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Ag-based nanofluidic system to enhance heat transfer fluids for concentrating solar power: Nano-level insights

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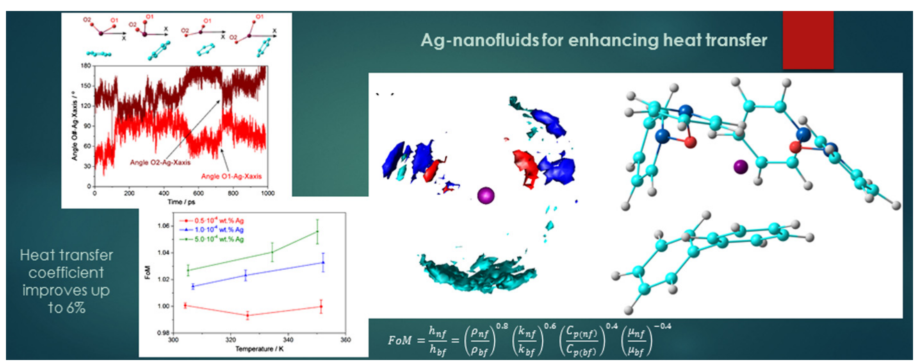
HIGHLIGHTS

- Ag-based nanofluid improves the heat transfer process in Concentrating Solar Power.
- The isobaric specific heat and thermal conductivity were improved.
- MD calculations were performed to reach a better understanding of the nanofluid.
- The arrangement of the base fluid around the nanoparticles is revealed from MD results.

GRAPHICAL ABSTRACT



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ABSTRACT

One of the possible research lines for improving the Concentrated Solar Power (CSP) technology is the enhancement of the thermophysical properties of the Heat Transfer Fluids (HTF) used. This enhancement leads to reduce costs for producing electricity using this technology. So, this study presents the preparation of nanofluids in which Ag nanoparticles were added to a base fluid composed of a eutectic mixture of diphenyl oxide and biphenyl. The base fluid is a heat transfer fluid commonly used in concentrating solar power plants. The nanofluids were shown to have improved thermal properties, the heat transfer coefficient increasing by up to 6% compared with the base fluid. Thus, their use could lead to enhancements in the overall efficiency of CSP plants. Accordingly, nanofluids were prepared with varying nanoparticle concentrations and their properties were characterized, including their physical and chemical stability, viscosity, isobaric specific heat and thermal conductivity. In addition, molecular dynamic calculations were performed to reach a better understanding of the nanofluid system at a molecular level. The isobaric specific heat and thermal conductivity values followed the same experimental tendency. An analysis of the radial distribution functions (RDFs) and spatial distribution functions (SDFs) shows that there is a first layer of base fluid molecules around the metal in which the oxygen atoms play an important role. This first layer encourages the directionality of the movement in the heart of the nanofluid, which leads to enhanced thermal properties.

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1. Introduction

One of the challenges facing society today is the need to meet the growing demand for energy while minimalizing the environmental impact on the planet [1]. Solar energy is a renewable source of energy that can be used to a large extent to this end [2]. In fact, global solar radiation flux can reach values of *c.a.* 900–1000 W/m^2 on summer days [3]. In this regard, the conversion of solar energy into electricity is of interest, and concentrating solar power (CSP) systems play an important role as the thermal energy converters used in electric power generation [4,5]. To do this, high temperatures (400–500 °C or higher) must be reached and CSP systems achieve this by concentrating solar radiation on special receivers, converting solar radiation into thermal energy [2,6]. The different kinds of receivers are designed to capture the maximum amount of radiation reaching them, and they can be classified according to their focus geometry as point- and line-focus concentrators. Examples of focus concentrators are solar tower systems and parabolic dishes, while line-focus concentrators include linear Fresnel and parabolic-trough collectors (PTCs) [6,7]. Among these, PTCs are the systems generating the most commercial interest [4,7]. The PTC solar field can be integrated in a steam turbine plant either directly, through a direct steam generator (DSG technology), or indirectly, by heating thermal oil for generating steam in a heat exchanger (HTF technology) [6].

As a result, different lines of research are trying to improve the global efficiency of the plants by taking on board the new knowledge gained. One line of research is related with improving the thermal properties of the heat transfer fluid (HTF) used in CSP plants based on parabolic cylinder collectors. These collectors are responsible for storing and transporting the heat generated [7–9]. Improving the thermophysical properties of the fluids used is of particular interest for enhancing the heat transfer processes that take place in these plants as this should result in an increase in their overall efficiency. In this sense, the use of nanofluids has been shown to be an interesting option for enhancing the thermal properties of base fluids [7–14]. Nanofluids are colloidal suspensions of nanometric particles in a base fluid. Suspending nanoparticles in an HTF has been shown to improve such properties as its thermal conductivity, heat transfer coefficient or isobaric specific heat [10,11,15–18]. In turn, an increase in thermal conductivity is known to make HTFs more efficient. However, there are not many studies in the literature about nanofluids based on the HTFs used in CSP plants because most of the studies are based on fluids for low-temperature applications such as water or ethylene glycol. Furthermore, with the HTFs used in CSPs it is necessary to use low concentrations of nanoparticles. These analyses are not common in the literature since heat transfer may take place through particle-particle contact [19] and so high concentrations of nanoparticles are normally used. But the use of high concentrations also has the drawback of significant increases in viscosity.

Thus, the review of the literature reveals that CSP is one of the most interesting alternatives to conventional energy sources nowadays, and that there are advantages to be gained from the use nanofluids in CSP for high temperature applications. In this sense, the study of new nanofluids prepared with heat transfer fluids other than water or ethylene glycol is of great interest, particularly if these fluids are to have a future commercial use. The use of nanofluids within the heat transfer energy market is forecast to increase by over 2 billion dollars in the future, making it a promising field of study [20,21]. Thus, effective nanofluids that can optimise the use of a resources such as solar energy are candidates for consideration as value-added materials that produced a decreased impact on the environment [22,23].

This study has used nanofluids based on a eutectic mixture of biphenyl ($C_{12}H_{10}$) and diphenyl oxide ($C_{12}H_{10}O$), a HTF used in CSP plants. These fluids are not usually studied, unlike conventional ones, such as water or ethylene glycol (typical heat transfer fluids) [24]. Commercial Ag was used in three low concentrations. Metal nanoparticles were chosen because several studies have reported that they increase thermal conductivity [10,15,25–28], while low concentrations were used to prevent significant increases in viscosity. Also, several studies have reported improvements in some thermal properties of nanofluids with low concentrations of metal nanoparticles. For example, Patel et al. reported a significant increase in the effective thermal conductivity of nanofluids with Au, using toluene as the base fluid [26]. To determine how adding nanoparticles affected the base fluid, some properties of the nanofluids prepared were characterized, including their chemical and physical stability, density, viscosity, isobaric specific heat and thermal conductivity. In addition, to understand the molecular behaviour of this kind of nanofluid systems, molecular dynamics simulations were performed. The highest experimental concentration of Ag in the base fluid ($5.0 \cdot 10^{-4}$ wt.%) was chosen. The isobaric specific heat, diffusivity and thermal conductivity values were obtained and compared with the experimental values, a good correlation being observed. Finally, the structural properties of the nanofluid system were obtained by analysing their radial distribution functions (RDF) and spatial distribution functions (SDF). The analysis of the theoretical results showed that the interaction between the metal and base fluid plays an important role in enhancing the thermal properties of these systems. The synergy between the experimental and theoretical results in order to understand the thermal behaviour in the nanofluid system is a new approach for the study of this kind of systems. Clearly, this approach is original, and the explanation of the macroscopic properties based on nano-level interactions is a real advance in the analysis of nanofluids.

2. Material and methods

2.1. Experimental

The nanofluids used in this study were prepared following a two-step method [29]. The first step involves synthesizing the nanomaterial to be used and the second consists of dispersing the nanomaterial in the fluid base. The base fluid was a commercial heat transfer fluid composed of the eutectic mixture of biphenyl ($C_{12}H_{10}$, 26.5%) and diphenyl oxide ($C_{12}H_{10}O$, 73.5%), supplied by The Dow Chemical Company©, model Dowtherm A. These compounds have practically the same vapour pressures so the mixture can be treated as if it were a single compound. The nanomaterials used were commercial Ag nanoparticles (purity ≥99%, density 10,490 kg m^{-3} at 298 K, Sigma-Aldrich) with a particle size of <100 nm.

To prepare the nanofluids, an initial nanofluid was prepared with a mass concentration of 0.01 wt.%. They were prepared using 100 mL of the base fluid, the quantity of nanoparticles to obtain the stated concentration and the same amount of polyethylene glycol (PEG, MW: 400, Sigma-Aldrich). A sonication method was used to obtain the colloidal suspension of nanoparticles. It was applied for 3 h (~50 W output power) using a Sonics Vibra Cell VCX 750 sonicator, controlling the evaporation of the base fluid. Aliquots were taken from the initial nanofluid to prepare nanofluids with a mass concentration of $0.5 \cdot 10^{-4}$, $1.0 \cdot 10^{-4}$ and $5.0 \cdot 10^{-4}$ wt.%, adding base fluid until reaching 100 mL. Next, the nanoparticles were dispersed again following the procedure described above.

Several properties of the nanofluids prepared were characterized. Their chemical stability was analysed using Vis-NIR

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