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Limits of selectivity of direct volumetric solar absorption

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Abstract

Direct volumetric absorption of solar radiation is possible with fluids which have controlled optical properties. As with conventional surface absorbers, it is possible to make direct absorbing collectors ‘selective’ where short wavelength absorption is maximised, but long wavelength emission is minimised. This work investigates the fundamental limits of this concept as it pertains to nanofluid-based direct absorbing collectors. This is especially important at higher operating temperatures (100–600 °C) where radiative losses increase significantly.

A study of optical parameters of collector components is conducted herein to investigate the best theoretically (and practically) achievable ‘selective’ nanofluid-based direct absorbing collectors. When the effect of the short wavelength optical properties was investigated, a short wavelength optical depth of 3 was found to be sufficient for efficient absorption of solar radiation while scattering is minimised. It is also advantageous to use a base fluid which shows weak absorption at long wavelengths to reduce emission losses.

Overall, this study directs future research of direct absorption by underlying theoretical and real-world limitations of a selective direct absorbing collector – an emerging receiver technology that can be used for efficient solar thermal harvesting.

Keywords: Direct absorption; Selective absorption; Nanofluids; Optical properties

1. Introduction

Nanofluids are making their way in a variety of engineering disciplines, ranging from heat exchangers to optical therapeutics (Taylor et al., 2013a). While nanofluids have been heavily researched for their enhanced thermal properties, a growing number of researchers have started to investigate other promising applications (Taylor and Phelan, 2009; Taylor et al., 2013a). Of particular interest to this work is their tunable optical properties and the prospect of using the nanofluids in direct absorption solar thermal energy harvesting (Otanicar et al., 2010). Direct absorption collectors (DACs) use nanofluids with strong absorption properties (within the solar spectrum) to volumetrically absorb solar radiation. Volumetric absorbers have several advantages over conventional surface absorbers. In surface absorption, solar radiation energy is first absorbed and converted into heat by an absorbing surface. This heat energy must then be transferred to the

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Nomenclature

A	absorbance
B	blackbody emission intensity (W/m^2 nm)
Cr	solar flux concentration ratio
DAC	direct absorption collector
E	emittance
EFS	efficiency factor of selectivity
G	solar irradiation (W/m^2)
I	radiation intensity (W/m^2 nm)
n	refractive index
R	reflectance
T	temperature (°C)
T	transmittance

Greek symbols

δ	dirac function
λ	cut-off wavelength (nm)
μ	cosine of direction
σ	Stefan Boltzmann constant (W/m^2 K^4)
τ	optical depth
ω	scattering albedo

Subscripts and superscripts

BB	blackbody weighted
bottom	value at bottom boundary
c	collimated
cover	value for cover
dh	directional–hemispherical
h	hemispherical
long	long wavelength
nanofluid	value for nanofluid
SOL	solar weighted
sol	of the solar spectrum
short	short wavelength
top	value at top boundary
tr	transport
λ	spectral

fluid by conduction and then convection, which results in a temperature drop. This problem does not arise in DACs as solar radiation is directly absorbed by the heat transfer fluid itself. Another issue in surface absorption is the high radiative and convective heat losses at the absorbing surface as the outer boundary has the highest temperature. In DACs, however, this can be avoided by carefully designing them to obtain mean fluid temperatures higher than the outermost surface (Lenert and Wang, 2012).

It has been shown, both theoretically and experimentally, that nanofluid-based DACs can be 5–10% more efficient than conventional solar collectors (Khullar et al., 2013; Otanicar et al., 2010; Phelan et al., 2013; Taylor et al., 2011b; Tyagi et al., 2009). Experimentally, researchers have investigated the range of optical properties available with spherical nanoparticles made of different materials such as gold, silver, graphite, copper, aluminium and nickel (Kameya and Hanamura, 2011; Khullar et al., 2014; Taylor et al., 2012b, 2011a). Particles with other shapes like carbon nanotubes (Otanicar et al., 2010), carbon nanohorns (Mercatelli et al., 2011; Sani et al., 2011), and core–shell type nanoparticles (Lenert and Wang, 2012; Lv et al., 2012; Otanicar et al., 2013b) have also displayed optical properties suitable for the direct absorption of solar energy. Otanicar et al. (2010) predicted that increasing particle size would reduce the collector efficiency while Tyagi et al. (2009) predicted a slight increase of efficiency with increasing particles size. Veeraragavan et al. (2012) developed an analytical model based on dimensionless parameters to help design volumetric solar receivers. The Veeraragavan model is capable of predicting the maximum system efficiency and length of a DAC for known heat loss and solar irradiation values. The optimisation study carried out by Lenert and Wang (2012) showed that collector efficiency also increases with increasing solar concentration and fluid layer thickness. Another interesting study by Otanicar et al. (2011) investigated the effect of having a nanofluid with an extinction coefficient varying along the fluid depth. They showed that having an exponentially increasing extinction coefficient along the fluid depth (potentially realised by using magnetic nanoparticles (Lenert and Wang, 2012; Otanicar et al., 2011) is the most favourable, as the attenuation of solar irradiance occurs away from the surface exposed to the surroundings.

Despite the numerous research efforts discussed above, there have been no reports of a *selective* DAC. A selective absorber captures most of the incoming solar radiation while minimising the radiative heat loss. *Selective surface* absorbers, such as TiNOx and black chrome coated copper/aluminium substrates, are becoming ubiquitous in conventional solar collectors – most modern, commercial evacuated tube and glazed flat plate collectors will have a selective absorber surface coating. Selective absorption of solar radiation is important for mid and high temperature (100–600 °C) solar harvesting when radiative heat losses become significant. While the thin dark coating is efficacious at absorbing solar radiation, the low emissivity of the underlying smooth metal substrate prevents radiation heat losses. If developed, a *selective* DAC with similar properties has the potential to further increase the efficiency of nanofluid-based volumetric absorption. (One should also note that very high operating temperatures are not considered here. At very high temperatures, selectivity becomes unimportant as the solar and emission spectra start to overlap considerably.)

As such, the current work systematically analyses the components of a DAC to determine their theoretical radiative limitations. Since it is possible to suppress convection