Optical and dielectric properties of ethylene glycol-based nanofluids containing nanodiamonds with various purities

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Abstract

The work reports on the characterization of optical and dielectric properties of nanofluids consisting in pure nanodiamonds suspended in ethylene glycol. The study is carried out at four concentrations within the range from 0.01 to 0.1 wt%, and for two different types of nanodiamond powders, differing each other in the purity of the diamond phase (87% or 97%). Optical extinction, even at the investigated extremely low concentrations, results significantly increased in the colloids with respect to the pure base fluid, while the refractive index at 589.3 nm remains practically unchanged. Dielectric properties of nanofluids are related with the content of nanodiamonds particles. While the complex permittivity of tested samples is dependent on a small extent, the electrical conductivity is strongly affected by the increase of nanodiamond concentration.

Keywords: nanodiamonds, nanofluids, solar collectors, optical properties, dielectric properties, solar absorption.

1. Introduction

Nowadays, the global energy demand is constantly growing, due to the increase of the worldwide population and the fast development of the emerging-market countries. Undoubtedly, the fulfillment of this request represents one of the major challenges our society has to cope with. The upcoming depletion of conventional fossil fuels, as well as the urgent need for a drastic reduction of green-house gases, led many national and international institutions to strongly promote the development of energy-saving techniques and renewable energies systems. However, the transition process towards an increasingly clean and efficient energy global system is complex, because of both technical and economic issues. For this reason, the scientific
research world is constantly struggling to find innovative solutions, which must be both effective and commercially expendable in order to compete on the market [1,2].

Within the framework of renewable resources, the solar one represents one of the most promising ways to meet the forthcoming needs, concerning both power and heat. The technologies which harness the solar source can be classified into two main groups: photovoltaic and thermal. The latter refers in turn to many different applications, which include, among others, concentrated solar thermal (CST) and concentrated solar power (CSP) systems. In both these types of scheme, the solar radiation is converged on a central receiver, with the aim of increasing the temperature of a working fluid. The thermal energy carried by this fluid can be used directly for heating purposes (CST systems) or converted in electricity (CSP systems), depending on the temperature level that has been reached [3,4].

In this context, the development of nanomaterials is opening interesting perspectives recently and may have promising implications also for solar energy. These new-generation materials gained the attention of multiple research fields, because their properties match well with the requirements of many different applications [5]. This is the reason why the number of publications concerning nanomaterials has been dramatically increasing since their first appearance in the scientific world. A few examples can better highlight the multidisciplinary implications of such materials.

Extremely popular application fields of nanomaterials are biology, medicine and drug delivery. To report just an example, Sharmila et al. [6] proved that palladium nanoparticles obtained through an eco-friendly, non-toxic and low-cost process, showed a high bactericidal efficacy and a noticeable catalytic activity. Chen et al. [7] presented a simple and effective method to synthesize polymerized-glucose coated Fe₃O₄ magnetic nanoparticles for drug delivering. Changing the field and looking at the electronics world, Kim et al. [8] proposed a novel one-step process to produce Cu-Ag core-shell nanoparticles with favourable electronic and stability properties, promising e.g. for printed electronics on flexible substrates. As regards the energy sector in its broadest sense, nanomaterials may find applications in energy storage systems, fuel cells, in biorefinery plants for the production of biofuels, or in devices for the reduction of polluting emissions at the exhaust of diesel engines. Li and Liu [9] carried out a morphological characterization and an experimental study on the electrochemical properties of reduced graphene oxide composites, modified with CeO₂ nanocrystals. They found that the combination of these nanostructures led not only to a high specific capacitance, but also to an excellent charge-discharge cycling stability: both these properties made them promising electrode materials for supercapacitors. Hasché et al. [10] performed a study on PtCu₃ and PtCo₃ nanoparticle fuel cell catalysts, comparing their activity and long-term stability with a commercial catalyst made of pure Pt. Their outcomes highlighted a superior electrochemical performance of both PtCu₃ and PtCo₃ nanoparticles, in terms both of surface specific reactivity and cycling durability. Wang et al. [11] synthesized two types of acid-functionalized silica-coated Fe/Fe₃O₄ magnetic nanoparticles, and compared their catalytic activities in two model reactions.
of the biodiesel production, showing that these nanostructures have a noticeable potential for biodiesel production, even from low-grade feedstocks such as waste cooking oil. Fino et al. [12] experimentally investigated nanosized oxides catalysts of three different types, intended for the simultaneous removal of soot and NOx from the exhaust gases of a diesel engine. They found that the CoCr2O4 catalyst ensured the best compromise between soot and NOx removal at temperatures below 400 °C.

Besides those which have been cited so far, a further huge application field of nanoparticles is represented by some types of systems where heat transfer is involved. This kind of utilization of nanomaterials is worth a little more comprehensive discussion, since it is also linked to the motivation of the present work. When heat transfer problems are addressed, one of the most important requirements of the heat carrier fluid is its thermal conductivity, which obviously has to be as high as possible. Choi and Eastman [13] were the first who suggested that metallic nanoparticles could be dispersed into some conventional heat transfer fluid to boost its thermal conductivity. This innovative concept was referred to as “nanofuid” from then on. In their study, they made use of a mathematical model, developed for solid-liquid systems, to calculate the increase of thermal conductivity which was theoretically achievable mixing copper nanoparticles into water. They found that the magnitude of such increment could range from a factor of 1.5 at a volume fraction of 5% to a factor of about 3.5 at a volume fraction of 20%. Despite these values have been proved later to be not so realistic [14–16], the work of Choi and Eastman opened the path towards a new prolific branch of research. Since that moment, a huge number of combinations between conventional heat transfer fluids (i.e. the so-called “base fluid”) and nanoparticles of various types has been examined [17,18]. The resulting extremely wide variety of resulting nanofluids made the range of possible applications equally diversified, so that a comprehensive overview of all of them would require a dedicated paper: the reader is eventually addressed to the works of Saidur et al. [19] and of Tawfik [20] for a detailed information. Here, it is worth focusing only on the application of nanofluids in direct absorption solar collectors (DASCs). Unlike conventional absorbers, which consist of a tube coated with a dark spectrally-selective material, DASC tubes are transparent: this allows the light heating directly the working fluid, without the need of an intermediate passage through the external layer. This provides a lower total thermal resistance. Furthermore, if the whole system is well designed, the highest temperature is reached in the inner zone of the fluid bulk rather than on the outer surface of the tube, like for the conventional absorbers: this reduces the convective losses towards the environment. The concept of DASC was first proposed by Minardi and Chuang in 1975 [21], but it did not succeed because of the employed working fluid, which often consisted of Indian ink: besides being toxic, it is unstable at high temperatures and may induce serious issues to the mechanical parts of the plant, like pumps or hydraulic components [22,23]. Nowadays, the availability of nanofluids could help overcoming these barriers, even if many challenges are still open. In fact, a high thermal conductivity is just one of the many requirements that the working fluid of a solar absorber should fulfil. Besides it, the following properties are equally important [24]: high vaporization
temperature; low freezing temperature; high thermal stability; high thermal capacity; low viscosity; low flammability; no corrosivity; no toxicity; cheapness; and easy availability. Furthermore, provided the lack of the conventional outer coating, the nanofluid used in a DASC has also to be an efficient absorber in the wavelengths range of the sunlight spectrum [23]. This is the reason why carbon-based nanoparticles are one of the most highly recommended ones for this application: they have been proved to absorb most of the sunlight energy, or at least to do that in the spectral range where the solar irradiance is higher [25]. The group of carbon-based nanostructures include fullerenes, graphene, single and multi-walled nanotubes, and nanodiamonds: all these allotropes stand out for their chemical, mechanical, electrical and thermal properties [26].

In particular, nanodiamonds are extremely interesting nanostructures, since they provide most of the properties of bulk diamond [27]: among them, their outstanding chemical stability is definitely the most interesting for DASC applications. Nanodiamonds have been tested with different oils, water, and glycols [28]. Żyła et al. [29] performed an experimental analysis on the thermophysical properties of a nanofluid based on ethylene glycol and loaded with a mixture of graphite and nanodiamonds, containing two different ash percentages. Samples with nanoparticles mass concentrations from 1 to 5 wt% were investigated, showing that they behave as yield stress fluids with viscoelastic structure, and that their viscosity increases as the nanoparticles content grows. In addition, the thermal conductivity weakly increases with the nanoparticle concentration, showing no dependence on the ash content. On the other hand, the electrical conductivity is very strongly influenced by the nanostructures, which make it up to 200 times bigger at the highest tested concentration. Sani et al. [30] studied the same type of nanofluids, even if at much lower concentrations (from 0.0025 to 0.01 wt%), in order to undertake an optical characterization of those nanomaterials. For low input energies, the results highlighted that a substantial drop of the transmittance was provided, especially for wavelengths from 300 to 1400 nm and with increasing effect as the nanoparticle concentration was increased. Furthermore, for high input energies (up to 0.75 J/cm²), the nanofluids exhibited a non-linear behavior: beyond a certain limit, no further transmittance increase was achieved even if the input energy flux was raised. These findings made those nanofluids promising candidates for concentrating solar collector applications, for which the whole study was intended. More recently, Żyła et al. [31] carried out an experimental investigation on rheological and thermal behavior of ethylene glycol containing nanodiamonds with 97% and 87% purity, at mass concentrations ranging from 1 to 10 wt%. The results showed that these nanofluids have a viscoelastic, non-Newtonian, thixotropic behavior, which depends on the purity of the nanodiamond phase. Moreover, the isobaric heat capacity of the nanofluid decreases as the concentration of the nanoparticles increases, and this drop is larger for 97% purity nanodiamond phase. On the other hand, the thermal conductivity is not considerably affected by the addition of nanoparticles into the ethylene glycol.
In the present study, nanofluids consisting of ethylene glycol and nanodiamonds with two different purities (97% and 87%) were experimentally investigated at concentrations ranging from 0.01 to 0.1 wt%. The present analysis had the purpose of further characterizing the basic physics of these fluids, moving forward from the study of Żyła et al. [31] and taking into account further physical properties. In particular, the attention was focused on the interaction of nanofluid samples with electromagnetic radiation. Therefore, we studied the optical extinction coefficient, the refractive index and the dielectric properties as a function of the nanoparticle type and concentration. In addition, the AC electric conductivity has been measured as well. The investigated properties are of interest for assessing both fundamental material properties and the nanofluid potential for various energy applications, such as, besides the DASCs [32,33] mentioned above, high voltage transformers [34–36] and fuel cells [37,38].

2. Materials and methods

Two types of nanopowders were used for this study: each of them featured a different purity of the nanodiamond phase (ND), which was of 97% for the first type and of 87% for the second. Both nanopowders were purchased from PlasmaChem GmbH (PlasmaChem GmbH, Berlin, Germany). The samples were prepared with a two-step method, using vials of 50 ml. The first step of the preparation consisted in putting the nanopowder into the vial: the mass of nanopowder changed from sample to sample as a function of the concentration, and it was measured on an analytical balance WAS 220/X (Radwag, Radom, Poland) with an accuracy of 0.1 mg. The second step consisted in adding the correct amount of ethylene glycol (EG), in order to fulfil the desired nanoparticles loading. Based on the two different purities of the ND phase, 97% and 87%, the two groups of samples were labelled EG-ND97 and EG-ND87, respectively.

To make the samples as uniform as possible, they underwent 30 min of mechanical mixing into an IKA Vortex 3 shaker (IKA, Staufen, Germany) just after their preparation. Then, they were kept into an Emmi 60 HC ultrasounds water bath (EMAG, Moerfelden-Walldorf, Germany) for 200 min. Finally, a high-energy ultrasounds probe (Sonics Vibracell VCX130, Sonics & Materials Inc, Newtown, USA) was immersed in each sample for 3 min with 50% amplitude. This allowed to break any residual nanoparticles cluster and assured a very good homogeneity.

Both for ND87 and ND97, four different nanoparticle concentrations were investigated: 0.01 wt%, 0.025 wt%, 0.05 wt%, and 0.1 wt%. As regards the measurements of the refractive index, they were performed immediately after the preparation of the samples. On the other hand, to evaluate the effects of ageing on the extinction coefficient of the nanofluids, two different sets of measurements were performed on it. The first one was carried out just after the preparation of the samples, for each of the aforementioned concentrations. The
second one was undertaken 9 months after the preparation, only for the 0.01 wt% and 0.1 wt% concentrations.

As concerns this second stage of the measurements, the samples were refreshed using a 50 W, 46 kHz ultrasonic bath for 10 minutes, before performing each measurement. Ultrasonic treatment is a well-established way to break agglomerates of nanoparticles in nanofuids, as it was presented in the recent review paper by Asadi et al. [39].

Transmittance spectra were acquired between 190 and 2600 nm wavelength, using a double beam UV-VIS spectrophotometer (Perkin Elmer Lambda900) and a demountable cell [40,41].

To measure the refractive index of the samples, we used an Abbemat 350 Refractometer (Anton Paar OptoTec GmbH, Seelze-Letter, Germany). This device uses an LED light source emitting at 589.3 nm and a synthetic sapphire prism. We placed a little amount of sample (250 μl) into the specific measurement hollow, using an HTL Discovery Comfort DV1000 single channel pipette. Then, we covered the hollow with a magnetic-clamping cap, in order to ensure that the sample was isolated from the external environment. Then, the sample underwent a preset ramp of increasing temperature from 15°C to 75°C, with steps of 5°C. For each step, as soon as the temperature stabilized, the refractometer automatically measured the refractive index. For each sample, we repeated this process three times, and finally we took the average value of the refractive index for each temperature step.

The dielectric properties (permittivity, electrical conductivity, loss factor) of the two types of ethylene glycol nanodiamond nanofuids were investigated with broadband dielectric spectroscopy (Concept 80, Novocontrol GmBH, Montabaur, Germany). The measurements were performed in the frequency range from 0.1 Hz to 1 MHz and at temperatures between 15 and 75°C, with steps of 5°C. The temperature was controlled with an accuracy of 0.5°C.

3. Results and discussion

Figure 1 shows the extinction coefficient spectra for the EG-ND87 and EG-ND97 samples, respectively. As apparent, there are no significant differences between the two kinds of sample. For both of them, the extinction coefficient increases as the mass concentration of nanoparticles becomes higher, but only in the visible range: as early as the region about 1200 nm is approached, the extinction coefficient turns out to be independent from the nanoparticles concentration, showing that, in this spectral region, light extinction is only due to the base fluid. In fact, both plots of Figure 1 show the extinction coefficient of the pure base fluid for reference (corresponding to the pink curve, very near to zero on the first half of the X-axis). From this comparison, the role of nanodiamond additives in increasing the optical extinction of the samples from the UV to the near infrared clearly emerges. If the differences among the two sample types are concerned, the
extinction coefficients are very similar for ND87-ND97 samples. Slightly higher values (5-10% relative difference) could be obtained for the ND87 sample at the highest investigated concentration, while at the lower concentrations, differences, if any, lie within the experimental uncertainty.

Figure 1 – Extinction coefficient spectra of: A) EG-ND87 samples; B) EG-ND97 samples and comparison with the pure base fluid (pink curves).
Figure 2 and Figure 3 compare the extinction coefficient spectra of EG-ND87 and EG-ND97 samples, respectively, measured immediately after their preparation and after 9 months, for 0.01 wt% and 0.1 wt% concentrations. The experimental uncertainty is also reported on the curves. As apparent, despite a slight exception for the 0.1 wt% EG-ND97 sample, all the differences between the spectra of the fresh samples and the aged ones are included into the uncertainty bars, confirming the remarkable stability of nanodiamond suspensions. In fact, once the samples were briefly refreshed as described in the previous section, their optical behaviour did not turn out to differ from the original one.
Figure 2 – Comparison between the extinction coefficient spectra of sample EG-ND87, measured just after the preparation (red line) and after 9 months (black line): A) 0.01 wt% concentration; B) 0.1 wt% concentration.
Figure 3 – Comparison between the extinction coefficient spectra of sample EG-ND97, measured just after the preparation (red line) and after 9 months (black line): A) 0.01 wt% concentration; B) 0.1 wt% concentration.

The evidenced spectral properties result extremely important to characterize the sunlight extinction behavior of the nanofluids and their energy storage capability. The sunlight extinction fraction, EF, of the incident sunlight \( I(\lambda) \) [42] which is extinct in the fluid after a propagation path of length \( x \) is given by the expression [32,33]:
\[
EF(x) = 1 - \frac{\int_{\lambda_{\text{min}}}^{\lambda_{\text{MAX}}} I(\lambda) \cdot e^{-\mu(\lambda)x} \, d\lambda}{\int_{\lambda_{\text{min}}}^{\lambda_{\text{MAX}}} I(\lambda) \, d\lambda}
\]  

where \(\mu(\lambda)\) is the spectral extinction coefficient and \(\lambda_{\text{min}}\) and \(\lambda_{\text{MAX}}\) are 300 and 2600 nm, respectively.

Figure 4 shows the calculated EF fraction for the EG-ND87 nanofluids and that of the pure ethylene glycol. We can see that the presence of nanodiamonds dramatically modifies the interaction of the fluid with solar radiation. In fact, with pure base fluid, after a path length as long as 60 mm, only 33% of the incoming sunlight is absorbed. With suspended nanodiamonds, we obtain a sunlight extinction of 98% at the same path length (60 mm) for the sample with the lowest concentration and the total extinction in gradually shorter lengths as the nanoadditive concentration is increased (40 mm for the 0.025%, 25 mm for the 0.05% and 20 mm for the 0.1% concentrations).

Figure 4 – Calculated sunlight extinction as a function of the propagation length within the nanofluids.

Figure 5 and Figure 6 show the refractive index of the EG-ND87 and EG-ND97 samples, respectively, as a function of the temperature. Both figures report also the ratio \(R_{i\text{nf}}/R_{i\text{bf}}\) between the refractive index of the nanofluid samples and the one of the pure base fluid. As apparent, the nanoparticles did not affect the trend of the refractive index, in comparison with the pure EG, for any of the investigated concentrations. This behavior applied both to ND87 and to ND97 nanoparticles. The ratio \(R_{i\text{nf}}/R_{i\text{bf}}\) highlights that the largest relative variation in comparison with pure EG, occurring at the highest tested temperature (75°C) for the highest
investigated ND concentration (0.1 wt%), amounted to only 0.022% (for the ND97 sample). Such little
deviations were included in the accuracy range of the refractometer and should not be ascribed to any actual
change occurring in the physical properties of the samples.

![Refractive Index vs Temperature](image1)

**Figure 5 –** A) Refractive index of the EG-ND87 samples, as a function of the temperature; B) Ratio between
the refractive index of the EG-ND87 samples and the one of the base fluid, as a function of the temperature.
Figure 6 – A) Refractive index of the EG-ND97 samples, as a function of the temperature; B) Ratio between the refractive index of the EG-ND97 samples and the one of the base fluid, as a function of the temperature.

Figure 7 shows the real part of the dielectric permittivity of both types of EG-ND nanofluids as a function of the frequency at 25°C. The permittivity of these two types of nanofluids presents a very similar behavior in the tested frequency range. In case of both EG-ND87 and EG-ND97 samples, the dependence of permittivity on frequency can be divided into two parts. The first part includes the low frequencies range (approximately up to 120 Hz), where the permittivity slightly increases with the nanoparticles load, for both types of nanofluids. Simultaneously, in this region, the permittivity of all samples shows a linear decrease as the frequency becomes higher. Additionally, the increase in concentration of nanodiamonds slightly shifts the
border between these two regions towards higher frequencies. The second part of the permittivity curves (above 120 Hz) is close to be constant and almost unaffected by the increase of the concentration of nanoparticles, for both EG-ND87 and EG-ND97 nanofluids.

The data depicted in Figure 8 also show that, for both the EG-ND87 and EG-ND97 nanofluids, the nanoparticles have a small effect on the imaginary part of the permittivity, particularly for concentrations below 0.1 %. The increase in concentration of nanoparticles makes the imaginary part of permittivity higher, within the whole tested frequency range. Only for the EG-ND97 sample with 0.1 % concentration, the effect of nanoparticle addition is noticeably higher.

Figure 7 – Real part of the permittivity of A) EG-ND87 and B) EG-ND97 samples as a function of the frequency, at 25°C.
In contrast with permittivity, the electrical conductivity is more affected by the concentration of diamond nanoparticles, as presented in Figure 9. The impact of both types of nanoparticles on the behavior of the electrical conductivity of ethylene glycol is very similar. The main differences are in the increment of the electrical conductivity. EG-ND87 nanofluids generally show a lower enhancement in the electrical conductivity, except for the lowest tested concentration (0.01 wt%), for which the increase is higher than that of the EG-ND97 nanofluid.

For all the investigated concentrations of nanodiamond particles, both for the 87% and 97% purities, the external altering electric field creates similar effects in the whole tested frequency range, even if with different intensities. In the low frequency range, a slight increase of the electrical conductivity with increasing frequency can be noticed for all the samples: this is related to the polarization effect of the electrode. This phenomenon can be observed up to 1 Hz for all the samples. In the regions above this frequency, the electrical conductivity is constant, or its changes are very small, which means that it is not affected by the frequency of the electric field. Based on these regions, it is possible to designate a constant value of conductivity for each nanoparticles concentration of the EG-ND nanofluids, as presented in Table 1 and plotted in Figure 9 as solid lines. As regards the EG-ND87 nanofluids, the electrical conductivity enhancement between each concentration seems to be close to constant, except for the 0.01 wt% and 0.025 wt% cases, which provide roughly the same increment in comparison with pure EG. On the other hand, in the EG-ND97 nanofluids the enhancement of electrical conductivity is not constant and exhibits a significant increase when the fraction of particles increases. Accordingly, as compared to pure ethylene glycol, the highest increase was recorded for the nanofluid containing nanoparticles with higher purity and with the highest tested concentration (0.1 wt%), and it was over 700%.
Figure 9 – Electrical conductivity of A) EG-ND87 and B) EG-ND97 samples as a function of frequency, at 25°C. Dots are experimental data, lines are constant conductivities calculated from each plateau.

Table 1 – Electrical conductivity of EG-ND nanofluids and its enhancement for various mass concentrations, at 25°C.

<table>
<thead>
<tr>
<th>φ_m [\text{-}]</th>
<th>Electrical conductivity [\mu \text{Scm}^{-1}]</th>
<th>Electrical conductivity enhancement [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EG-ND87</td>
<td>EG-ND97</td>
</tr>
<tr>
<td>0.000</td>
<td>0.529</td>
<td>0.529</td>
</tr>
<tr>
<td>0.010</td>
<td>0.768</td>
<td>0.644</td>
</tr>
<tr>
<td>0.025</td>
<td>0.811</td>
<td>0.839</td>
</tr>
<tr>
<td>0.050</td>
<td>1.058</td>
<td>1.333</td>
</tr>
<tr>
<td>0.100</td>
<td>1.574</td>
<td>3.797</td>
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</table>

Figure 10 presents the variation of loss factor with the frequency of the external electric field. For all the investigated samples, some peaks are visible, which are related to the relaxation process occurring in the samples. Based on the frequency at which peaks appear, the relaxation time can be calculated using the following equation:

\[ \tau = \frac{1}{2\pi f} \]
The results of these calculations were summarized in Table 2 and presented in Figure 11. The obtained results clearly indicate that the addition of nanoparticles involves different impacts on the relaxation process, depending on whether their purity is 87% or 97%. For the EG-ND87 samples, the relaxation time remains unaffected below 0.05% nanoparticles concentration, while, if the concentration increases further, the relaxation time starts decreasing. On the other hand, for the EG-ND97 samples, the relaxation time starts changing from the lowest tested concentrations: apart from the first measured concentration (0.01%), which involves an increase of the relaxation time, it keeps decreasing as the nanoparticles concentration becomes higher.

![Figure 10 – Loss factor of A) EG-ND87 and B) EG-ND97 samples as a function of the frequency, at 25°C.](image)

<table>
<thead>
<tr>
<th>( \phi_m [-] )</th>
<th>( \tau [\text{ms}] )</th>
<th>EG-ND87</th>
<th>EG-ND97</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>1.99</td>
<td>1.99</td>
<td></td>
</tr>
<tr>
<td>0.010</td>
<td>1.99</td>
<td>2.79</td>
<td></td>
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<tr>
<td>0.025</td>
<td>1.99</td>
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<tr>
<td>0.050</td>
<td>1.02</td>
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<tr>
<td>0.100</td>
<td>0.73</td>
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</table>
4. Conclusions

This work reports on a systematic investigation of the optical and dielectric properties of nanodiamond suspensions in ethylene glycol, as a function of the diamond phase purity (87% and 97%) and of the nanoparticles concentration. No significant differences have been detected in the spectral optical extinction coefficient of the two nanoparticle types. The addition of nanoparticles significantly increases the extinction coefficient of nanofluids in the UV-blue spectral region, while their contribution decreases for increasing wavelengths: in the near-infrared above about 1200 nm, it is the base fluid that determines the extinction coefficient of the colloid. Optical properties do not appear to be significantly changed in 9-months aged samples with respect to freshly prepared ones, confirming the remarkable stability of colloids. If the interaction with sunlight is concerned, nanodiamond colloids show a considerably higher sunlight extinction with respect to the pure base fluid, arising in the total extinction of input solar radiation in a path length of 20-60 mm for the investigated 0.1-0.01 wt% concentrations. Increasing the nanoparticle concentration shortens the total extinction length and makes the deposed energy more localized near the input surface.

The obtained results favorably propose nanodiamond-based colloids for solar energy applications like low-temperature solar collectors. Similar nanofluids, consisting of a mixture of graphite and nanodiamonds suspended in ethylene glycol and intended for solar applications as well, were previously tested by Sani et al. [30]. They exhibited a higher sunlight extinction effect in comparison with the nanofluids of the present work, even at noticeably lower concentrations. Nevertheless, they were characterized also by a strong instability, which arose in nanoparticles clustering and their sedimentation. Conversely, despite of their lower light absorption capability, the nanofluids here presented displayed an excellent stability and showed to be easily refreshable even after months. This feature makes them very attractive for DASCs applications, for which the time durability of the working fluid has traditionally represented a barrier against their actual
development [22]. Moreover, the evidenced optical properties of nanofluids do not appear to be related to the purity of the nanodiamond phase (87% and 97%), which is a very interesting result in view of the economical feasibility of practical applications. The small differences (5-10%) detected in the extinction coefficients of the highest concentration samples could be easily overcome, if needed, by a slight reduction of the concentration of the lower purity sample, to align the extinction coefficient values.

As for the refractive index, which is an important parameter for the design of systems interacting with electromagnetic radiation, the measured value at 589.3 nm for nanofluids resulted practically unchanged with respect to the pure ethylene glycol case, due to the extremely low nanoparticle concentrations.

Dielectric properties of nanofluids depend on the concentration of nanoparticles. The effect is more visible for higher concentrations, especially for the nanoparticles with higher purity. The highest impact of the addition of nanoparticles was observed for the electrical conductivity: its largest enhancement, which was observed at 0.1 wt% concentration for both types of nanofluid, reached 380 % and 720 % for EG-ND87 and EG-ND97, respectively. Nanoparticles also influenced the shift of the relaxation process towards higher frequencies, which resulted in the reduction of the relaxation time with the increase of the nanoparticles concentration.

Acknowledgments

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Nomenclature

Acronyms

AC
Alternate Current
CSP
Concentrated Solar Power
CST
Concentrated Solar Thermal
DASC
Direct Absorption Solar Collector
EG
Ethylene Glycol
ND
Nanodiamonds
UV-VIS
Ultraviolet-Visible Wavelength Range
### Greek symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>( \tan\delta )</td>
<td>Loss Factor</td>
<td>[-]</td>
</tr>
<tr>
<td>( \varepsilon' )</td>
<td>Real Part of Complex Permittivity</td>
<td>[-]</td>
</tr>
<tr>
<td>( \varepsilon'' )</td>
<td>Imaginary Part of Complex Permittivity</td>
<td>[-]</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>Wavelength</td>
<td>[nm]</td>
</tr>
<tr>
<td>( \mu )</td>
<td>Extinction Coefficient</td>
<td>[cm(^{-1})]</td>
</tr>
<tr>
<td>( \varphi_m )</td>
<td>Nanoparticles Mass Fraction</td>
<td>[%]</td>
</tr>
<tr>
<td>( \sigma' )</td>
<td>Electrical Conductivity</td>
<td>[S cm(^{-1})]</td>
</tr>
<tr>
<td>( \tau )</td>
<td>Relaxation Time</td>
<td>[s]</td>
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### Latin symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
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<tbody>
<tr>
<td>( EF )</td>
<td>Extinction Fraction</td>
<td>[-]</td>
</tr>
<tr>
<td>( f )</td>
<td>Frequency</td>
<td>[Hz]</td>
</tr>
<tr>
<td>( I )</td>
<td>Sunlight Irradiance</td>
<td>[W m(^{-2}) nm(^{-1})]</td>
</tr>
<tr>
<td>( RI )</td>
<td>Refractive Index</td>
<td>[-]</td>
</tr>
<tr>
<td>( T )</td>
<td>Temperature</td>
<td>[°C]</td>
</tr>
<tr>
<td>( x )</td>
<td>Propagation length</td>
<td>[m]</td>
</tr>
</tbody>
</table>

### Subscripts

<table>
<thead>
<tr>
<th>Subscript</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>bf</td>
<td>Base Fluid</td>
</tr>
<tr>
<td>MAX</td>
<td>Maximum</td>
</tr>
<tr>
<td>min</td>
<td>Minimum</td>
</tr>
<tr>
<td>nf</td>
<td>Nanofluid</td>
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### References


