UV/Vis/NIR spectrophotometer according to the wavelength. With the analytical equations, we identified those key engineering parameters that affect the efficiency of an NVR: the Nusselt number of heat loss, the concentration of nanoparticles, the Peclet number, and aspect ratio. Also, we systematically observed the effects of key engineering parameters on the temperature fields and on the efficiency of the NVR. The current results clearly show that the efficiency calculated under the assumption of plug-flow through an NVR reported by previous researchers is overestimated in the case of high heat loss. Moreover, the present results show that NVR efficiency is proportional to the Peclet number as well as to the concentration of nanoparticles, while it is inversely proportional to the Nusselt number of heat loss and aspect ratio. The results of this study may be helpful to design and predict the efficiency of an NVR.

1. Introduction

In general, today's solar thermal receivers are surface-based absorbers with black coatings [1] that are designed to capture solar thermal energy. However, this surface-absorbing approach is limited due to the energy loss incurred during the heat absorption and transport processes [2–4]. In the surface-based absorbers, the coated solid plate first absorbs radiative solar energy and then transfers that energy from the solid absorber to a working fluid. During this process, a significant amount of energy is lost as a result of conduction, convection, and radiation due to the temperature difference between the plate and ambient air [2,3]. Moreover, due to their finite surface area, surface absorbers have limited ability to absorb and transfer high radiant fluxes [4]. Accordingly, the concept of volumetric receivers (VRs), or direct absorption solar collector (DASC), [4–8] was proposed as a volumetric-absorbing approach that would be able to overcome the limitations of the conventional surface-absorbing approach. Recently, nanofluids have been highlighted as a working fluid for VRs because they can efficiently absorb and transfer solar thermal energy due to their enhanced thermal and optical properties [2,3,9–12]. The main advantages of nanofluid-based volumetric receivers (NVRs) are summarized as follows:

(1) Nanoparticles can manipulate the optical characteristics of a base liquid such as the extinction coefficient [10,11,13]. Thus the efficiency of a solar thermal receiver can be improved by controlling the volume fraction and morphology of nanoparticles dispersed into nanofluids.
(2) An NVR is mechanically simple and cost-effective compared to conventional surface-based absorbers. Because the fluid volume in an NVR directly absorbs solar thermal energy, a surface-absorbing plate is not required [3], allowing significant cost and labor reductions due to the elimination of the complex manufacturing processes involved in creating surface-absorbing plates, including electroplating, anodization, evaporation, sputtering, and solar-selective paint coating [1].
(3) The convective and emissive heat loss incurred by NVRs is much lower than that of a surface absorber [2–4]. Because an NVR gradually absorbs solar thermal energy in fluid vol-

* Corresponding author. Tel.: +82 2 300 0179; fax: +82 2 1 3158 2191.
E-mail address: spjang@kau.ac.kr (S.P. Jang).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.08.091
0017-9310/

Nomenclature

AR	aspect ratio [x_{out}/H]
CR	concentration ratio
c_p	specific heat [J/kg K]
D	size of nanoparticle [nm]
G	Green function
G_s	incident solar radiation at the Earth's surface [W/m^2]
I	intensity of radiation [W/m^2]
J	intensity of light [W/m^2]
H	height of a receiver [mm]
h	Planck constant (=6.626 × 10^{-34} J s)
$h_{heat\ loss}$	convective heat transfer coefficient of heat loss [W/m^2 K]
$K_{ext,\lambda}$	spectral extinction coefficient [1/mm]
$K_{scat,\lambda}$	spectral scattering coefficient [1/mm]
k_λ	spectral extinction index
k_B	Boltzmann constant (=1.381 × 10^{-23} J/K)
k_c	thermal conductivity [W/m K]
L	length of multi-walled carbon nanotube [m]
m	relative refractive index ($m = (n_p + ik_p)/(n_f + ik_f)$)
l	path length [cm]
Nu	Nusselt number of heat loss
Pe	Peclet number
Pr	Prandtl number
$\dot{q}'''$	volumetric heat generation [W/m^3]
Re	Reynolds number
S_{att}	average attenuation of sunlight through the Earth's atmosphere (=0.73)
T	temperature [K]
U	fluid velocity [m/s]
v	speed of light in vacuum (=2.998 × 10^8 m/s)
x	size parameter ($x = \pi D/\lambda$)
x_{out}	length of receiver [m]

Greek symbols

α	eigenvalue
θ	dimensionless temperature
λ	wavelength [nm]
μ	dynamic viscosity [Pa s]
ζ	location of a source for the Green function
ρ	density [kg/m^3]
τ	optical thickness ($\tau = H \cdot K$)
ϕ	volume fraction of nanofluids
ψ, ξ	Riccati–Bessel functions
Ω	solid angle of the sun as viewed from the Earth (=6.8 × 10^{-5})
ω	albedo

ume along the receiver depth, the temperature of the top surface of the volumetric receiver is lower than that of the surface receiver. As a result, the temperature difference between the top surface and the ambient air is lower than that of the surface absorber, reducing losses of convective and emissive heat [2–4].

(4) Nanofluids possess superior thermal properties, such as high thermal conductivity [14] and a high convective heat transfer coefficient [15], which can be valuable when nanofluids are the working fluids in an NVR. Additionally, because nanofluids have a high degree of suspension stability, it is reasonable to expect low rates of clogging, sedimentation, fouling, and erosion compared with the micro-sized inclusions [2,3].

This novel concept can be applied not only to nonconcentrating flat-plate collectors [3,9,10] but also to concentrating solar-power systems [2,11]. Tyagi et al. [9] numerically showed the feasibility of nanofluids as a medium that absorbs direct sunlight in a nonconcentrating flat-plate solar collector using the Finite Difference Method (FDM). They found that the efficiency of the NVR was about 10% higher than that of conventional flat-plate solar collectors when the NVR was used in conjunction with water-based aluminum nanofluids (D = 5 nm, ϕ = 1.6%). Otanicar et al. [3] performed experimental and numerical studies on a small-scale solar thermal collector, using various aqueous nanofluids containing graphite nanoparticles (D = 30 nm, ϕ = 0.1%), silver nanoparticles (D = 20/40 nm, ϕ = 0.25%), and carbon nanotubes (D = 6–20 nm, L = 1–5 μm, ϕ = 0.1%). They revealed that the efficiency of the NVR with nanofluids was 5% higher than the efficiency of the small-scale solar thermal collector with pure water. However, the numerical results presented by Otanicar et al. [3] and Tyagi et al. [9] were limited because they considered only the plug-flow condition at the two plates and did used the Rayleigh approximation model, rather than the measured extinction coefficient of nanofluids. Moreover, Taylor et al. [11] demonstrated the feasibility of nanofluids in high-heat-flux solar collectors by using a laboratory-scale dish solar collector. They showed an efficiency enhancement of about 10% when they utilized Therminol VP-1-based graphite nanofluids (D = 20 nm, ϕ = 0.125%). However, they also used the uniform velocity condition to predict the efficiency of the collector numerically. Recently, Lee et al. [10] numerically investigated the collector efficiency considering the non-uniform velocity profile inside the channel with commercial software, COMSOL. However, they did not present an analytical solution of temperature field and the efficiency. Also, Veeraragavan et al. [12] devised an analytical model of dimensionless temperature and NVR efficiency. Although they analytically presented temperature profiles at the NVR, they used both the plug-flow condition at two plates and the absorption coefficient model of nanofluids, based on the Rayleigh approximation model calculated with optical properties of the graphite and Therminol VP-1at 500 nm wavelength. Moreover, they presented only the effect of heat-loss magnitude on the temperature profile and NVR efficiency and did not systematically present the important parameters that affect the efficiency of the receiver.

It is important to consider the spectral behavior of nanofluids and appropriate flow condition to obtain the analytical solutions because the temperature fields as well as the efficiency strongly depend on the velocity profile and the spectral behavior. Also, it is worthwhile to obtain the analytical solutions because key engineering parameters of the NVR efficiency can be identified. So, in this paper, based on the fully developed flow condition at the two plates, we present analytical equations for temperature profile and the NVR efficiency that take into account the experimentally measured extinction coefficient of the aqueous suspensions of multi-walled carbon nanotubes (MWCNT) according to the wavelength from 200 to 2000 nm. Based on the equations, we analytically identify the key engineering parameters: the Nusselt number of heat loss, the concentration of nanoparticles, the Peclet number, and aspect ratio. Also, we systematically present the effects of the key parameters on the temperature fields and the efficiency of the NVR, and our results clearly show that previous studies with plug-flow condition have overestimated the efficiency in the case of high heat loss.