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Effect of temperature and CuO-nanoparticle concentration on the thermal conductivity and viscosity of an organic phase-change material

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ABSTRACT

The main results of an experimental study of the effect of temperature and nanoparticle concentration on thermal conductivity and viscosity of a nanofluid are shown. The nanofluid was prepared with Octadecane, an alkane hydrocarbon with the chemical formula $CH_3(CH_2)_{16}CH_3$, as a base fluid and 75-nm CuO spherical nanoparticles. Since the base fluid is a phase change material (PCM) to be used in thermal storage applications, the engineered nanofluid is referred to as Nano-PCM. Three Nano-PCMs were prepared by the two-step method (2.5% w/v, 5.0% w/v, and 10.0% w/v). In order to increase the stability of the Nano-PCM, the surface of the CuO nanoparticles were modified with Sodium oleate, and it was verified by IR analysis. The modified CuO nanoparticles were dispersed with an ultrasonic horn. The thermal conductivity was measured with a thermal properties analyzer in the temperature range of 30–40 °C. The viscosity was measured in the temperature range of 30–55 °C. The results for the Nano-PCM showed that thermal conductivity is almost constant in the analyzed temperature range, and the viscosity decreases non-linearly with temperature. With respect to the effect of nanoparticle concentration, both thermal conductivity and viscosity increased with nanoparticle concentration. Thermal conductivity increased up to 9% with respect to the base fluid, and viscosity increased up to 60%, in both cases with increasing concentration. Finally, the viscosity measurements for different deformation rates (30–80 RPM) showed that the addition of nanoparticles modifies the rheological behavior of the base fluid, from a Newtonian to a shear thinning (power-law) non-Newtonian behavior.

1. Introduction

One approach to satisfy the demand of energy is to implement thermal storage systems, which are interesting and efficient alternatives for storing and supplying energy. Energy can be stored in three different ways; such as mechanical, electrical, and thermal energy [1]. These alternatives encompass the main current lines of research on systems and devices for energy storage. The storage of thermal energy consists in saving cold or heat for later use. The operation of these storage systems is based on the principle of the conservation of energy [2–4].

In the particular case of latent heat thermal storage systems, phase change materials (PCMs) are used, which absorb and release higher densities of energy during the phase change process. Usually, the phase change processes of interest are solidification and melting, since liquid-vapor phase transition involves higher volume changes, and pressure increase is considerable. For a particular application, the mean selection criteria of a PCM are the latent heat and the phase change temperature [5], which should correspond to the particular application. These properties depend mainly on the chemical characteristics of the materials, which can be organic compounds (paraffins, fatty acids, and alcohols), inorganic compounds (water, saline solutions, and hydrated salts), or eutectic mixtures [6]. The energy absorbed as latent heat is much higher than sensible heat. For instance, the heat capacity of a plate of a wall with 30% of PCM can be five times higher than a conventional wall of the same size [7].

In addition to latent heat and the phase change temperature, there are other important physical parameters when a PCM is chosen [8]: (i) an appropriate phase change temperature according to the application and available heat sources, This parameter defines the temperature range of operation of the system; (ii) a high phase change enthalpy, which assures high energy storage density; (iii) cyclic stability, which allows the material to undergo phase transitions as required; (iv) low sub-cooling, in order for the phase change to occur over a narrow temperature range, and it can be achieved easily, otherwise, temperature may increase or decrease substantially only by the change in sensible heat; (v) high thermal

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conductivity, so the absorption and desorption of energy can be achieved easily in a short time for a given volume of PCM.

Among organic PCMs (O-PCMs) we can find paraffins, fatty acids, and alcohols. These materials have a phase change temperature close to the comfort temperature, and the fusion enthalpies per unit volume are lower than those of inorganic PCMs, except for some alcohols. Some advantages of O-PCMs are that they are non-corrosive and they are not prone to sub-cooling, therefore they crystallize easily. Some of their drawbacks are their low thermal conductivities, they undergo important volume changes during phase transition, they are inflammable, their combustion may generate polluting gases, and they are very unstable at high temperatures because the bonds between the atoms are covalent [9]. Paraffins are the most widely used organic PCMs, since they cover a broad range of melting temperatures, even though their phase-change enthalpies are lower than those of other PCMs. These materials are hydrocarbons called alkanes, whose chemical formula is C_nH_{2n+2}, where n is the number of carbon atoms. Generally, the organic PCMs are of great importance in heating and refrigeration applications, especially those paraffins with melting temperatures close to comfort temperatures.

As already mentioned, appropriate PCMs must have high thermal conductivity [3,10], but paraffins have low thermal conductivity, which implies low heat transfer rates in heat storage systems. One approach to increase the thermal conductivity of a PCM is to add high thermal conductivity particles; when these particles are of nanometric size (<100 nm) the obtained material is called nanofluid, a term that was coined in 1995 by Choi and Eastmann [11] to refer to materials obtained from metallic nanoparticles suspended in a heat transfer fluid. The addition of nanoparticles modifies other properties of the base fluid, for instance electric, magnetic, optical, and physical properties such as melting point, thermal conductivity, density, and viscosity, and that is the reason why when a nanofluid is prepared the new properties should be studied in detail [12].

The preparation of a nanofluid is more complex than just adding and mixing nanoparticles in a base fluid, since it is very likely that after some minutes the nanoparticles form agglomerates that then decant. Therefore, the preparation must give rise to a stable nanofluid, that is, one whose nanoparticle composition and distribution remains as long as possible. Several studies have focused on developing preparation methods that give stability to nanofluids. The stability of nanofluids depends on several factors, mainly the chemical nature of the nanoparticles and the base fluid. The current preparation techniques are classified into two groups: Single-step methods and two-step methods [13]. The two-step methods start from the preparation of the nanoparticles as a dry powder by some physical or chemical process, and then, in a second stage, they are dispersed in the base fluid.

This is the most widely used technique, and the most convenient from the economic standpoint if preparation of nanofluids is required at a large scale. However, as time passes, the nanoparticles that are used, which have a high free surface energy, tend to agglomerate and decant [14]. Therefore, in order to achieve good stability, the dispersion of the nanoparticles (second stage) should be made by some high shear stress mixing treatment, or high magnetic or ultrasonic agitation that allows achieving good spreading and disintegration of the formed agglomerations when the materials are mixed. There are other technologies that provide greater stability, for instance the use of surface-active agents like surfactants and dispersants, which avoid the formation of aggregates or modify the pH of the dispersion [15].

Thermal conductivity is the property of the base fluid that it is desired to improve in most cases, and therefore there is a large amount of information available on the variation of this property with temperature and nanoparticle concentration, especially with common heat transfer fluids. Usually, the results reported in the reviewed studies show that the thermal conductivity of the nanofluids decreases as temperature rises, and it increases when nanoparticle concentration is increased. For instance, the results obtained by Masuda et al., remarked by Choi et al. [11], show this behavior. Barbés et al. [16] obtained similar results for a nanofluid prepared from water and copper oxide nanoparticles, the same as Ho et al. [17]. However, Esfe et al. [18], using magnesium hydroxide nanoparticles and ethylene glycol, found the opposite behavior, since for concentrations higher than 0.4% the thermal conductivity increases considerably with temperature. Barbes et al. [16] observed a similar behavior when ethylene glycol and copper oxide were used. A more detailed review of the behavior of the thermal conductivity of nanofluids can be found in the work of Wang et al. [19], who made a compilation of theoretical and experimental studies by different authors.

Regards to viscosity, Einstein proposed a theoretical model to obtain the effective viscosity of a suspension of spherical particles of volumetric concentration lower than 0.02 (v/v), and showed that the viscosity of the suspension is directly proportional to the volumetric concentration of nanoparticles, and it depends on the viscosity of the base fluid [20]. Usually, studies show that viscosity increases as nanoparticle concentration is increased, which means higher pressure loss and higher required pumping power [21]. The increasing viscosity due to the addition of nanoparticles has been reported in several papers, which agree on this general observation. However, with respect to the rheological behavior of these materials, different results have been found. Some works have outlined that the obtained nanofluids have a Newtonian behavior, while other reports have pointed out that a pseudoplastic or viscoplastic model can describe the rheological behavior of nanofluids. For instance, Hammat el al. [18] concluded that for a nanofluid with a $Mg(OH)_2$ nanoparticle concentration of 2% dispersed in Ethylene glycol, the viscosity increase is almost 60%, and the nanofluid is Newtonian. Also, Motahar et al. [22] found out that the addition of $MPSiO_2$ nanoparticles led to increased viscosity of Octadecane, even higher than 60% for a 5% wt concentration at 35 °C. In the same work, for concentrations lower than 3%, a Newtonian behavior was observed, and for higher concentrations the fluid behaved as non-Newtonian, specifically as a pseudoplastic fluid. Recently, Motahar et al. [23] also observed that a nanofluid prepared using Octadecane and TiO_2 nanoparticles showed increasing viscosity with nanoparticle concentration. Regarding the rheological behavior, the nanofluid showed a Newtonian behavior for concentrations lower that 2% wt, while for higher concentrations there was a transition to a non-Newtonian Bingham behavior. Regarding the effect of temperature on the viscosity of the nanofluid, all the reviewed studies showed that viscosity decreases as temperature rises [17,18,22,23]. A more detailed review of the viscosity of nanofluids can be found in the work of Sharma et al. [24].

The present work presents an experimental investigation about the behavior of thermal conductivity and viscosity of an O-PCM prepared from Octadecane and surface modified nanoparticles of CuO (Nano-PCM), as a function of both nanoparticle concentration, expressed as weight per volume fraction, (2.5, 5, and 10%w/v), and temperature (30–55 °C). The behavior of both obtained properties was compared with available models, to finally propose a model that describes the thermal conductivity and the viscosity of the Nano-PCM as a function of temperature and concentration.

2. Experimental

2.1. Materials

An organic PCM has been used (Octadecane reagent grade 99%, Sigma-Aldrich) as a dispersive medium for nanoparticles.