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Harvesting solar thermal energy through nanofluid-based volumetric absorption systems

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ABSTRACT

Today's nanofabrication methods have enabled nanoparticles to be synthesized having optical properties which are tailored to a variety of specific applications in the realms of biological and energy systems. These systems are distinctive in that light is absorbed predominantly by the nanoparticles which are distributed throughout the fluid. Here we report the first experimental study which quantitatively compares nanoparticle dispersions [amorphous carbon nanoparticles dispersed in ethylene glycol and multi-walled carbon nanotubes (MWCNTs) dispersed in distilled water] to conventional commercial materials (TiNOX® coated copper substrate) for their performance as selective solar absorbers. It has been found that under similar operating conditions, higher average stagnation temperatures are achievable if the electromagnetic radiation is allowed to directly interact with the bulk of the fluid (which is the case in a volumetric system). Moreover, the performance of these volumetric systems is sensitive to the amount (volume fraction) of the nanoparticles dispersed – which, in the limit, approaches surface absorption for high volume fractions. Furthermore, the spatial temperature distribution has been found to be consistent with the underlying theory of volumetric absorption.

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1. Introduction

Most of today's solar thermal technologies are constructed with surface-based absorbers, wherein solar irradiance is first absorbed by a solid surface (employing selective coatings) and then transferred to a working fluid through conduction and convection heat transfer. Selective coatings have high absorptivity across the incident spectrum of incident solar energy (0.3–2.5 μm) while simultaneously having low emissivity in the mid-infrared region (2.5–10 μm) of the spectra [1]. These characteristics make selective coatings quite suitable for harnessing incident solar irradiance. However, during such a process an inherent thermal barrier is present in the form of conductive and convective resistances between the absorbing surface and the working fluid. As a result, conversion of solar energy into thermal energy of the working fluid is not a very efficient process in surface absorption-based solar receivers. This problem becomes more pronounced in the case of concentrating solar collectors as the flux that must move across this barrier increases. In this case, excessively high surface temperatures can develop relative to fluid temperature – e.g. reported temperature differences (between the surface and fluid temperatures) have been as high as 500 °C [2]. Since radiative losses are proportional to the fourth power of the surface temperature, high surface temperatures lead to excessively high radiative heat losses. This problem can be reduced by allowing the incident solar radiation to interact directly with the working fluid without heating any other structures within the receiver.

Existing heat transfer fluids [such as ethylene glycol, Therminol VP-1 (special formulation of diphenyl oxide and biphenyl), molten salts, etc.] are not very good absorbers of solar radiant energy (they are essentially transparent to the solar spectrum [3,4]). Therefore additives are needed in order to create working fluids which absorb solar energy. Seeding the working fluid with micron sized particles, such as carborundum (silicon carbide) and silicon dioxide, can significantly enhance the fluid's solar energy absorption

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Nomenclature

English symbols

D	diameter
E	emissive power
$E_{absorbed}$	energy absorption capability
H	height
I	flux
I_0	incident flux
K	optical coefficient
T	temperature
Y	distance from the bottom surface
y	thickness of the fluid layer

Greek symbols

α	absorptivity
ε	emissivity
σ	Stefan–Boltzmann constant

Subscripts

a	absorption
amb	ambient
i	$1, 2, 3 \ldots n$
s	surface
stag	stagnation
v	volumetric

Abbreviations

MWCNTs	multi-walled carbon nanotubes
SAS	TiNOX®-based surface absorption system
TC	thermocouple
t-CVD	thermal–chemical vapor deposition
VAS	amorphous carbon nanoparticles/MWCNTs-based volumetric absorption system

capability [5]. However, micron-particle suspensions are not very stable and the particles tend to settle out of the suspension. Practical difficulties, such as clogging of pumps and valves, have limited the use of micron-particle suspensions as volumetric absorbers [6]. There are two competing forces in a small particle-suspension; namely Brownian motion (ensuring incessant motion of the particles) and the gravitational force. As the particle size becomes smaller (approaching the nanometer scale), Brownian motion becomes predominant and makes the suspension stable [7]. Furthermore, the chemical nature of the nanoparticles, pH, and viscosity of the dispersed phase has a profound effect on the stability of these nanoparticle dispersions [8]. These stable nanoparticle dispersions (popularly known as 'nanofluids') have recently been investigated for their thermo-physical [9–13] and optical properties [14–19]. Dispersing trace amounts of nanoparticles can significantly enhance the solar irradiance absorption capability of the base-fluid – by up to 7 orders of magnitude change in the extinction coefficient for <<1% volume fraction [14]. Excellent stability (relative to micron-particle suspensions) coupled with high solar energy absorption capability make nanofluids suitable for solar thermal applications [20–23]. Moreover, the fact that the optical properties of metallic and semiconductor nanoparticles are dependent on their shape, size, and the surrounding dielectric media [24–28] makes then easily exploitable for engineering highly solar selective nanoparticle dispersions at very low volume fractions.

The present work serves to understand the heat transfer mechanism in a volumetric absorption system employing nanoparticles-dispersions (amorphous carbon nanoparticles dispersed in ethylene glycol and MWCNTs dispersed in distilled water) as the working fluid. In order to assess the potential of volumetric absorption systems as efficient solar energy harvesters, these have been compared to a surface absorption-based system (employing TiNOX® copper coated substrate as the absorber material).

2. Theoretical basis

Energy conversion process in solar thermal systems involves the conversion of solar radiant energy into the thermal energy of the working fluid. In the first step, the solar irradiance is absorbed by a solar selective surface (in conventional surface absorption-based systems) or by the nanoparticles (in the case of volumetric absorption systems). In the second step, this absorbed energy is transferred to the fluid through conduction and convection heat transfer.

2.1. Radiative heat transfer in surface and volumetric absorption-based systems

Radiative heat transfer is one of the key heat transfer mechanisms which dictate the solar irradiance absorption capability and the losses from these solar thermal systems. Therefore, in order to assess the performance of the solar thermal systems, it is imperative to understand radiative heat transfer mechanism pertinent to volumetric and surface absorption-based systems.

Solar irradiance absorption capability in the case of surface absorption systems is characteristic of the surface material. A surface having absorptivity α_s is able to absorb absorptivity times the incident flux ($\alpha_s I_0$) [see Fig. 1(a)]. In the case of volumetric absorption systems, it depends on both the material (absorption coefficient $K_{a,v}$) and the thickness (y) of the liquid layer. Eqs. (1) and (2) depict the energy absorption capability for the volumetric absorption configurations [29] in Fig. 1(b) and (c), respectively.

$$E_{absorbed} = I_0[1 - \exp(-K_{a,v}y)] \tag{1}$$

$$E_{absorbed} = I_0[1 - \exp(-K_{a,1}y_1 - K_{a,2}y_2 \cdots\cdots - K_{a,n-1}y_{n-1} - K_{a,n}y_n)] \tag{2}$$

Now, if this liquid layer happens to be a nanofluid, then absorption capability can be easily engineered through control of volume fraction of nanoparticles and the layer thickness. The configuration in Fig. 1(c) is particularly interesting, since real nanofluid-based volumetric systems could be designed with different layers having different optical absorptivity values. These layers would create a non-uniform spatial distribution (arising from the flow profile, thermophoresis, or other phenomena), size distribution, and agglomeration of the nanoparticles. In effect, it is possible to design a volumetric absorption system such that it has absorptivity [for instance, a nanofluid layer (amorphous carbon nanoparticles dispersed in ethylene glycol) of 2 cm can theoretically absorb about 99% of the incident solar irradiance] greater than equal to that of commercially available solar selective surfaces [such as TiNOX® coated copper substrate (actually constituted of multiple layers such as protective antireflective layer, absorber layer, bonding layer, and copper substrate) having solar weighted absorptivity of 95% [30]].

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