Renewable Energy xxx (2017) 1–14

Contents lists available at ScienceDirect

Renewable Energy

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

Modelling of a direct absorption solar receiver using carbon based nanofluids under concentrated solar radiation

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ARTICLE INFO

Article history:
Received 23 January 2017
Received in revised form
28 April 2017
Accepted 6 June 2017
Available online xxx

Keywords:
Nanofluids
DASC
Direct absorption
Solar collector

ABSTRACT

The addition of nanoparticles in a base fluid can enhance its optical properties, in particular its absorption properties. Thus, nanofluids can be successfully used in solar collectors to absorb the solar radiation in their volume and avoid using an absorber plate. This paper investigates the application of aqueous suspensions as volumetric absorber in a concentrating direct absorption solar collector: a suspension of single wall carbon nanohorns (SWCNHs) in water is chosen as the nanofluid. A model of a solar receiver with a planar geometry to be installed in a parabolic trough concentrator is developed: the radiative transfer equation in participating medium and the energy equation are numerically solved to predict the thermal performance of the receiver. The developed model is capable to predict the temperature distribution, heat transfer rate and penetration distance of the concentrated solar radiation inside the nanofluid volume. The simulated performance of the direct absorption receiver has been compared with calculations and experimental data of two surface absorption conventional receivers under the same operating conditions.

1. Introduction

In solar thermal systems, the solar radiation is absorbed and transferred to a heat transfer fluid by means of solar collectors. The thermal performance of a solar collector can be evaluated by accounting the thermal and optical losses. Thermal energy is lost from the collector to the surroundings by conduction, convection and infrared radiation, while optical losses take account of the non-unitary transmittance and absorbance of the transparent cover and absorber medium, respectively. To achieve high performance, solar collectors should enhance the absorption from the sun and increase the heat transfer rate to the fluid decreasing heat losses to the surroundings such as reflection of sun radiation and heat transfer from the system to the surroundings [1].

In conventional solar thermal collectors, the photo-thermal conversion happens in a two-steps process: the solar radiation heats an absorber surface and then, part of the heat is transferred to the working fluid driven by a temperature difference. Due to the thermal resistance at the interface between the absorber surface and the heat transfer fluid, the effectiveness of the conversion is limited. A method to reduce the interface thermal resistance is to replace the absorber surface with the volumetric absorption in the working fluid. For this purpose, nanofluids present good prospect to successfully enhance the solar collector efficiency [2–4].

The concept of direct absorption of solar radiation was presented in the 70's as a simplification of conventional collector design to potentially enhance the efficiency by absorbing solar radiation within the fluid volume [5]. Minardi and Chuang [6] were the first to present a direct absorption solar collector using a suspension of micro-sized carbonaceous particles in shellac, known as India Ink, as volumetric receiver. Only in the last decades, thanks to the technological progress in the production of nanoparticles and preparation of nanofluids, the research community has found a renewed interest in direct absorption solar collectors (DASCs). Nanofluids are diluted suspensions of solid nanoparticles with a diameter less than 100 nm in a base fluid. Choi et al. [7] conceived these advanced fluids as substitutes of traditional media in processes that require highly efficient heat transfer. Numerous experimental and theoretical works on the application of nanofluids as heat transfer fluid in solar thermal system have been done, as reported by Lomascolo et al. [8] and by Kakaç et al. [9]. However, the

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http://dx.doi.org/10.1016/j.renene.2017.06.029
0960-1481/

Abbreviations

CFD	computational flow dynamics
CNT	carbon nanotube
CTAB	cetyl trimethylammonium bromide
DASC	direct absorption solar collector
DO	discrete ordinates (method)
EG	ethylene glycol
MWCNT	multi-wall carbon nanotube
PEEK	Polyetheretherketone
PTFE	Polytetrafluoroethylene
PG	propylene glycol
PTC	parabolic trough collector
RTE	radiative transfer equation
SST	shear stress transport (model)
SWCNH	single-wall carbon nanohorn

thermal properties of nanofluids are not a key issue in this paper. In fact, some nanofluids present peculiar optic properties that allow their use as absorbing and heat transfer medium in DASCs. In this kind of devices, the absorption of the solar radiation occurs directly in the fluid volume instead of being limited to the receiving surface. The main advantage of direct absorption of solar radiation is to avoid the thermal resistance between absorber surface and heat transfer fluid. Fig. 1 reports a schematic comparison between a conventional solar thermal collector and a direct absorption solar collector in terms of thermal resistances as can be found in Ref. [10]. Furthermore, the nanoparticles amount needed to enhance the optical properties of the base fluid is much smaller than that required to vary the thermo-physical properties of the heat transfer fluid.

2. Literature review on numerical studies on DASC

Several reviews on the application of nanofluid in solar energy were published in the last years. In the paper of Mahian et al. [11], current applications, future work and challenges of nanofluids in solar energy have been discussed. They concluded that experimental and numerical studies on solar collectors, in some cases,

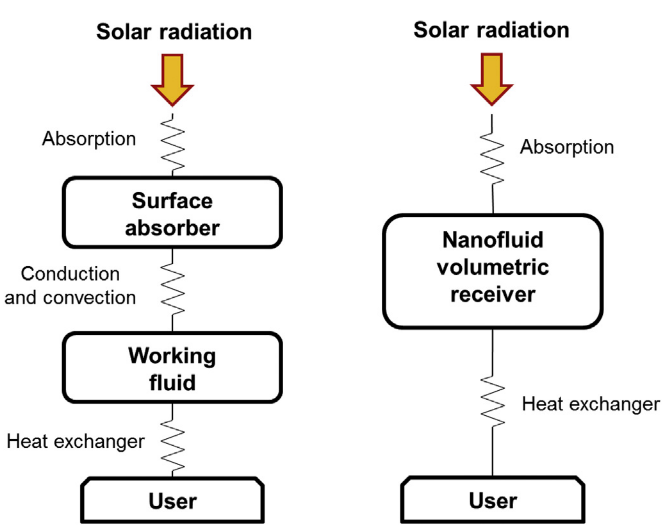

Fig. 1. Resistance network for the heat gain: comparison between conventional solar thermal collector (left) and direct absorption solar collector (right).

have been shown that the efficiency could be increased remarkably by the use of nanofluids. Javadi et al. [1] surveyed the main experimental and numerical works on the improvement of solar collectors by using nanofluids. The review of Verma et al. [12] focused on the progress of nanofluid application in solar collectors. Both experiments and models were reviewed. Sarsam et al. [3] limited their revision on the use of nanofluids in conventional solar collectors. After providing an overview on the experimental and numerical works that can be found in the literature, the authors identified the most significant challenges on using nanofluids in flat plate solar collectors. Recently, Leong et al. [13] presented an overview on current applications of nanofluids in solar systems. They observed that concentrating solar collectors such as parabolic trough collectors (PTC) have been given less attention among the researchers. The authors discussed several issues that need further investigation. Muhammad et al. [14] reviewed the use of nanofluids as heat transfer fluids and as volumetric absorbing fluids for enhancing the thermal performance of stationary solar collectors. The authors also discussed the impact of nanofluid usage in solar collector based on economic and environmental viewpoints. Other reviews on nanofluids in solar energy were presented by Borzogan & Shafahi [2], Saidur et al. [4], Abdin et al. [15], Nagarajan et al. [16], Hussein et al. [17] and Hossain et al. [18].

From all these reviews, it can be observed that in the last decades much effort has been made to perform both experimental and numerical studies. The most relevant numerical studies on the application of nanofluids in DASCs are presented in this paragraph and listed in Table 1.

Tyagi et al. [19] studied theoretically the use of Al_2O_3 water based nanofluids in low-temperature DASC. Using a steady-state two-dimensional model for heat transfer, they investigated the effects of different parameters on the efficiency of the collector. The results revealed that the efficiency increases slightly with an increase in the size of the nanoparticles. Otanicar et al. [20], based on the work of Tyagi et al. [19], have numerically evaluated the thermal performance of DASC for low-temperature applications based on nanofluids made from a variety of nanoparticles. In addition, the numerical model was compared with experimental data of a solar collector with direct absorption nanofluids. The experimental and numerical results demonstrated an initial rapid increase in efficiency with volume fraction, followed by a levelling off in efficiency as volume fraction continues to increase. They observed efficiency improvements up to 5% in solar thermal collectors by utilizing nanofluids for the absorption mechanism. Khullar and Tyagi [21] numerically investigated aluminium nanoparticles dispersed in different base-fluids (water, ethylene glycol, propylene glycol and Therminol® VP-1) for their suitability as working fluid in direct absorption linear parabolic solar collectors finding very similar results for all four nanofluids. In the work of Khullar et al. [22], the idea of harvesting solar radiation through usage of nanofluid-based parabolic solar concentrating collectors has been numerically explored. Veeraragavan et al. [23] have analytically investigated the effect of heat losses, solar concentration, nanoparticles loading and channel height on the efficiency of a volumetric flow receiver. Absorption of the solar radiation was modelled as a volumetric heat release inside the flowing nanofluid. They apply the developed model to a case study with graphite nanoparticles suspended in Therminol® VP-1. Ladjevardi et al. [24] investigated the applicability of graphite nanofluids in direct solar energy absorption. They developed a numerical code to study the effects of particles size and volume fraction on the extinction coefficient and efficiency of the solar collector. A model of transparent PTC based on gas-phase nanofluids has been presented by de Risi et al. [25]. The proposed solar collector has been modelled by means of a discretization in space under the assumptions of quasi steady-state conditions. The