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Numerical simulations of a parabolic trough solar collector with nanofluid using a two-phase model

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ABSTRACT

This study investigates numerically, in terms of Computational Fluid Dynamics (CFD), a Parabolic Trough Collector (PTC) system with nanofluid as the Heat Transfer Fluid (HTF). All the heat transfer mechanisms were taken into account to simulate the SEGS LS2-module PTC. The validation process showed very good agreement between the numerical results and the available test results from four typical testing conditions, with the use of Syltherm 800 liquid oil. Specifically, the maximum relative error observed for outlet temperature was 0.3% and 7.3% for the collector efficiency. In order to address the nanofluid modeling problem the two-phase approach was preferred (against single-phase) and validated against experimental and numerical results for a circular tube under constant wall temperature. Overall, a total of 20 different simulation cases were performed for the LS2 module, for a range of nanoparticle (Al_2O_3) concentrations (0%–4%), thus making it possible for a parametric evaluation on the LS2 efficiency. In addition, the temperature and velocity fields of the Syltherm 800/Al_2O_3 nanofluid were associated with the enhanced heat transfer occurring at higher nanoparticle concentrations. A boost up to 10% on the collector efficiency was reported for Al_2O_3 concentration of 4%, which is in accordance with relevant studies.

1. Introduction

1.1. Parabolic trough solar collectors – numerical modeling

Parabolic trough solar collectors (PTC) are systems with light structures and low cost technology that deliver high temperatures with good efficiency. A metal tube, covered with a glass tube to reduce heat losses, is placed along the focal line of the receiver (Fig. 1). Several prototype and commercial PTCs were manufactured over the last four decades and relevant experimental studies were conducted. One of the types most extensively investigated, being also the PTC type of interest here, is the SEGS LS-2 module, for which experimental data were obtained by Dudley et al. [1], aiming at calculating its thermal performance and heat losses.

Furthermore, over the past decade, ever increasing capabilities have become available for also addressing PTC systems numerically, in terms of Computational Fluid Dynamics (CFD). The relevant scientific studies focused mainly on two different flow configurations and respective computational domains: one that comprises the absorber tube and the heat transfer fluid, and a second type that addresses the entire PTC system (absorber tube, heat transfer fluid, glass cover and annulus space between absorber and glass cover).

Concerning the first type, He et al. [2] and Sadaghiyani et al. [3] used a coupled simulation method based on Monte Carlo Ray Tracing (MCRT) and CFD software to solve the complex coupled heat transfer problem in the LS-2 PTC, evaluating among others the collector performance. Studies that belong in the second category include, Cheng et al. [4] who used numerical simulations of coupled heat transfer characteristics in the receiver tube in combination with the MCRT method and the FLUENT software, in which the heat transfer fluid and physical model were Syltherm 800 liquid oil and LS2 parabolic solar collector from the testing experiment of Dudley et al. [1], respectively. Cheng et al. [5] extended the work of Cheng et al. [4] studying typical heat transfer fluid types and residual gas conditions.

As in the aforementioned studies, Islam et al. [6] also used LS2 [1] module to perform conjugate heat transfer simulations for a concentrating solar thermal collector, with modeling heat transfer performances of faceted absorbers for concentrating photovoltaic

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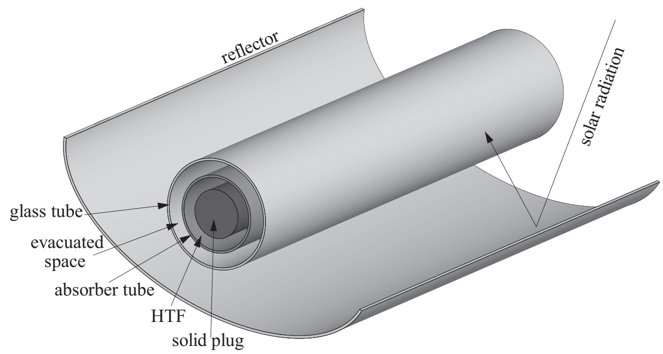

Fig. 1. Physical model of the LS-2 parabolic trough solar collector.

applications in mind. Mwesigye et al. [7] conducted numerical simulations for the LS2 module in which they added perforated plate inserts. Wang et al. [8] used a solar ray trace method and the finite element method (FEM) to solve the complex problem coupled with fluid flow, heat transfer and thermal stress in a PTC system.

1.2. Enhanced thermal behavior of solar systems using nanofluids

Recent studies have shown that a promising technique to improve thermal conductivities of heat transfer fluids and therefore to enhance heat transfer, is to suspend solid particles of nanoscale dimensions in the fluids to create suspensions known as *nanofluids*. Even though the anomalous increase in the thermal conductivity with respect to the base fluid presented in early studies on nanofluids could not be confirmed in later experiments (such as the benchmark study of Buongiorno [9] with over 30 participants worldwide), research on the application of nanofluids in various fields, among them solar energy utilization, has been steadily growing over the past few years. This is reflected in quite a few recent literature reviews [10–14]. Aside from the original focus on thermal conductivity, other features of nanofluids such as optical properties, efficiency and transmission as well as extinction coefficients of solar systems have made them more attractive in this field compared to conventional fluids [13]. Some limitations are certainly also present, such as instability, agglomeration, increased pumping power, erosion and corrosion of the heat transfer equipment [14].

1.2.1. Experimental studies

Flat plate solar collectors occupy a large portion of the relevant literature on experimental studies carried out to this day, whereby efficiencies have been found to increase by up to 30% with the use of nanofluids [13]. The literature also shows that a much investigated system of application is the direct absorption collector as well as the photovoltaic-thermal (PVT) collector, where the enhancement is more significant [14]. On the other hand, limited number of studies have been conducted on application of nanofluids in concentrating collectors such as the PTC.

Jafar and Sivaraman [15] carried out an experimental investigation of a PTC with a Al_2O_3/water nanofluid in conjunction with nail twisted tape inserts, under laminar flow conditions. Heat transfer was found to increase through the use of the nanofluid, with a further enhancement due to the effect of the twisted tapes. More recently Kasaeian et al. [16] in an experimental study have considered a PTC with multi walled carbon nanotube (MWCNT)/oil based nanofluid as the working fluid. Their results showed an efficiency improved by up to 7% compared to pure oil. Turkyilmazoglu [17] also studied the heat transfer enhancement effects of nanofluids in circular concentric pipes under the influence of partial velocity slips on the surfaces. He used a single phase nanofluid model to get the fully developed exact laminar flow and temperature fields.

1.2.2. Computational studies

Concerning now computational studies that include the use of nanofluids with configurations that are close to the LS2 module, Moghari et al. [18] studied heat transfer enhancement of a mixed convection, laminar Al_2O_3/water nanofluid flow, in an annulus with constant heat flux boundary condition employing two phase mixture model. Their simulation results showed that at a given Reynolds (Re) and Grashof (Gr) numbers, increasing nanoparticles volume fraction increases the Nusselt number and that the inner wall had larger values than their corresponding values at the outer wall.

Kasaeian et al. [19] studied the fully developed turbulent mixed convection heat transfer of Al_2O_3/synthetic oil nanofluid numerically (with single-phase approach) in a PTC with uniform heat flux. Their results showed that the Nusselt numbers and the convection heat transfer coefficients have a direct dependency on the volume fraction of the nanofluid.

Khullar et al. [20] have considered also the enhancements arising from the improved optical properties of a nanofluid (absorption, scattering) in their modeling of a parabolic collector with aluminum nanoparticles dispersed in Therminol-VP1. They developed a two-dimensional heat transfer model which incorporated volumetric absorption effects in terms of absorption and scattering mechanisms. Improvements in efficiency of 5–10% were found compared to a conventional concentrating parabolic collector.

Sokhansefat et al. [21] studied the three-dimensional fully developed turbulent mixed convection heat transfer of Al_2O_3/synthetic oil nanofluid in a trough collector tube with a non-uniform heat flux. They also investigated the effect of Al_2O_3 particle concentration in the synthetic oil on the rate of heat transfer from the absorber tube, using the FLUENT software and the single-phase approach in order to simulate the effect of the nanoparticles.

It becomes evident from the above that there is a very limited number of studies incorporating nanofluids in PTCs. Furthermore, the use of the two-phase approach in modeling nanofluids, has been shown in comprehensive relevant review studies, for instance the one by Vanaki et al. [22], to give more accurate results in most problems investigated compared to the single-phase approach. More specifically, in Ref. [22], comparisons between the two approaches were reviewed for single- and two-phase nanofluids, for laminar and turbulent forced and mixed convection in various geometries against experimental data. The performance of the two models was quite problem-dependent and determined by the Reynolds number, the flow regime and the particle concentration in particular. Generally, however, where quantitative data for the discrepancies were provided, values for the two-phase model were mostly less than 10%, whereas for the single-phase, homogeneous model the respective values, even though small in some cases, were mostly higher than 10% with values as high as 30% reported in one study.

In view of the above, the goal of the present study is to approach numerically, the use of nanofluids in a common PTC module (such as the LS-2 of Dudley et al. [1]), with the more accurate two-phase approach and examine the fluid flow and heat transfer characteristics of such configuration. Furthermore, realistic thermal boundary conditions are employed, taking into account the actual radiative flux distribution on the tube absorbing surface using an optical analysis model.