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EXPERIMENTAL APPROACH ON THERMAL DIFFUSIVITY OF A PEG NANOFLUID

BY

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Abstract. The main purpose of heat transfer fluids is to transport heat energy between two media, with the best possible efficiency, the lowest possible energy losses, in an optimal time with an improved system performance. It is known that the addition of nanoparticles to a base fluid considerably improves its heat transfer properties and polyethylene glycol (PEG) based nanofluids are a new class of heat transfer fluids obtained by dispersing different kinds of nanoparticles (carbon nanotubes, graphene, magnesium oxide, zinc oxide, copper, alumina, etc.) in a liquid polyethylene glycol (PEG), having a low molecular weight. PEG is a chemical compound with relatively low viscosity, which is thermally and chemically stable, non-corrosive, non-toxic, being an ideal medium for developing heat transfer fluids. In the case of nanofluids, a series of thermal, physical and rheological properties are monitored and this paper presents a brief analysis of some experimental results on thermal diffusivity, an essential property for the characterization of nanofluids for heat transfer.

Keywords: nanofluid, nanoparticles, heat transfer, polyethylene glycol, nanofluids.

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1. Introduction

Polyethylene Glycol (PEG) is a versatile synthetic polymer with many uses in the pharmaceutical, chemical, agricultural industry, cosmetics, bioengineering, energy and various other fields. The name is followed by a number describing the average molecular weight of the compound. (e.g. PEG200 has an average molecular weight of 200 g/mol). The chemical formula can be written H−(O−CH2−CH2)n−OH where n represents the number of ethylene oxide units corresponding to the molecular weight.

The applications of PEG compounds in heat transfer directly depend on their molecular weight. While polyethylene glycol with molecular weight above 1000 g/mol, which is solid at ambient temperature, is suitable for a limited range of practical applications, compounds with low molecular weight (PEG 200, PEG 400, PEG 600) can be successfully used as base liquids for the preparation of nanofluids (Marcos *et al*., 2020a; Chereches *et al*., 2022; Ponmani *et al*., 2019; Babar *et al*., 2019; Ravikanth *et al*., 2009; Minea *et al*., 2025).

At the same time, the type, shape, size and concentration of the nanoparticles used play an essential role in terms of thermophysical properties and behavior during heating and cooling operations of the suspensions. Depending on the efficiency, stability, chemical compatibility, cost and application, there are various studies in the literature that explore a series of nanofluids with different types of nanoparticles, the most commonly used of which are metallic nanoparticles, of Copper, Silver, Aluminum (Marcos *et al*., 2020a) metal oxides, Al_2O_3, ZnO, TiO_2, CuO, Fe_2O_3 (Rizwan *et al*., 2022) or carbon nanoparticles, carbon nanotubes or graphene.

Two methods of nanofluid preparation are described in the literature. The single-step method, where the synthesis of nanoparticles is carried out by physic-chemical methods (sol-gel method, precipitation, physical vapor deposition, laser ablation) directly in the base fluid, and the two-step method, where the nanoparticles are synthesized prior to addition to the liquid (Babar *et al*., 2019).

In order to characterize nanofluids, a series of essential physicochemical properties are pursued in the design and optimization of cooling and heating systems where they can be integrated (Table 1).

Table 1
Main thermophysical properties for heat transfer fluids, as described in the literature

Nr. crt.	Physical property	Symbol / Unit of Measure	Description/Comments
1	Density	$\rho = \frac{m}{V}$ [kg/m³]	Influences suspension stability, heat capacity, diffusivity (Vajjha *et al*., 2009)
2	Thermal conductivity	k [W/m·K]	The ability of the fluid to conduct heat. It increases with increasing nanoparticle concentration (Cojocariu *et al*., 2025)

3	Dynamic viscosity	μ [Pa·s]	Increases with the nanoparticle concentration (Cojocariu *et al*., 2025)
4	Specific heat	Cp [J/kg·K]	Usually it increases with temperature and decreases with higher nanoparticle fraction (Ravikanth *et al*., 2009)
5	Thermal diffusivity	$\alpha = \frac{k}{\rho \cdot C_p}$[m²/s]	It decreases with temperature and is significantly influenced by the type of nanoparticles and concentration (Minea *et al*., 2024)

2. Thermal diffusivity

Thermal diffusivity is defined as the measure of the rate of heat diffusion within a material, indicating its responsiveness to thermal changes. It is an intensive property represented by the quotient of the thermal conductivity and the volumetric heat capacity (the product of density and specific heat capacity). This characteristic is indispensable across various engineering disciplines, particularly in the design of systems requiring specific thermal performance, such as heat dissipation (heat sinks) and thermal insulation in the aeronautical and energy sectors.

Thermal diffusivity is a property calculated based on thermal conductivity, density and specific heat, according to Eq. (1):

$$\alpha = \frac{k}{\rho \cdot Cp} \tag{1}$$

where: α is thermal diffusivity (m²/s), k = thermal conductivity (W/m·K), ρ = density (kg/m³), cp = specific heat at constant pressure (J/kg·K)

It can be observed that the thermal diffusivity is directly proportional to the conductivity and inversely proportional to the specific heat and density. It is influenced by both the base fluid and the type and concentration of nanoparticles and depends on the extent to which the thermal conductivity increases and by the manner in which the specific heat capacity and density vary with temperature. Usually, the density increases with increasing temperature as well as the specific heat. There are cases in which the specific heat is constant at moderate temperature increases.

2.1. Thermal diffusivity of nanofluids as a function of nanoparticle concentration

Recent studies have investigated the addition of nanoparticles to various PEG-based fluids with the aim of improving their thermophysical properties. Experimental results in the literature demonstrate the variation of these parameters with the concentration of nanoparticles in the base fluid.

Minea et al. (2025) showed that the addition of MWCNTs (up to 1 wt.%) in PEG 400 significantly improved the thermal conductivity (up to 12.7%) and thermal diffusivity (up to 13.5%). Marcos et al. (2020b) used PEG 400 as the base fluid and in the studied temperature range, pure PEG400 exhibits thermal diffusivity values, α, from 7.13×10^{-8} to 7.15×10^{-8} m^2/s. Experimental results showed that the addition of silver nanoparticles (Ag) in PEG400 leads to a small gain in thermal diffusivity, but below 2% for the highest concentration tested (1.1 wt.%).

Compared to other properties, these variations in diffusivity are modest, reflecting the fact that although conductivity increases with nanoparticle concentration, the effects on density and specific heat tend to partially offset the benefits. In another study, Marcos et al. (2018) showed that the thermal diffusivity increases with nanoparticle loading and decreases with temperature rise. The best result in terms of thermal diffusivity is obtained at 0.5 wt.%, with a maximum improvement over the base material of 21% at 333.15 K.

Murshed et al. (2005) manufactured several types of nanofluids by dispersing 1 to 5% by volume of titanium dioxide (TiO_2) nanoparticles, aluminum oxide Al_2O_3, and aluminum nanoparticles in ethylene glycol and motor oil. The thermal diffusivities of these nanofluids, determined experimentally, were found to increase substantially with increasing volume fraction of nanoparticles in the base fluids. Nanofluids containing a small amount of nanoparticles have significantly higher diffusivity values than those of the base fluids. Furthermore, it was found that the size and shape of the particles have an effect on the effective thermal diffusivity of the nanofluids.

2.2. Thermal diffusivity of nanofluids depending on the type of nanoparticles

Minea et al. (2024) observed that the thermal diffusivity increases by approximately 33.86% for the PEG + 2.50% MgO suspension compared to the base fluid. While the MgO suspensions performed better in thermal performance compared to those with TiO_2, in terms of conductivity and diffusivity results. Zhang et al. (2006) studied the influence of the type of nanoparticle using carbon nanotubes, aluminum oxide and gold nanoparticles dispersed in water and toluene, respectively. The results showed a pronounced increase in thermal diffusivity in the case of carbon nanotubes dispersed in water, compared to the other two types of nanoparticles, highlighting both the influence of the size and shape of the nanoparticles.

2.3. Influence of temperature on thermal diffusivity

The influence of temperature on thermal diffusivity is complex, as diffusivity is a composite property calculated from three other temperature-dependent factors, as: thermal conductivity, density and specific heat capacity.

Generally, as temperature increases, the following trends are observed, which collectively determine the change in thermal diffusivity. The key temperature effects can be outlined as:

1. Thermal Conductivity generally increases with temperature due to increased phonon (heat carrier) activity, but the increase often levels off at higher temperatures.

2. For most materials, the specific heat generally increases with temperature, especially at temperatures well below the melting point. This means the material's ability to store heat increases.

3. Density generally decreases slightly with increasing temperature due to thermal expansion.

3. Materials, Sample Preparation and Measuring Equipment

Four samples containing MgO dispersed in the PEG200 base fluid were manufactured, in mass concentrations of 0.25, 0.5, 1 and 2.5 wt.%. Magnesium Oxide (CAS no. 1309-48-4) and PEG200 (CAS no. 25322-68-3) were purchased from Sigma Aldrich (St Louis, USA) (Table 2). Thermal conductivity was measured using the C-Therm Trident system: Basic K TR-Trident-S11-CM coupled with the Basic-k module with MTPS (Modified Transient Plane Source) sensor. Density was measured using the KRUES DS7050 densimeter. Thermal conductivity and density measurements were performed up to 333 K.

Table 2
Properties of PEG200 and MgO, according to the manufacturer

Chemical compound	Description
PEG 200	CAS: 25322-68-3 Formula: $(C_2H_4O)nH_2O$ Molecular weight: 190-210 g/mol Vapor pressure is <0.01 h Pa at 293 K Density: 1.124 g/cm^3
MgO	CAS: 1309-48-4 Molecular weight: 40.30 g/mol Dimensions: max. 50 nm Density: 3.580 g/cm^3

The samples were weighed on an analytical balance (KERN ADJ 100-4) and homogenized using a Vortex combined with a GETI GUC02A ultrasonic bath.

The Eq. (2) was used to calculate the concentrations:

$$\varphi_{\mathrm{the}} = 100\frac{M_{NP}}{V_{PEG}\cdot\rho_{PEG}+M_{NP}} \tag{2}$$

where: φ_{the} = theoretical mass concentration, V_{PEG} = 30 ml, ρ_{PEG} = density of PEG, M_{NP} = mass of nanoparticles.

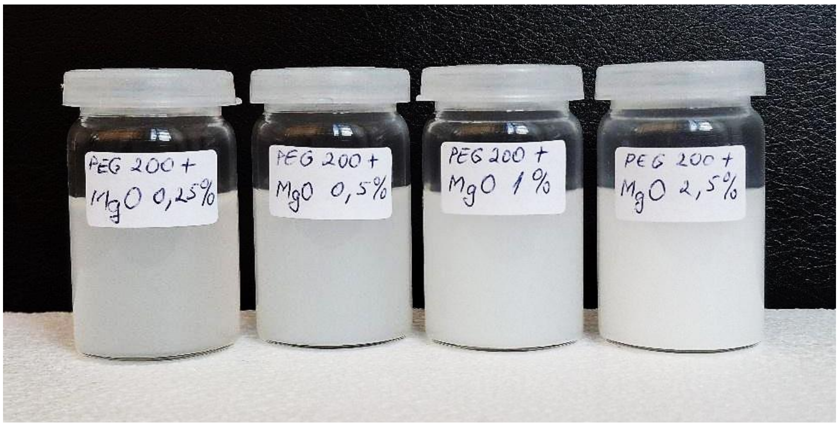

Fig. 1 – Photos of the manufactured samples.

4. Experimental results and discussions

Thermal conductivity was measured starting from ambient temperature (i.e. 295.15 K) up to 333.15 K. The experimental results clearly demonstrate the increase in thermal conductivity with increasing nanoparticle fraction; the largest improvement being recorded for the sample with 2.5 wt.% MgO. This phenomenon has been observed in the literature for all nanofluids. The explanation lies in the fact that solid nanoparticles possess an intrinsic thermal conductivity much higher than that of the base fluid.

Additionally, the specific heat was calculated based on the experimentally read conductivity and effusivity results and based on the effusivity, as it writes:

$$e = \sqrt{k \cdot \rho \cdot c_p} \quad (3)$$

where: k, ρ and c_p are the thermal conductivity, density and specific heat.

The results for the specific heat follow the same trend as the conductivity, increasing with increasing temperature but also with the nanoparticle fraction, the highest values specific heat being obtained for the sample with the highest concentration. The experimental results are discussed in detail in the previously published work by Cojocariu et al. (2025).

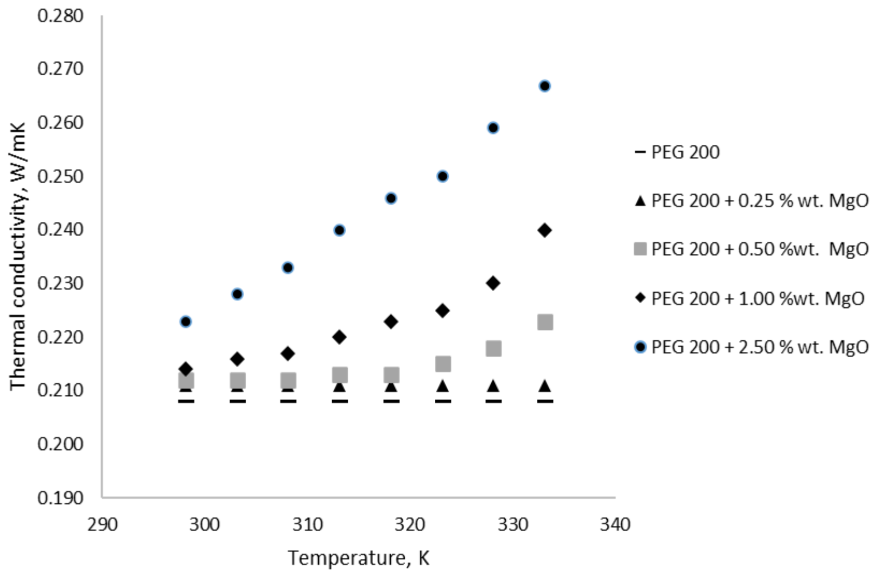

Fig. 2 – Experimental results for thermal conductivity variation with temperature.

Density measurements were performed at a temperature range of 293.15 – 313.15 K. The density decreases with temperature for all samples, which is a normal phenomenon for all nanofluids.

The influence of nanoparticle concentration on thermophysical properties is reported in Table 3. The relative amount was calculated as the ratio between the value obtained for the nanofluid and that for the base fluid.

Table 3

Relative thermal properties results: comparison at 293 K

	Nanoparticle addition to PEG 200, in wt.%			
	0.25	0.5	1	2.5
Relative thermal conductivity	1.014	1.019	1.028	1.072
Relative density	1.003	1.004	1.007	1.014
Relative specific heat	1.005	1.007	1.018	1.047
Relative thermal diffusivity	1.005	1.007	1.002	1.008

In the case of diffusivity calculated at ambient temperature, the results do not follow the same trend as the other thermal properties. For example, in the case of the sample with 1% MgO a decrease in diffusivity was observed compared to the samples with lower concentrations of nanoparticles (i.e. 0.25 and 0.5 wt.%).

The influence of temperature on thermal diffusivity is presented in Fig. 3, noting that it varies quite little in the considered temperature range.

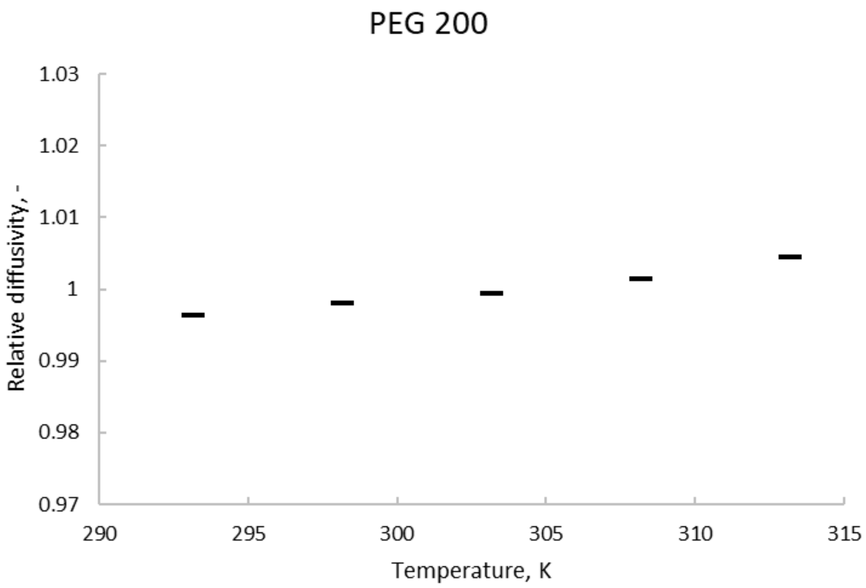

Fig. 3 – Relative thermal diffusivity of PEG 200 sample.

More exactly, for PEG 200, relative diffusivity shows a slight increase with values ranging approximately from 0.99 to 1.01, as can be seen from Fig.3.

In the case of PEG 200 with 0.25 wt.% MgO sample, relative diffusivity shows a slight increase up to 308 K with a decrease at the highest temperature of 313 K, results being portrayed in Fig. 4. Furthermore, in Fig. 5 are presented the results for 0.5 wt.% MgO sample, where it can see that the relative diffusivity displays approximately constant values except a slight decrease at 308 K.

In the case of 1 wt.% MgO sample, relative diffusivity shows an increase, following the same trend as the base fluid sample from 0.994 at room temperature up to 1.006 at the highest temperature (see Fig. 6 for details). Plus, for the highest concentration sample (i.e. with 2.5 wt.% MgO), the relative diffusivity displays approximately constant values up to 303 K followed by an obvious increase up to 1.012 at 313 K.

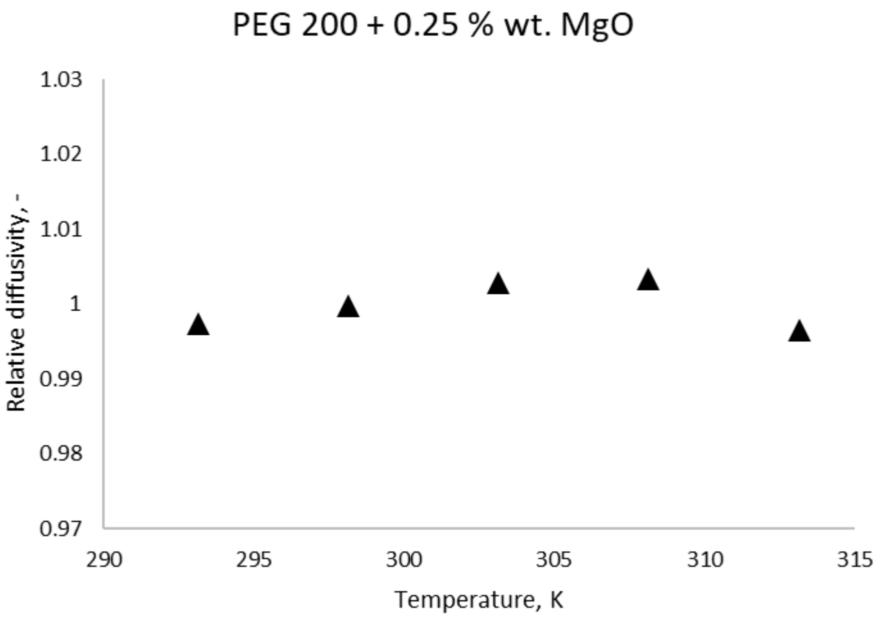

Fig. 4 – Relative thermal diffusivity of PEG 200 + 0.25% MgO sample.

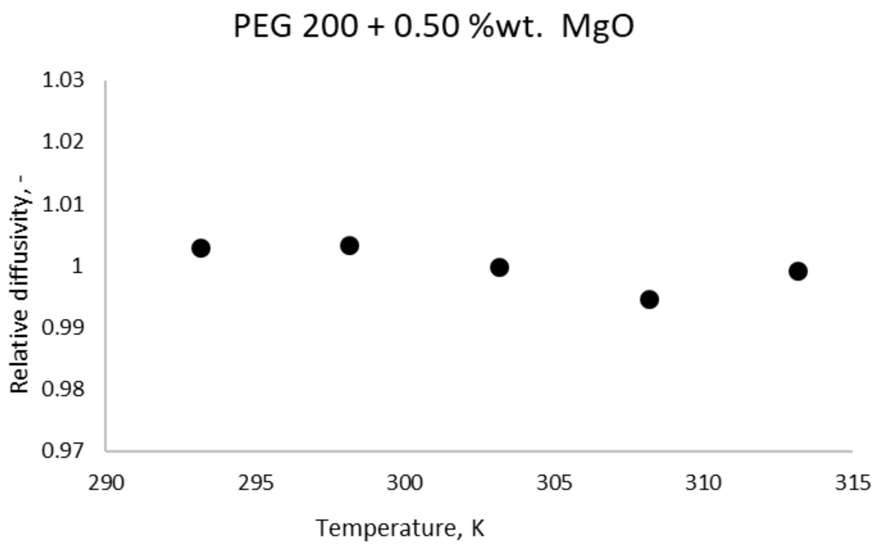

Fig. 5 – Relative thermal diffusivity of PEG 200 + 0.5% MgO sample.

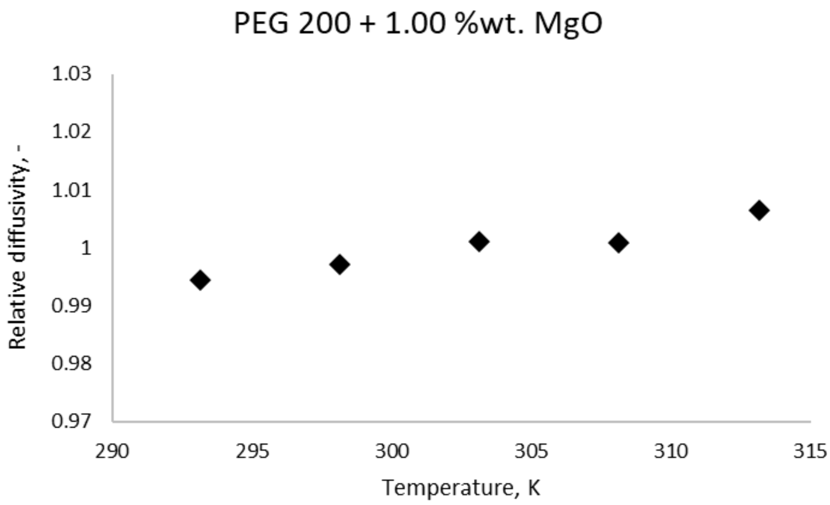

Fig. 6 – Relative thermal diffusivity of PEG 200 + 1% MgO sample.

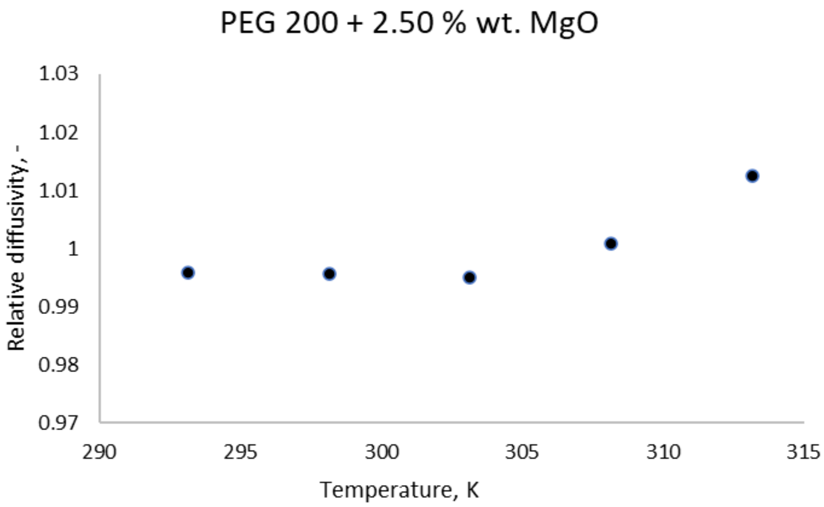

Fig. 7 – Relative thermal diffusivity of PEG 200+ 2.5% MgO sample.

Although the addition of nanoparticles and temperature raises the thermal conductivity of the suspensions, the thermal diffusivity remains largely consistent. This is because the simultaneous decrease in density effectively balances the conductivity increase, while the specific heat shows only minor variation. This stable thermal diffusivity is a key factor in predicting the reliable heat transfer performance required for sustainable energy systems.

5. Conclusions

This work discusses the variation of thermal diffusivity with temperature for a PEG based nanofluid. The main conclusions can be summarized as:

– Thermal diffusivity is directly proportional to the conductivity and inversely proportional to the specific heat and density being influenced by both the base fluid as well as the type and concentration of nanoparticles.

– The thermal diffusivity is influenced by the increase in thermal conductivity as well as by the functional dependence of specific heat and density on temperature.

– Relative diffusivity of PEG 200 and its MgO nanofluid shows a generally increasing trend with temperature. with minor variations depending on MgO concentration.

– Lower concentrations, between 0.25–0.5 wt.%, show modest or irregular changes, while higher concentrations (1 to 2.5 wt.%) display a clearer temperature-dependent increase, indicating enhanced thermal transport at elevated temperatures.

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ABORDARE EXPERIMENTALĂ PRIVIND DIFUZIVITATEA TERMICĂ A UNUI NANOFLUID PE BAZĂ DE PEG

(Rezumat)

Scopul principal al fluidelor de transfer termic este de a transporta energia termică între două medii, cu cea mai bună eficiență posibilă, cu cele mai mici pierderi de energie posibile, într-un timp optim și cu o performanță îmbunătățită a sistemului.

Este cunoscut faptul că adăugarea de nanoparticule la un fluid de bază îi îmbunătățește considerabil proprietățile de transfer termic, iar nanofluidele pe bază de polietilenglicol (PEG) reprezintă o nouă clasă de fluide de transfer termic obținute prin

dispersarea de nanoparticule (nanotuburi de carbon, grafenă, oxid de magneziu, oxid de zinc, cupru, alumină etc.) într-o bază lichidă de polietilenglicol (PEG) cu o masă moleculară mică, cuprinsă între 200 și 600 g/mol.

PEG-ul este un compus chimic cu viscozitate redusă, este stabil termic și chimic, non-coroziv, non-toxic, fiind un mediu ideal pentru dispersarea nanoparticulelor. În cazul nanofluidelor, sunt monitorizate o serie de proprietăți termice, fizice și reologice, iar această lucrare reprezintă o scurtă analiză a unor rezultate experimentale privind difuzivitatea termică, o proprietate esențială pentru caracterizarea nanofluidelor destinate transferului de căldură.