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Dramatically enhanced thermal properties for TiO_2-based nanofluids for being used as heat transfer fluids in concentrating solar power plants

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ABSTRACT

The paper presents an analysis of the properties of TiO_2-based nanofluids such as their physical stability and heat transfer performance. The nanofluids were prepared with a eutectic mixture of diphenyl oxide and biphenyl with the addition of TiO_2 nanoparticles and 1-octadecanethiol (ODT), used as a surfactant. The nanofluids were tested to determine their thermal and physical properties, such as stability, density, viscosity. The introduction of TiO_2 nanoparticles accompanied with equal quantity of ODT was seen to sharply enhance the properties of the system in terms of heat transfer in concentrating solar power (CSP) plants. In particular, the system became stable after 3–5 days, and the settlement rate depended on the nanoparticle concentration. There was a slight increase in density and viscosity of no more than 0.12% and 4.85%, respectively. The thermal properties improved significantly, up to 52.7% for the isobaric specific heat and up to 25.8% for the thermal conductivity. The dimensionless Figure of Merit parameter (FoM), which is based on the Dittus-Boelter correlation, was used as a criterion for evaluating efficiency. At all the temperatures tested the nanofluid with $2.5 \cdot 10^{-4}$ wt% (volume fraction of 2.44%) of TiO_2 performed best, increasing the efficiency by up to 35.4% with regard to the pure heat transfer fluid (HTF) used in CSP plants. Thus, nanofluids based on TiO_2 nanoparticles seem to be a promising alternative to HTFs in CSP plants.

1. Introduction

Nowadays, alternative energy sources are of a great interest and importance and one of the strategic aims of modern science is to develop them and make them popular. Concentrating solar power (CSP) has been recognized as a promising source of renewable energy due to its minimized environmental impact on the planet compared with conventional energy sources [1]. CSP plants operate by converting the solar energy that is spontaneously concentrated on the collectors due to irradiation into electricity. Concentrators can be classified according to their focus geometry into two groups: point-focus concentrators and line-focus concentrators. The point-focus concentrators group consists of solar tower systems and parabolic dishes, while line-focus concentrators include linear Fresnel and parabolic-trough collectors (PTCs) [2,3]. The largest commercial interest is generated by PTCs [3,4], technology that 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) [2]. The variety of technologies results in different research lines that are trying to enhance the overall efficiency of the plants by acquiring new knowledge and improving the fundamental understandings.

One of the research lines is related with the heat transfer fluid (HTF) used in CSP plants. These plants are based on cylindrical collectors, which are responsible for storing and transporting the heat generated [1,3,5], Increasing the efficiency of the plants by improving the thermophysical properties of the heat transfer fluids

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Nomenclature

ρ	Density kg m^{-3}
φ	Volume fraction %
μ	Dynamic viscosity mPa s
h	Heat transfer coefficient a.u.
k	Thermal conductivity W m^{-1} K^{-1}
D	Thermal diffusivity mm^2 s^{-1}
C_p	Isobaric specific heat J kg^{-1} K^{-1}
ζ	Zeta potential mV
κ	Boltzmann constant m^2 kg s^{-2} K^{-1}
η	Collector efficiency
$\dot{m}$	Flux mass kg s^{-1}
$T_{m,i}$	Inlet temperature K
$T_{m,i}$	Outlet temperature K
A	Cross-sectional area of the pipe m^2
G_t	Global solar irradiance W m^{-2}
T_s	Pipe surface temperature K
q_s''	Heat flux J s^{-1}

Subscripts

eff	Effective
bf	Base fluid
nf	Nanofluid
NP or np	Nanoparticle

Abbreviations

HTF	Heat Transfer Fluid
CSP	Concentrating Solar Plant
PTC	Parabolic-through collectors
CHF	Critical Heat Flux
SAA	Surface Active Agent
ODT	1-Octadecanethiol
DLS	Dynamic Light Scattering
TMDSC	Temperature Modulated Differential Scanning Calorimeter
LFA	Laser Flash Analysis

used is of particular interest as far as one main aim is to enhance the heat transfer processes that take place in these plants. Considering the above, introducing nanoparticles into the HTF to produce nanofluids could be a promising option for enhancing the thermal properties of the HTF as nanoparticles have been proven to be strong modifiers [1,3,5–10].

Nanofluids are colloidal suspensions of nanometric particles in a base fluid. Previous studies have shown that suspending nanoparticles in a HTF can improve some properties such as its thermal conductivity, heat transfer coefficient and isobaric specific heat [6,7,11–14]. In turn, an increase in thermal conductivity is known to make HTF more efficient.

Most of the nanofluid-related studies investigated low-temperature applications. As a result, little research has been done into nanofluids based on the HTF used in CSP plants, which is evidenced by the small amount of literature available. Moreover, the HTF used in CSP plants generally requires the use of low concentrations of nanoparticles. Few such research studies can be found in the literature since heat transfer may take place through particle-particle contact [15] and high concentrations of nanoparticles are normally used. However, the use of high concentrations also has the drawback of significant increases in viscosity, the agglomeration of nanoparticles and subsequently sedimentation. Nevertheless, some authors have reported significant improvements in nanofluids with low nanoparticle concentrations. Patel et al. [16] showed a sharp increase in the effective thermal conductivity of Au-based nanofluids using toluene as the base fluid at a very low concentration of Au nanoparticles. Wei et al. also reported the enhanced thermal conductivity of nanofluids with low concentrations of CuS/Cu_2S [17] and Cu_2O [18]. In our previous research, we tested some nanofluids with metal nanoparticles such as Cu and Ni and showed considerable increases in thermal properties and heat transfer efficiency accompanied by high physical and chemical stability [1]. There is great number of studies involving low temperature oxide-based nanofluids. Particularly, Kim et al. [19] reported that very dilute dispersions of alumina, zirconia and silica nanoparticles in water showed significant critical heat flux (CHF) enhancement. TiO_2-based nanofluids play an important role in studies of oxide nanofluids, evidenced by a large number of papers devoted to dispersions of such species in water and other low temperature fluids such as ethylene glycol [20]. Moreover, TiO_2 is considered one of the best materials for real-world use since it is safer and has better qualities. For example, it is not toxic, which is an essential requirement for its large-scale application [21]. TiO_2 is not toxic itself, but effects of the interaction of human beings and nanoparticles are under investigation. In the case of TiO_2, some problems can occur if a high number of nanoparticles are ingested [22] but this would occur with all kind of nanoparticles. Also, TiO_2 nanoparticles are and it is produced on an industrial scale, making it economical and appropriate for high-volume applications in the thermal fluid field. Moreover, TiO_2 nanoparticles show chemical stability, acid and caustic corrosion resistance as well as high temperature resistance [21]. Finally, TiO_2 nanoparticles have shown excellent dispersivity in both polar and non-polar base fluids, and it can be further improved by adding specialized dispersants [20].

Abbassi et al. [23] reported that for low concentrations of TiO_2 nanoparticles in water any negative changes due to the low concentration were not significant enough to outweigh the benefits from other characteristics such as CHF. Thus, the possibility of some enhanced thermal properties without any major negative effects motivated us to use nanofluids with very low concentrations of TiO_2.

This study used as a base fluid nanofluids based on a eutectic mixture of biphenyl ($C_{12}H_{10}$) and diphenyl oxide ($C_{12}H_{10}O$), namely the HTF used in CSP plants [24,25]. These fluids are not usually studied, unlike conventional ones such as water or ethylene glycol [26]. Commercial TiO_2 was used in different concentrations with three different nanoparticle-surfactant ratios. Low concentrations were used to prevent significant increases in viscosity and decreases in the physical stability of the system. Their physical stability was studied by means of particle size, ζ potential and UV–vis spectroscopy measurements as functions of time. The efficiency of the nanofluids was analyzed from measurements of density, viscosity, isobaric specific heat and thermal conductivity, the latter calculated as a ratio between the heat transfer coefficient of a nanofluid and that of a base fluid.

2. Materials and methods

2.1. Preparation of TiO_2-ODT nanofluids

The nanofluids were prepared following the two-step method [27]. The first involves synthesizing the nanomaterial to be used