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Impact of nanofluids, radiation spectrum, and hydrodynamics on the performance of direct absorption solar collectors

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ABSTRACT

The coupled radiative transfer and thermal energy equations were numerically solved for a nanofluid-based, direct absorption solar collector (DASC) using a Rayleigh scattering approximation for the optical properties of the nanofluid. The flow field was solved using a vorticity-stream function formulation. The numerical model was validated against published results in the literature. The effects of collector aspect ratio, incident radiative flux, heat loss coefficient, inlet flow velocity, nanoparticle size, and nanoparticle concentration were determined for four different types of nanoparticles. It was established that the impact of these parameters on collector performance was determined by the extent to which they affected the outlet temperature gain and thermal losses to the ambiance. Through the exact solution of the flow field, it was established that performance deviations from the fully-developed assumption were encountered for small collector aspect ratios, especially with high Reynolds numbers ($Re > 1500$). Moreover, with the exception of cases with very low Reynolds numbers ($Re < 40$), assuming a plug flow profile throughout the collector was shown to cause performance overestimations. Sensitivity of DASC performance to the type of incident radiation spectrum was also investigated and it was found to be largely dependent on spectral distribution of the extinction coefficient of the nanoparticle. The common assumption of a blackbody incident spectrum results in performance overestimations for certain types of nanoparticle suspensions (e.g., silver) more than others (e.g., graphite). Using a higher nanoparticle volume fraction causes the efficiency of the collector to be more insensitive to the incident spectrum type. For a given nanofluid material and thickness, it was established that an optimum nanoparticles concentration existed.

Nomenclature

AR	aspect ratio, $AR = \frac{L}{H}$ (–)
C	specific heat capacity (J/(kg·K))
D	nanoparticle diameter (nm)
f	friction factor (–)
f_v	volume fraction (%)
H	height of the collector (m)
h_L	combined heat loss coefficient (W/(m^2·K))
I	spectral radiative heat flux (W/(m^2·µm))
I_0	incident radiative heat flux (W/(m^2·µm))
k	thermal conductivity (W/(m·K))
K_a	absorption coefficient (1/µm)
K_e	extinction coefficient (1/µm)
L	length (m)
m	relative (or normalized) complex index of refraction (–)
n	refractive index (real part of complex index of refraction) (–)
Nu_L	heat loss Nusselt number, $Nu_L = \frac{h_L H}{k_{nf}}$ (–)
q	heat flux (W/m^2 or suns. 1 sun = 993 W/m^2)
Q	power (W)
P	pressure (Pa)
Q_a	absorption efficiency (–)
Q_e	extinction efficiency (–)
Q_s	scattering efficiency (–)
R	reflectivity (–)
Re	Reynolds number, $Re = \frac{u_{in} H}{\nu_{nf}}$ (–)
t	time (s)
T	temperature (K)
u	velocity in x-direction (m/s)
v	velocity in y-direction (m/s)
W	width (m)

Greek letters

α	size parameter (–)

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β radiation propagation directional cosine with respect to y-axis (–)
ζ vorticity (1/s)
η efficiency (–)
κ absorptive index (imaginary part of complex index of refraction) (–)
λ wavelength (μm)
μ dynamic viscosity (Pa·s)
ν kinematic viscosity (m^2/s)
ρ density (kg/m^3)
τ transmissivity (–)
ϕ hydraulic diameter (m)
ψ stream function (m^2/s)

Subscripts and superscripts

a ambient
avg average
bb blackbody
bf base fluid
e entrance
f final
gc glass cover
i initial
in inlet
inc incident
nf nanofluid
np nanoparticle
opt optical
out outlet
p pumping
r radiative
th thermal
use useful

Abbreviations

DASC direct absorption solar collector
HTF heat transfer fluid
LSP localized surface plasmon
RTE radiative transfer equation

1. Introduction

The solar thermal collector is one of the most widely-used devices for renewable energy utilization due to its simple operation principles, ease of deployment, and promising solar-to-useful conversion efficiency [1]. Conventional solar thermal collectors operate based on the principle of surface absorption of solar radiation and subsequent heat transfer to a working heat transfer fluid (HTF) embedded within the absorber [2]. As compared to the two-step solar-to-useful conversion process in conventional collectors, the HTF in a direct absorption solar collector (DASC) directly receives and collects solar radiation by means of volumetric absorption. This eliminates the issue of thermal resistance between the HTF and surface absorber [3,4]. Moreover, reduced convection and radiation losses are characteristic of DASCs as compared to surface solar collectors due to the thermal trapping effect observed in volumetric absorbers [5]. Minimizing both thermal resistance to the HTF and thermal losses to the ambience are two out of three critical factors that define the performance of a solar thermal collector. The third factor is the radiation absorption ability. Volumetric radiation absorption takes place in a DASC by means of either gas-particle suspensions [6–8], or liquid-particle suspensions, or porous media [9]. Liquid-particle suspensions could be based on microparticles (such as colored dyes) [10,11] or nanoparticles [12,13]. The advantage of utilizing nanoparticles is much higher absorption efficiency relative to the scattering efficiency [14]. Moreover, and as opposed to microparticles, nanoparticles can be put into conventional liquid pumping and piping machinery with little particle instability, abrasion, or clogging issues [13]. Nanoparticles also offer improved heat transfer properties (e.g., thermal conductivity) compared to colored dyes. The engineered colloidal suspension of nanoparticles within a base fluid is called a nanofluid.

Kumar and Tien [15] and Tyagi et al. [16] pioneered the efforts in modeling the radiative behavior and thermal performance of DASCs subject to low-flux solar radiation. By testing a variety of nanofluids, Luo et al. [17] concluded that 30–100 K outlet temperature gains and 2–25% collector efficiency improvements are possible when using nanofluids instead of pure fluids for volumetric absorption. Delfani et al. [18] used an experimental and numerical approach to verify that using nanofluids instead of pure fluids results in a 10–29% efficiency improvement. Similar conclusions were reached by Otanicar et al. [19] and Karami et al. [20] who demonstrated that using pure fluids, absorptive bottom surfaces gave better performance than reflective ones. Using a nanofluid instead of the pure fluid under the same conditions gave the best performance [19,20]. Using a three-dimensional numerical model for the fluid flow and radiative transfer equation, Kaluri et al. [21] analyzed the performance of a high-flux DASC using two absorbing fluids (a water-based graphite dispersion and a copper sulfate solution) with up to 28% efficiency improvements achieved at higher optical concentration ratios. In their study, for the same incident power, the spatial distribution of concentrated radiation was taken into account and it was shown that at high optical concentration ratios, the smaller spot diameters of concentrated radiation on the DASC's surface resulted in significantly lower heat losses to the ambience from the top surface. Cregan and Myers [22] developed an analytical model for an inclined low-flux DASC that used a power-law approximation of total spectral radiative heat flux attenuation within the collector along incidence direction. From their parametric studies, the authors concluded that collector performance is insensitive to particle diameter and that beyond a certain volume fraction of nanoparticles, collector efficiency levels off. In order to maximize broadband absorption of the solar spectrum, Lee et al. [23] used an optimized water-based blend of four silica-gold core-and-shell nanoparticles at different core and shell sizes. By tuning the thickness of the gold shells with respect to the size of the silica cores, localized surface plasmonic peaks were shifted to coincide with the solar spectrum. Using a Monte Carlo algorithm for the radiative transfer equation and a finite element code for the energy equation, they were able to show that the collector efficiency using the blended nanofluid is comparable to that of an aluminum nanofluid, although the nanoparticles concentration of the former is an order-of-magnitude lower than the latter. Published nanofluid-based DASC studies are classified as shown in Table 1.

Previous studies have used either plug flow [4,16,19,24] or fully-developed flow [29,34] to describe the flow field in a DASC. The former assumption is only valid for creeping flow, which is not practical in DASC systems. The latter assumption, while more realistic, ignores entrance region effects in a developing flow. Using an analytical approach, Lee and Jang [34] confirmed that the assumption of a plug flow profile throughout the collector results in substantial performance overestimations, especially for cases with high heat loss coefficients and high Reynolds numbers. The effect of flow dynamics at entrance region on a DASC thermal performance has not been investigated. Also, previous studies have commonly used non-solar spectra (most usually, a blackbody profile [18,24,26,30,33,36,38]) for incident radiation heat flux. Such spectrum profiles (e.g., an ideal blackbody profile) do not take into account atmospheric attenuation effects on the extraterrestrial solar spectrum. This can be problematic because absorption and scattering efficiencies of a nanofluid are highly wavelength-dependent.

The main objective of this study is to investigate numerically the validity of several optical and hydrodynamic approximations commonly used in modeling the performance of DASCs and to determine their effect on heat transfer. This includes the extent to which the hydrodynamic flow profile affects temperature field and overall thermal performance. Also the sensitivity of the performance of the collector on