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Thermal efficiency comparison: Surface-based solar receivers with conventional fluids and volumetric solar receivers with nanofluids

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ABSTRACT

This paper reports on a comparative study of the difference in thermal efficiency between surface-based solar receivers (SRs) with conventional base fluids and volumetric solar receivers (VRs) with water-based multi-walled carbon nanotubes (MWCNT) nanofluids. The analytical solutions for temperature distribution and thermal efficiency of SRs and VRs are theoretically obtained to identify the key engineering parameters that affect the thermal efficiency of both solar receivers. In order to confirm the analytical solutions, we experimentally measured the thermal efficiency of both solar receivers according to the volume fraction and the Peclet Number. Moreover, the experimental results are compared with the analytical solutions. Based on the comparison, we show that the analytical solutions can reasonably estimate the thermal efficiency with respect to the volume fraction and the Peclet number. Furthermore, the analytical and experimental results indicate that the efficiency of both solar receivers are proportional to the volume fraction (ϕ) (not applicable for SRs) and the Peclet number (*Pe*), while it is inversely proportional to the Nusselt number of heat loss (*Nu*) and the aspect ratio (*AR*). Finally, this study systematically demonstrates the nanofluid-based VRs can be achieved higher efficiency compared to the conventional SRs over 10%.

1. Introduction

Over the past two decades, nanofluids, which are stable suspensions of solid nanoparticles in liquids, have attracted great attention as an advanced heat-transport medium due to their outstanding conductive [1–5] and convective [6–10] heat transport capabilities. Recently interest in nanofluids has been growing in the research field of solar thermal energy due to their potential application as an absorption medium of radiant thermal energy [11–20]. Many researchers have focused on the use of nanofluids as a solar-energy absorption medium associated with a novel concept of liquid-based volumetric solar receiver [11–20].

In general, surface-based solar receivers (SRs) such as flat-plate solar collectors (FPSCs) and parabolic trough collectors (PTCs) have been widely used to receive solar thermal energy. However, the traditional SRs firstly captured the radiative solar energy by a thin metal plate or tube and then transferred it to a working fluid [12,14,16]. During this procedure, a lot of energy is lost and thus the increment of outlet temperature and thermal efficiency are restricted [11,12,14,16]. Moreover, the SRs are not appropriate to effectively absorb the high-radiant fluxes due to their finite absorption area confined in the two dimensions [21]. In order to overcome these limitations, the volumetric solar receivers (VRs) (also called *direct-absorption solar collectors, DASCs*) [11–20] using nanofluids were proposed as a volume-based absorption mechanism. The first benefit of the nanofluid-based VRs is that the nanoparticles can handle the optical characteristics of conventional base fluids to be suitable for the direct absorption of solar thermal energy [12,13,15–18]. The second is that the nanofluid-based VRs are mechanically simple, and their manufacturing cost will be reduced because they don't require an absorbing metal plate or tube to capture the solar thermal energy [12]. Lastly, the convective and emissive heat losses of the nanofluid-based VRs are much lower than that of SRs [12,16] because the nanofluid-based VRs directly absorb the solar thermal energy in a fluid volume. However, the development of the nanofluid-based VRs is still in its early stages, and a systematic comparative study of the thermal efficiency between VRs and SRs has not been sufficiently implemented yet. For example, Tyagi et al. [11] and Taylor et al. [14] compared the numerical results of VRs with the previous experimental data of

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Nomenclature

A_s	surface area of receiver [m^2]
A_n	Fourier coefficient of the analytical solutions for volumetric receivers
AR	aspect ratio [L/H]
B	bias error
B_n	Fourier coefficient of the analytical solutions for surface-based receivers
C	concentration ratio
c_p	specific heat [J/kg·K]
D_{MWCNT}	diameter of multi-walled nanotube [nm]
F	absorbed sunlight fraction
G	Green function
G_s	incident solar radiation at the Earth's surface [W/m^2]
G_{ss}	incident solar radiation from a solar simulator [W/m^2]
I_λ	spectral intensity [W/m^2]
$I_{0,\lambda}$	spectral intensity of solar radiation [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	extinction coefficient [1/mm]
k_b	Boltzmann constant (=1.381 × 10^{-23} J/K)
k_c	thermal conductivity [W/mK]
L_{MWCNT}	length of multi-walled carbon nanotube [nm]
L	length of a receiver [m]
l	path length [cm]
$\dot{m}$	mass flow rate [g/s]
nn	sample size
Nu	Nusselt number of heat loss $\left[\frac{h_{heat\ loss}H}{k_c}\right]$
P	estimated precision error of sample mean
Pe	Peclet number
$\dot{q}'''$	volumetric heat generation [W/m^3]
$\bar{\dot{q}}'''$	dimensionless volumetric heat generation $\left[\frac{\dot{q}'''(y)\cdot H}{C\cdot T_{glass}\cdot G_s}\right]$
q_s''	absorbed heat flux in the surface receiver [W/m^2]
S_{att}	average attenuation of sunlight through the Earth's atmosphere (=0.73)
s	standard deviation
T	temperature [K]
T_{glass}	transmittance of glass
T_r	transmittance
T_{sun}	temperature of sun (=5,800 K)
$t_{\mathrm{df},95\%}$	value of t-distribution with 95% confidence level at nn-1 degree of freedom
U	fluid velocity [m/s]
u	uncertainty
x	x-direction [m]
$\bar{x}$	dimensionless x-direction $\left[\frac{x}{Pe\cdot H}\right]$
Y_n	eigenfunction
y	y-direction [m]
$\bar{y}$	dimensionless y-direction $\left[\frac{y}{H}\right]$

Greek symbols

α_λ	spectral absorptance
β_n	eigenvalues
ε_λ	spectral emittance
ϕ	volume fraction of nanofluids
η	thermal efficiency
λ	wavelength [nm]
ν	speed of light in vacuum (=2.998 × 10$^8 m/s$)
θ	dimensionless temperature of volumetric receiver $\left[\frac{k_c(T-T_{amb})}{C\cdot T_{glass}\cdot G_s\cdot H}\right]$
θ_s	dimensionless temperature of surface-based receiver $\left[\theta-\frac{q_s''}{Nu\cdot C\cdot T_{glass}\cdot G_s}\right]$
ρ	density [kg/m^3]
Ω	solid angle of the sun as viewed from the Earth (6.8 × 10^{-5})

Subscripts

amb	ambient
b	black body
c	cut-off
in	inlet
NF	nanofluids properties
n	number of terms in series solutions
out	outlet
SRs	surface-based solar receiver
SS	solar simulator
VRs	volumetric solar receiver

SRs. However, their geometries in comparison are different from each other and thus its comparison results between VRs and SRs are limited and still insufficient. Otaniar et al. [12] initially compared the efficiency of both receivers experimentally but they used a simple matte-black paint as a coating of absorption plate instead of a solar-selective coating. Thus, this comparison had limitations for actual comparison because today's common solar collectors generally use a solar-selective coating to absorb the solar thermal energy [16]. Khullar et al. [19] recently performed more systematic comparison for the two receivers. However, their studies were investigated under the no-flow condition, and they did not present the thermal efficiency of SRs and VRs. Therefore, the systematic comparison results between the VRs and SRs are still required to practically evaluate the feasibility of the nanofluids-based VRs.

Therefore, this paper provides a systematic comparison of the thermal efficiencies of VRs and SRs, using analytical and experimental approaches. We obtain the analytical temperature distributions and thermal efficiency of SRs and VRs using simple assumptions. Based on the analytical results, we identify the key engineering parameters, which are the volume fraction of MWCNTs, the Peclet number, the Nusselt number of heat loss, and the aspect ratio of geometry, that affect the efficiency of both solar receivers. Especially, we experimentally observe the effects of the volume fraction and the Peclet number among key engineering parameters on the thermal efficiency with water-based MWCNT nanofluids. Finally, we systematically compare the efficiency of two solar receivers and explore the feasibility of VRs with nanofluids compared to the SRs with conventional working fluids.

2. Nanofluids preparation and optical characteristics

The water-based MWCNT nanofluids are manufactured as follows. First, 0.005 vol% of MWCNT (D_{MWCNT} = 20 nm, L_{MWCNT} = 1–25 μm, Korea) and 0.2 wt% of sodium dodecyl benzene sulfonate (SDBS; Sigma-Aldrich) are placed in the jars of a planetary ball mill (PQ-N04, Across International) with a small amount of