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EFFECT OF THE SHAPE OF NANOPARTICLES AND BASE FLUIDS ON THE THERMOPHYSICAL PROPERTIES OF NANOFLUIDS

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Abstract. *The current work aims the experimental investigation of the thermophysical properties of nanofluid with different sizes of nanoparticles and different base fluid. The nanofluids were produced based on a mixture of water and ethylene glycol (50:50% wt.) and also OT-100 thermal oil. The nanoparticles used were silver and carbon nanotubes dispersed into the base fluid using the two-step method. The nanofluids thermophysical properties, thermal conductivity, viscosity, and density were measured experimentally. Increases in thermal conductivity and dynamic viscosity of all samples were observed with the addition of nanoparticles. These behaviors were attributed to the influence of the base fluid and the effects of movement and iteration between nanoparticles and nanoparticles with the base fluid of the samples. Models were proposed to evaluate the thermal conductivity and viscosity showing good agreement with the experimental results and also the results found in the literature.*

Keywords: *Nanofluids, nanoparticles, mathematical models, thermal conductivity and viscosity*

1. INTRODUCTION

In the last few decades, numerous groups of advanced materials have been developed for different applications. These nanomaterials have at least one geometrical dimension of less than 100 nm (Casey, 2006). They include carbon nanotubes, nanofibers, nanoclays, nanocomposites, nanoporous materials, nanowires, and nanoparticles (NPs). NPs based on a mixture of water and ethylene glycol (50:50% wt.) and also OT-100 thermal oil are the focus of this work.

Selvan et al. (2016), reported the convective heat transfer characteristics of water-ethylene glycol mixture fluids seeded with silver nanofluids under laminar, transitional, and turbulent regime. They observed that the enhancement of thermal conductivity and the chaotic movement of nanoparticles accelerate the energy transfer process between the fluid and the wall is the possible reasons for the improvement in the heat transfer coefficient. The pressure drop increases with increasing concentration of the particle and mass flow rate of the nanofluid.

Naddaf and Heris (2018), investigated the performance of diesel oil using carbon-based nano additives evaluated. The results showed an increase in thermal conductivity and electrical conductivity of all nanofluids in all weight concentrations compared to the pure diesel oil at the constant temperature. In addition, with increasing temperature, thermal conductivity and electrical conductivity increased for all weight concentrations.

Contreras et al. (2018), presented an experimental investigation of the thermohydraulic performance of nanofluids, composed of graphene and silver nanoparticles with a binary mixture of equal parts of water and ethylene glycol (50:50% wt.) as base fluid, in automotive radiators. According to the experimental results, all samples of nanofluids showed increases in dynamic viscosity as compared to the base fluid. The results showed a maximum increase of 10.8% for silver nanofluid at room temperature. Dependence of the dynamic viscosity on temperature was observed, with smaller increases in this property at higher temperatures.

Said et al. (2019), suggested a best practice for analyzing the usage of nanofluids in heat transfer applications for an actual car radiator. This work investigates the use of aluminum oxide (Al_2O_3) and titanium dioxide (TiO_2) nanoparticles dispersed in distilled water and ethylene glycol at 50:50 volumetric proportions. The results showed a maximum enhancement of the thermal performance by 24.21% using Al_2O_3 at a volume fraction of 0.3%. The friction factor and performance evaluation criterion (PEC) for the radiator experiments are calculated in order to determine the penalty in the pressure drop and to evaluate it properly. Finally, it is found that the values of PEC lie in the range of 1.03-1.31, which indicates significant flow enhancement.

Ghaffarkhah et al. (2020), investigated the thermal conductivity, dynamic viscosity, and breakdown voltage for four different types of transformer oil-based nano-lubricants. According to authors, nanofluids containing pure multi-walled carbon nanotubes (MWCNTs) have an increase in the average thermal conductivity compared to hybrid nanoparticles and as dielectric properties of carbon-based hybrid nanofluids, much better than those pure MWCNTs nanofluids.

Bai et al. (2020), investigated the thermal conductivity and tribological properties of ethylene glycol/water-based nanofluids with hydroxylated short multi-walled carbon nanotubes (SMWCNTs(OH)). At 60°C, the thermal conductivity of the nanofluids increases significantly and reaches 6.0% at the volume fraction of 25% for ethylene glycol/water. It is shown that the SMWCNTs(OH) has a good self-lubrication antifriction effect in the water base nanofluids for the GCr15 (high carbon chromium bearing steels) friction pair. Meanwhile, the wear loss of the wear scar is greatly reduced, and the friction coefficient is reduced by 15.4% compared with the pure water, which shows a good application prospect of nanofluids in pump drive fluid loops.

Based on experimental results for thermal conductivity and viscosity in samples of nanofluids based on (H2O:EG 50:50% wt.) and OT-100, were proposed mathematical models that allow obtaining those physical properties. The correlations consider the effect of the concentration of the nanoparticle and the effects of the viscosity and thermal conductivity of the base fluid and the nanoparticle. The models also depend on constants associated with possible effects of shape and size of each type of nanoparticle.

2. EXPERIMENTAL PROCEDURE

The samples of nanofluids were realized using two-step method. The nanoparticles were acquired in powder of a functionalized solution in high weight concentration and scattered in two types of base fluids. The first is a mixture of water and ethylene glycol with 50% of mass concentration of each substance (H_2O:EG 50:50% wt.). The second base fluid used was the thermal oil LUBRAX OT-100 supplied by PETROBRAS.

2.1 Nanofluids based on water and ethylene glycol (H_2O:EG 50:50% wt.)

To produce the nanofluids based on water and ethylene glycol (H_2O:EG 50:50% wt.), a routine described in Fig. 1 was established. Were used nanoparticles of two different categories of base materials; nanoparticles based on carbon (carbon nanotubes) and nanoparticles based on inorganic materials (Ag), with different nanoparticle size and morphology as can be shown in Tab 1.

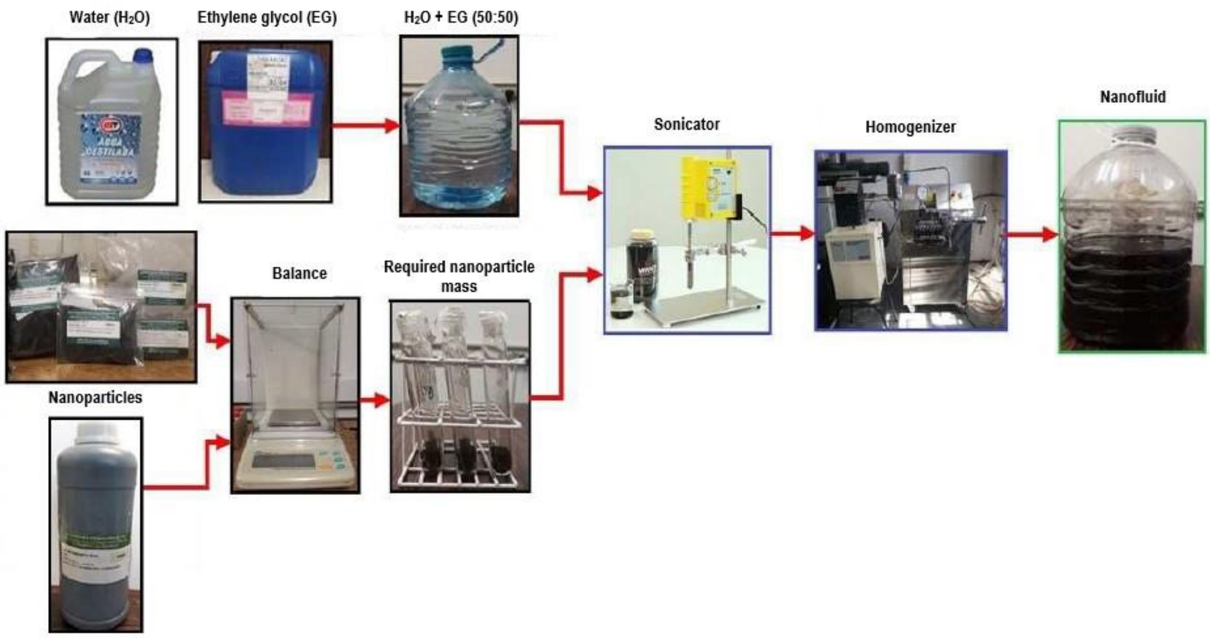

Figure 1. Nanofluid production process.

Therefore the samples of nanofluids produced were the result of a process of dispersion, sonication and homogenization of nanoparticles in powder form or dispersed in a functionalized water based solution of high concentration. Both powdered nanoparticles and functionalized solution were supplied by Nanostructures & Amorphous Materials.

Table 1. Description of nanofluid samples produced*.

Sample	Nanoparticle/diameter [nm]	Base fluid	[% Vol.] ϕ	[% mass] wt.
Ag_80_1	Ag/80	H_2O:EG 50:50% wt.	0.005	0.0493
Ag_80_2	Ag/80	H_2O:EG 50:50% wt.	0.010	0.0986
Ag_80_3	Ag/80	H_2O:EG 50:50% wt.	0.050	0.4915
CNT_800_1	MWCNT / [20 – 30]	H_2O:EG 50:50% wt.	0.001	0.0019
CNT_800_2	MWCNT / [20 – 30]	H_2O:EG 50:50% wt.	0.005	0.0098
CNT_800_3	MWCNT / [20 – 30]	H_2O:EG 50:50% wt.	0.010	0.0197
CNT_800_4	MWCNT / [20 – 30]	H_2O:EG 50:50% wt.	0.050	0.0988

*The physical properties of nanoparticles used to compute this table were provided by the manufacturer.

To determine the amount of mass of nanoparticles a routine was developed in the EES software. In this sense, the desired volumetric concentration for each nanofluid and the final volume (V_f = 3500 ml) were previously defined.

2.2 Nanofluids based on thermal oil (OT-100)

To produce nanofluids nanotube based on thermal oil (OT-100) supplied by PETROBRAS, the routine applied in the synthesis of all samples has been slightly changed from that implemented for samples of nanofluids based on (H_2O:EG 50:50% wt.). Thus, the production process of nanofluids based on (OT-100) is described in the Fig. 2. Also, were used nanoparticles of two different categories of base materials, nanoparticles based on carbon (Carbon nanotubes) and nanoparticles based on inorganic materials (Ag), with different morphology and size of nanoparticles.

Samples of nanofluids were produced based on thermal oil LUBRAX (OT-100) as described in Tab 2, and not were realized gravimetric tests to verify the final volumetric concentration before testing in the experimental bench. Based on results obtained of gravimetric tests in samples based on (H_2O:EG 50:50% wt.) was considered an extra addiction of nanoparticle mass (5% more than nanoparticle mass necessary for each concentration).

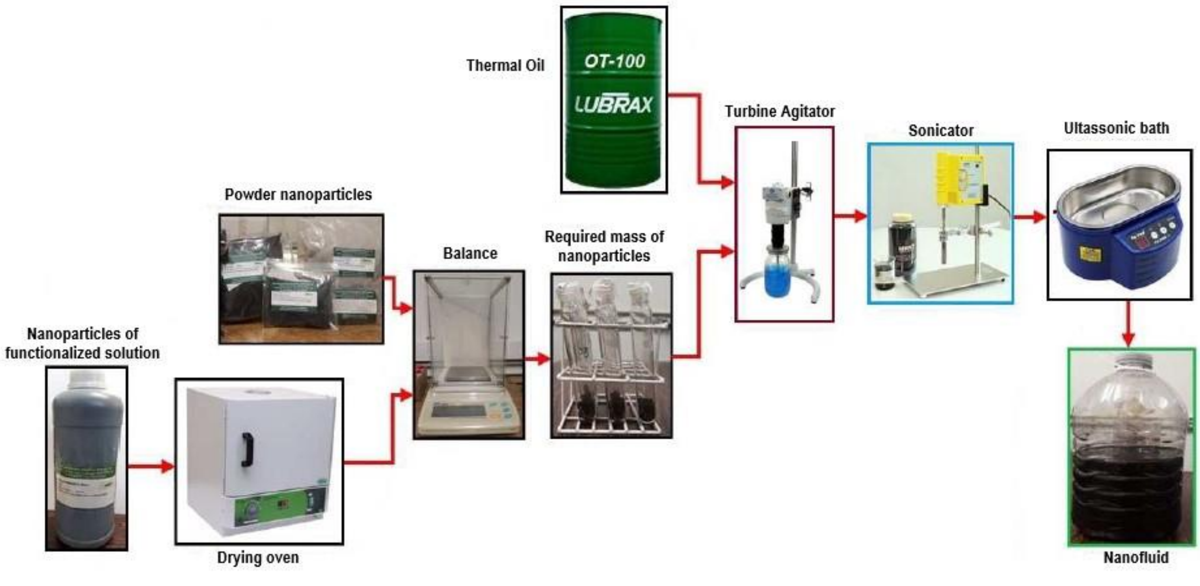

Figure 2. Nanofluid production process.

The main difference of production process between nanofluids based on thermal oil and water-ethylene glycol is that the homogenizer is not used in high pressure due the risk of contamination of the samples by any external agent and the contamination among samples due to the difficult of cleaning the equipment.

Table 2. Description of nanofluids samples produced based on (OT-100)*.

Sample	Nanoparticle/diameter [nm]	Base fluid	[% Vol.] ϕ	[% mass] wt.
OT-Ag_20_1	Ag / 20	OT-100	0.005	0.0592
OT-Ag_20_2	Ag / 20	OT-100	0.010	0.1183
OT-Ag_20_3	Ag / 20	OT-100	0.050	0.5892
OT-CNT_800_1	MWCNT / [20 – 30]	OT-100	0.005	0.0119
OT-CNT_800_2	MWCNT / [20 – 30]	OT-100	0.010	0.0237
OT-CNT_800_3	MWCNT / [20 – 30]	OT-100	0.050	0.1185

*The physical properties of nanoparticles used to compute this table were provided by the manufacturer.

3. RESULTS

This section presents the experimental results of the thermal conductivity and dynamic viscosity measurements for nanofluids samples based on (H_2O:EG 50:50% wt.) and thermal oil (OT-100). Comparison of experimental results with those obtained in the literature is also presented as well the correlations between the mathematical model used and the experimental data.

Fig. 3 and 4 show the experimental results for thermal conductivity of Ag nanofluids samples in relation to different temperatures at which measurements were taken.

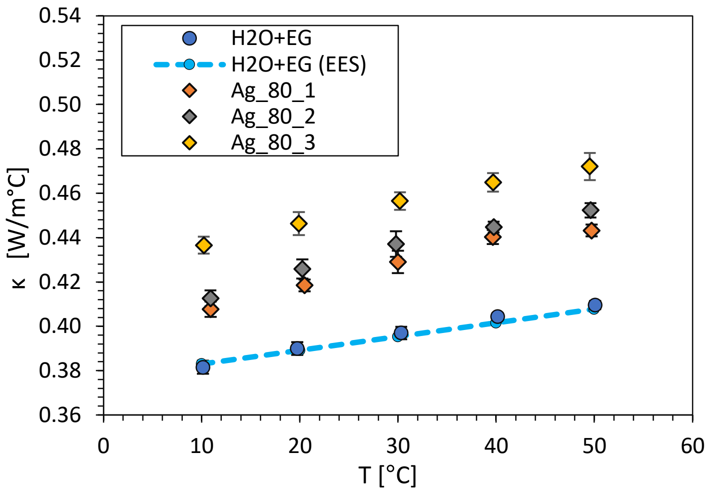

Figure 3. Thermal conductivity of Ag nanofluids with 80 nm of diameter in relation to different temperatures.

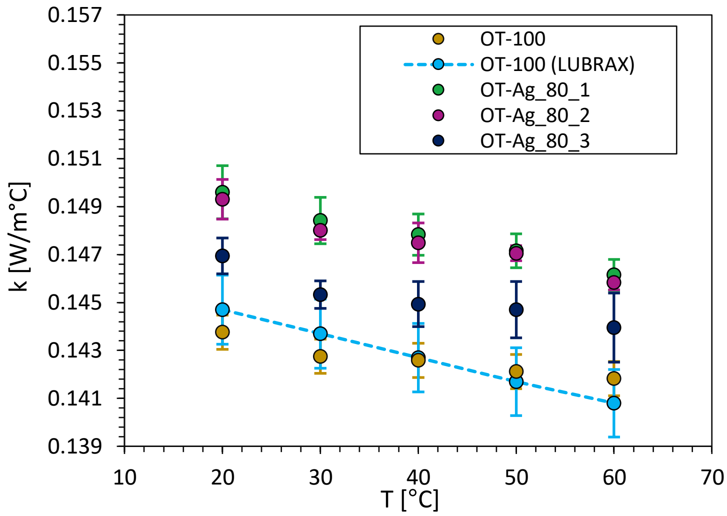

Figure 4. Thermal conductivity of Ag nanofluids with 80 nm of diameter in relation to different temperatures.

In Fig. 3 shows that on average increases were 7.8, 9.6, and 14.8% for samples Ag_80_1, Ag_80_2 e Ag_80_3 respectively. Therefore, in Fig. 3 is observed as an increment of nanofluid thermal conductivity with the increase of temperature and with the increase of the volume concentration of nanoparticles. At high temperatures, the reduction of the surface energy of the nanoparticle is favored, reducing the possibility of nanoparticle agglomeration and causing a decrease in viscosity leading to an intensification of Brownian motion. In Fig. 4 shows that on average increases were 3.7, 3.4, and 1.8% for samples OT-Ag_80_1, OT-Ag_80_2 e OT-Ag_80_3 respectively. This behavior was different from the observations made in the nanofluid samples based on (H2O: EG 50:50 wt%) that used the same type of nanoparticles (Ag_80).

This divergence may be related to the motion effects due to nanoparticle interaction and Brownian motion may have been minimized due to the high dynamic viscosity of the thermal oil (OT-100), minimizing the increases of thermal conductivity.

Fig. 5 and 6 present the experimental results of measurements performed for dynamic viscosity of nanofluids samples based on (H_2O:EG 50:50% wt.) and thermal oil (OT-100). It is important to highlight the good agreement between the dynamic viscosity experimental data and the model proposed for samples based on (H_2O:EG 50:50% wt.), which have a maximum deviation of 1.13% within the analyzed temperature range.

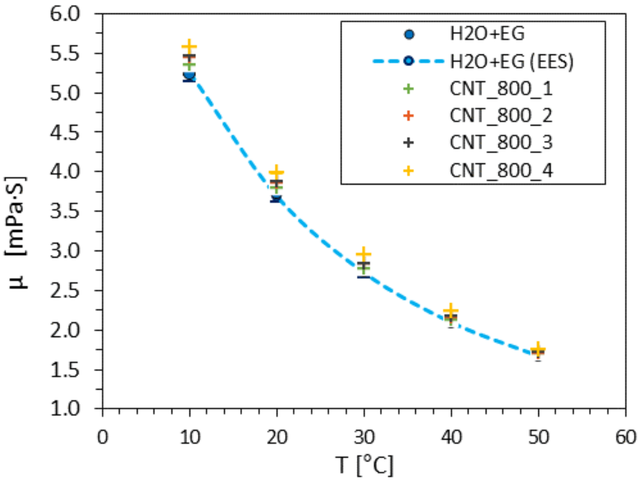

Figure 5. Dynamic viscosity of CNT_800 in relation to different temperatures.

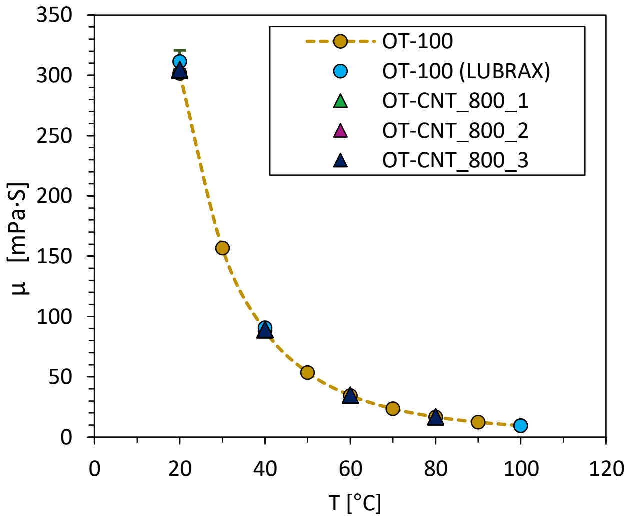

Figure 6. Dynamic viscosity of OT_CNT_800 in relation to different temperatures.

In Fig. 5 we can see that the nanofluids samples present dynamic viscosity values higher than base fluid, where viscosity increments obtained for nanofluids samples of carbon nanotubes with aspect ratio (r=l/d=800) were on average 1.9%, 3.4%, 3.8% and 6.8% for samples of CNT_800_1, CNT_800_2, CNT_800_3, and CNT_800_4 respectively. In Fig. 6 the viscosity increments obtained were in average 0.63%, 0.90% and 1.28% for samples of

CNT_800_1, CNT_800_2, and CNT_800_3 respectively. Is important to note that dynamic viscosity of (H_2O:EG 50:50% wt.) is almost 100 times smaller than thermal oil (OT-100), favoring the interactions between nanoparticles.

According to (TIMOFEEVA, GAVRILOV, et al., 2007) in a steady state a particle of cylindrical shape or an elongated cluster can have two types of movement due to Brownian movements:

The first one, the rotational movement around the center of the length of the nanotube and second translational movement that can happen in parallel or perpendicular to the length of the nanotube. In this sense, when the average spacing between the particles is much greater than the largest particle size (length of the nanotube), the rotation and translation movements are not restricted between them.

Therefore, it is expected that the shear stress will be little influenced because of the interactions between the nanoparticles, minimizing the effect of the shape on increasing the viscosity of the nanofluid. This effect is intensified when the base fluid is more viscous.

Fig. 7 show a comparison between the experimental results and literature data for dynamic viscosity of MWCNT based on thermal oil in relation to different temperature range. It is observed that the dynamic viscosity decreases exponentially with the increase of temperature.

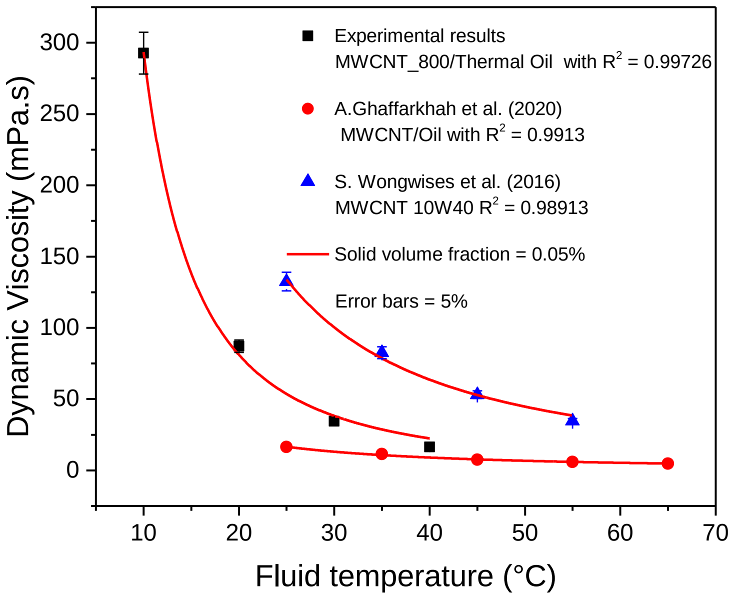

Figure 7. Comparison between experimental results and literature data for dynamic viscosity.

The discrepancy among the experimental results literature data in relation to dynamic viscosity as can be seen in Fig. 7 can be explained by mass concentration (%wt.) in the samples, the constant r^2 is a percentage of the response variable variation that explained by the fitted regression line computed by Origin Software. As higher the mass concentration, the viscosity increase.

3.1 Mathematical models proposed for thermophysical properties

Based on experimental results of thermal conductivity in samples of nanofluids based on (H_2O:EG 50:50% wt.), was proposed a mathematical model described in the Eq. (1) that allow to obtain this physical property. The correlation considers the effect of nanoparticle concentration (ϕ) and the thermal conductivity effects of based fluid (k_{bf}) and nanoparticle (k_{np}). The model is also dependent of two constants, C_1 and C_2 described in the Tab. 3, associated with possible effects of shape and size of each type of nanoparticle. R^2 is the proportion of the variance in the dependent variable (k_{nf}) that is predictable from the independent variables (k_{np}, k_{bf}, ϕ, C_1, C_2).

$$k_{nf}\left(k_{np}, k_{bf}, \phi\right) = \left(1 + \frac{k_{np}}{C_1} \cdot \phi^{C_2}\right) \cdot k_{bf} \tag{1}$$

Table 3. Thermal conductivity constant model for nanofluids samples based on (H_2O:EG 50:50% wt.).

Nanofluid	C_1	C_2	R^2
CNT_800	1718	0.4141	0.985
AG_80	365.1	0.2721	0.992

A correlation of thermal conductivity of samples based on thermal oil OT-100 also is proposed. The model described in Eq. (2) was reasoned in the experimental results obtained of samples nanofluids with silver nanoparticles and carbon nanotubes, OT-Ag_80 and OT_CNT_800.

$$k_{nf}\,(k_{np}\,,k_{bf}\,,\phi)=\left(1+\frac{k_{np}}{C_1}\cdot\phi^{C_2}\right)\cdot k_{bf}\,+C_3\cdot\phi \tag{2}$$

The model proposed consider the effect of nanoparticle concentration and the thermal conductivity effects of based fluid and nanoparticle. The model depends of three constants, C_1, C_2 and C_3 described in the Tab. 4. In this model, the constants C_1 and C_2 may be associated with the possible effects of the shape and size of the nanoparticle. However, the constant C_3 is associated to effect of nanoparticles aggregation that in function of concentration tend to increase, allow the instability of the sample, consequently minimizing conductivity increment. R^2 is the proportion of the variance in the dependent variable (k_{nf}) that is predictable from the independent variables (k_{np}, k_{bf}, ϕ, C_1, C_2, C_3).

Table 4. Thermal conductivity constant model for nanofluids samples based on (OT-100).

Nanofluid	C_1	C_2	C_3	R^2
OT_Ag_80	10060	0.009565	-6.177	0.972

From the experimental results of dynamic viscosity for the samples of nanofluids based on (H_2O:EG 50:50% wt.), was proposed a mathematical model described in Eq. (3) that allow to obtained the dynamic viscosity of nanofluids (μ_{nf}) samples which is dependent of nanoparticles concentration (ϕ) and viscosity of based fluid (μ_{bf}). The model depends on a constant C for each type of nanofluid according to the Tab. 5 where R^2 is the proportion of the variance in the dependent variable (μ_{nf}) that is predictable from the independent variables (μ_{bf}, ϕ, C).

$$\mu_{nf}\,(\mu_{bf}\,,\phi)=(1+C\cdot\phi)\cdot\mu_{bf} \tag{3}$$

Table 5. Dynamic viscosity constant model for nanofluids samples based on (H_2O:EG 50:50% wt.).

Nanofluid	C	R^2
CNT_800	152.10	0.997
AG_80	42.37	0.999

The model proposed to determine the viscosity of nanofluids samples based on thermal oil (OT-100) is the same that described in Eq. (3) to viscosity of samples based on (H_2O:EG 50:50% wt.). However, the constant C, characteristic of each sample of nanofluid based on thermal oil is described in the Tab. 6 where R^2 is the proportion of the variance in the dependent variable (μ_{nf}) that is predictable from the independent variables (μ_{bf}, ϕ, C).

Table 6. Dynamic viscosity constant model for nanofluids samples based on (OT-100).

Nanofluid	C	R^2
OT_Ag_80	12.90	1

Fig. 8 and 9 present comparisons among experimental results, literature data and model proposed for thermal conductivity and dynamic viscosity respectively for Ag based on mixture of (H_2O:EG 50:50% wt.). The deviation among the results were 5% on average.

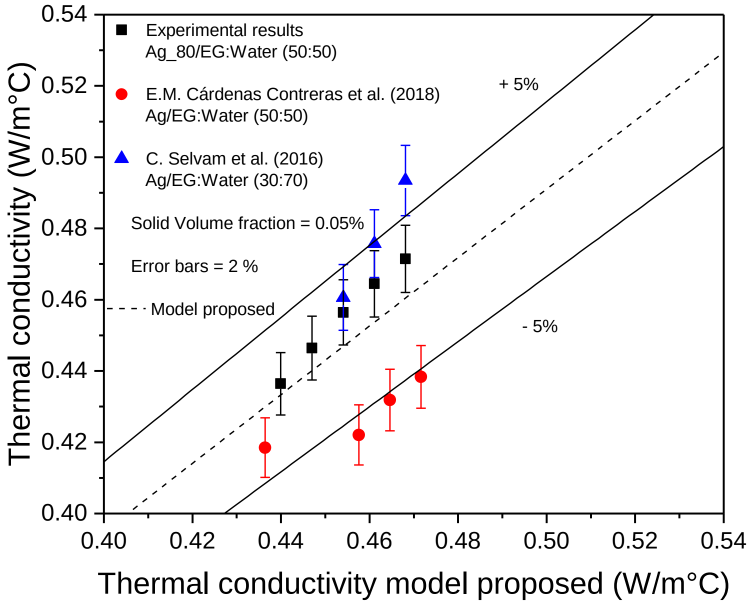

Figure 8. Comparison among experimental results, literature data and model proposed for thermal conductivity.

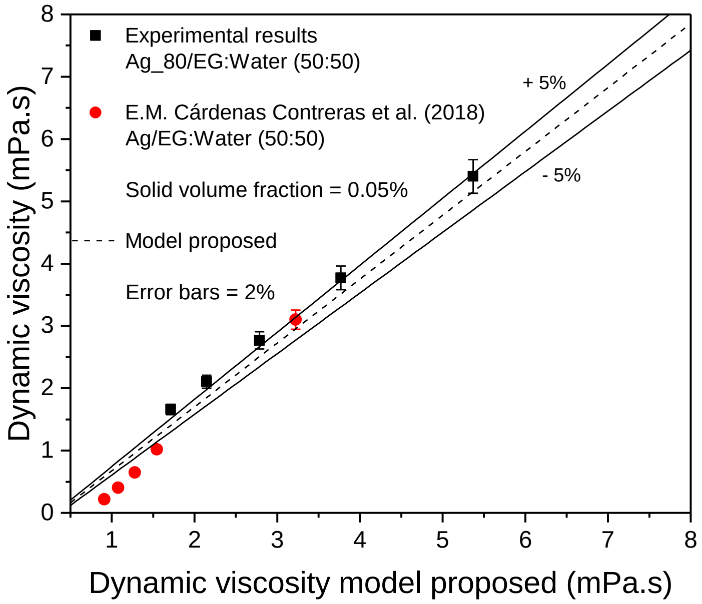

Figure 9. Comparison among experimental results, literature data and model proposed for dynamic viscosity.

We can observe a good agreement for both comparisons in Fig. 8 and 9, despite the dispersion between experimental results and the literature data the standard deviation was on average 5% indicating reasonable reliability of mathematical model proposed to obtain approximations for thermal conductivity and dynamic viscosity.

3.2 Correlation

To compute the correlation between the experimental results and the model proposed were used the method described by Holman (2012), where the correlation coefficient is defined by:

$$r = \left[1 - \frac{\sigma_{y,x}^2}{\sigma_y^2}\right]^{1/2} \tag{4}$$

where σ_y is the standard deviation of y given as:

$$\sigma_y = \left[\frac{\sum_{i=1}^{n}(y_i - y_m)^2}{n-1}\right]^{1/2} \quad (5)$$

and:

$$\sigma_{y,x} = \left[\frac{\sum_{i=1}^{n}(y_i - y_{ic})^2}{n-2}\right]^{1/2} \quad (6)$$

The y_i are the actual value of y, and y_{ic} are the values computed from the correlation equation for the same value of x. The division by n-2 results from the fact that we have used two derived variables a and b in determining the value of y_{ic}. We might say that this removes two degrees of freedom from the system of data. The correlation coefficient r may also be written as:

$$r^2 = \frac{\sigma_y^2 - \sigma_{y,x}^2}{\sigma_y^2} \quad (7)$$

where, now, r^2 is called coefficient of determination.

Fig. 10 show the correlation between experimental results and the model proposed for thermal conductivity using Ag_80 based on (H_2O:EG 50:50% wt.).

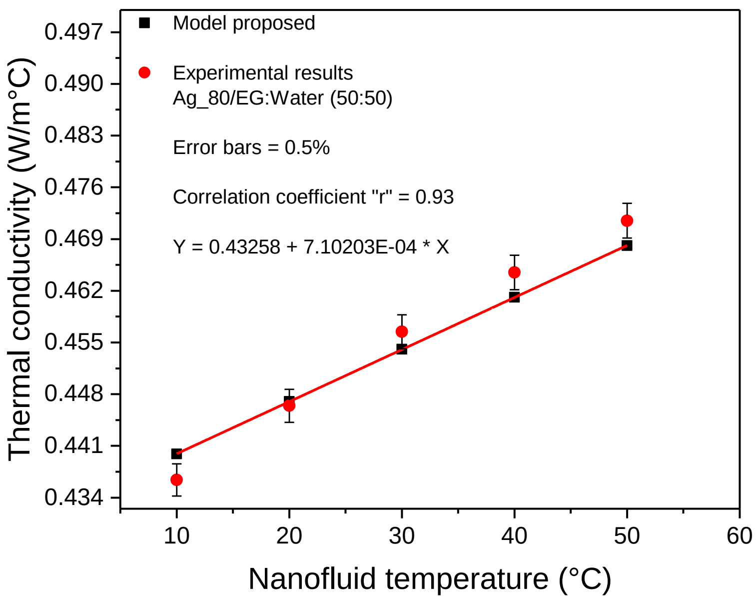

Figure 10. Correlation between experimental results and model proposed for thermal conductivity.

The proposed correlation “r” found was 0.93 with experimental results within maximum error of 3%. Hence, this correlation can be used for estimate a reasonable approximation for thermal conductivity nanoparticles based on (H_2O:EG 50:50% wt.) and thermal oil (OT-100).

4. CONCLUSIONS

The results obtained of measurements for thermal conductivity of samples based on (H_2O:EG 50:50% wt.) and thermal oil (OT-100), indicated increments above the predictions obtained by the effective means theory (EMT).Thus, increases in conductivity compared to the base fluid of up to 18.6% were observed for nanofluids based on thermal oil.

The viscosity of nanofluids was also another parameter experimentally determined, indicated increments slightly significative in the samples based on (H_2O:EG 50:50% wt.). The nanofluids samples based on thermal oil (OT-100) did not present significative differences in comparison with the values obtained for the base fluid.

Finally, was proposed correlations to the thermophysical properties (thermal conductivity and viscosity) that model the behavior of the results obtained experimentally for all nanofluid samples analyzed.

5. ACKNOWLEDGEMENTS

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