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Experimental Evaluation of Thermal Conductivity and Other Thermophysical Properties of Nanofluids Based on Functionalized (–OH) Mwcnt Nanoparticles Dispersed in Distilled Water

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Abstract

A possible way to increase thermal conductivity of working fluids, while keeping pressure drop at acceptable levels, is through nanofluids. Nanofluids are nano-sized particles dispersed in conventional working fluids. A great number of materials have potential to be used in nanoparticles production and then in nanofluids; one of them is Multi-Walled Carbon Nano Tubes (MWCNT). They have thermal conductivity around 3000 W/mK while other materials used as nanoparticles like CuO have thermal conductivity of 76.5 W/mK. Due to this fact, MWCNT nanoparticles have potential to be used in nanofluids production, aiming to increase heat transfer rate in energy systems. In this context, the main goal of this paper is to evaluate from the synthesis to the experimental measurement of thermal conductivity of nanofluid samples based on functionalized (–OH) MWCNT nanoparticles. They will be analyzed nanoparticles with different functionalization degrees (4% wt, 6% wt, and 9% wt). In addition, it will be quantified other thermophysical properties (dynamic viscosity, specific heat and specific mass) of the synthetized nanofluids. So, the present work can contribute with experimental data that will help researches in the study and development of MWCNT nanofluids. According to the results, the maximum increment obtained in thermal conductivity was 10.65% in relation to the base fluid (water).

Keywords

Nanofluids, Multi-Walled Carbon Nano Tubes (MWCNT), Functionalization Degree, Thermal Conductivity, Thermophysical Properties

1. Introduction

The use of solid particles suspended in water, like micro-scale ones, in order to increase their thermophysical properties, or improve heat transfer rate, is an old research field. It began with Maxwell publication at the end of the 19th century [1]. According to Silva [2], the use of micro-scale particles, has some disadvantages like: sedimentation—particles settle after some time, which reduces their thermal capacity; wear—it is possible to reduce sedimentation by increasing fluid velocity, but it will increase wear inside equipment; clogging—due to particle size, channels tend to become clogged, particularly in narrow cooling channels; pressure drop—increase quite significantly, what limits their application; thermal conductivity—it is proportional to particles concentration, but can potentiate previous problems. A possible way to increase thermal conductivity of working fluids, while keeping pressure drop at acceptable levels, is through nanofluids.

Nanofluids are nano-sized particles dispersed in conventional working fluids. Choi and Eastman [3] were the first authors to use the term "nanofluid" when publishing the results of their theoretical research. Subsequent developments in nanofluid engineering have contributed to the rapid growth of nanotechnology and surface sciences over the last decade [4]. Since the second half of 1990s, a wide range of nanofluids has been developed, using different types of nanoparticles combined with different preparation processes as can be verified in many actual researches like the ones [5] [6] [7] [8].

According to Li *et al.* [9], any solid nanoparticle with high thermal conductivity can, in principle, be used as additive for nanofluids production. Thermal conductivity of solids is generally greater than liquids [10]. As can be verified in Li *et al.* [9], Multi-Walled Carbon Nano Tubes (MWCNT) have thermal conductivity around 3000 W/mK while other materials used as nanoparticles like CuO and Si have thermal conductivity of 76.5 W/mK and 148 W/mK, respectively. Due to this fact, MWCNT nanoparticles have potential to be used in nanofluids production, aiming to increase heat transfer rate in energy systems, and then increase their thermal efficiency, as can be observed in many actual researches under development [11] [12] [13].

Currently, there is a great effort to develop reliable models capable of predicting the thermal behavior of nanofluids due to the wide variety of parameters that influence their thermal conductivity. However, according to Lamas *et al.* [14], no model has been able to accurately predict thermal conductivity of different nanoparticles in suspension.

Essentially, most of the currently proposed models to determine nanofluids thermal conductivity, including nanoparticles based carbon nano tubes (CNT), derive from Maxwell one, capable of determining thermal conductivity in solid-liquid suspensions [15]. It considers the thermal conductivity of nanoparticles and base fluid, in addition to the volumetric concentration of nanoparticles in suspension. Maxwell model is limited by not taking into account factors such as surface area, nanoparticle diameter or its geometry, among others. This can be confirmed by comparing various experimental data with the results predicted by Maxwell model, where experimental increases in thermal conductivity are always superior to the results predicted by Maxwell.

The model proposed by Hamilton and Crosser [16] considers a statistically homogeneous non-spherical particle distribution in a base fluid and no interaction between particles. This model uses Maxwell's fundamental equations to determine the thermal conductivity of the dispersed microscopic particles. It introduces an empirical factor related to particles sphericity (geometry). The works of Xie *et al.* [17], Wen and Ding [18], and Liu *et al.* [19] mention the model proposed by Hamilton and Crosser [16]. According to such authors, for low nanoparticles concentrations, theoretical results showed good agreement with experimental data.

In relation to experimental procedures to evaluate nanofluids thermal conductivity, Xuan and Li [20] measured the thermal conductivity of Cu/water and Cu/oil nanofluids for volume concentrations of 2.5% and 7.5%. They were observed increase in thermal conductivity of 78% and 24%, respectively. The thermal conductivity of TiO_2/(deionized water) nanofluids at 5% volume concentration was measured by Murshed *et al.* [21]. They reported 33% of enhancement in thermal conductivity in the base fluid. In the research performed by Leong *et al.* [22], they devised a correlation in which a nanolayer is considered as one of the main mechanisms for increasing nanofluids thermal conductivity. Their results were compared with available experimental data. Thermal conductivity of the nanolayer with a thickness of 1 nm was estimated to be 3 times that of the base fluid for Al_2O_3/water nanofluid, and for CuO/water nanofluid, its thermal conductivity was estimated to be 5 times that of the base fluid. In the research carried out by Rocha *et al.* [23], water-based nanofluids of Al_2O_3 and ZrO_2 were studied and characterized for their promising use in heat transfer applications. Three different volumetric concentrations (0.01%, 0.05%, and 0.1%) of the cited nanofluids were prepared. The experimental measurements were performed at different temperatures. Thermal conductivity, viscosity and specific mass of the nanofluids were measured. It was concluded that volume concentration, particle size/shape and temperature are important variables.

With regard to studies about thermal conductivity of carbon nanotubes, Munkhbayar *et al.* [24] analyzed such parameter for MWCNT/H_2O nanofluids with temperatures between 30˚C and 45˚C. They used nanoparticles with specific dimensions (D = 20 nm, and L = 5 μm). They concluded that increments in thermal conductivity were increased due to increasing volume concentration and temperature. The maximum increment observed for thermal conductivity was 18% at 45˚C. Still, Soltanimehr and Afrand [25] analyzed the thermal conductivity of MWCNT nanofluids with volume concentration equal to 1% and temperatures between 25˚C and 50˚C. These authors found an increment in thermal conductivity of up to 34.7% at 50˚C. Additionally, Wen and Ding [18] studied the influence of temperature on the thermal conductivity of MWCNTs/ water nanofluids; according to them, for temperatures below 30˚C, thermal conductivity varies linearly with temperature.

Complementing the cited studies about thermal conductivity of MWCNT nanofluids, in addition to recent ones [26] [27] [28] [29] about the same subject, the main goal of this paper is to evaluate from the synthesis to the experimental measurement of thermal conductivity of nanofluid samples based on functionalized (−OH group) MWCNT nanoparticles provided by CTNano (Center for Technology in Nanomaterials and Graphene) in Brazil. They will be analyzed nanoparticles with different functionalization degrees in relation to the weight of the −OH group (4% wt, 6% wt, and 9% wt). In addition, it will be quantified other thermophysical properties (dynamic viscosity, specific heat and specific mass) of the synthetized nanofluids. Such properties are important in heat transfer applications involving nanofluids.

As thermal conductivity can be considered the most important physical property responsible for heat transfer, and no model is yet able to determine sufficiently nanofluids thermal conductivity [30]. It is necessary to search for more experimental data to achieve greater understanding about this physical phenomenon. In this way, the present work can contribute with experimental data that will help researches in the study and development of MWCNT nanofluids.

2. Materials and Methods

In this section are described the experimental steps necessary to achieve the main aim of the work. They are: nanoparticles characteristics and nanofluids synthesis in addition to the experimental procedure to evaluate nanofluids thermophysical.

2.1. Nanoparticles Characteristics and Nanofluids Synthesis

Functionalized MWCNT nanoparticles (4% wt; 6% wt and 9% wt, in weight of −OH group) provided by Center for Technology in Nanomaterials and Graphene (CTNano) of Federal University of Minas Gerais (UFMG) were acquired to perform the experimental analysis described in next sections. Such nanoparticles are shown in **Figure 1**, while their physical and geometrical characteristics are in **Table 1**. It was utilized particles with −OH (hydroxyl group) functionalization to make carbon nanotubes (CNT) more hydrophilic, and so increase the stability of MWCNT/H_2O nanofluid samples to be synthetized. If nanofluids are stable, experimental measurements of their thermophysical properties, like thermal conductivity and density, become more realiable and precise.

Figure 1. Functionalized MWCNT nanoparticles provided by CTNano.

Table 1. Characteristics of functionalized MWCNT nanoparticles provided by CTNano.

Purity	>95%
Functionalization degree (% in weight of –OH group)	4% wt; 6% wt e 9% wt
Nanoparticles diameter (nm)	10 - 20 (4%); 20 - 40 (6%); 50 - 80 (9%)
Nanoparticles lenght (μm)	10 - 30 (4%); 10 - 30 (6%); 10 - 20 (9%)
Color	Black
Morphology	Elongated tube
Fusion point (˚C)	3652
Boiling point (˚C)	Not determined
Thermal conductivity (W/m·K)	5000
Molar weight (g/mol)	12.01
Density at 20˚C (g/cm^3)	2.1
Specific heat (kJ/kg·K)	0.71
Purity	>95%

MWCNT/H_2O nanofluid samples were produced according to a two-step method composed by ultrasonic vibration and high pressure homogenization processes. It was used a Ya-Xun sonicator (ultrasonic bath, model 3060, operating frequency 42 kHz, power 30 W/50W) in addition to a APL-500 high pressure homogenizer provided by Artepeças company (flow 100 - 500 liters/hour). Nanoparticles masses were measured on a Gehara balance (model BK500). Next, MWCNT nanoparticles were added to the base fluid (distilled water) and then subjected to the sonicator and to the high pressure homogenizer to produce the nanofluids. In Figure 2 is schematized this two-step method. Table 2 presents the characteristics of the nanofluids obtained, including their volumetric concentration plus the required masses of MWCNT nanoparticles and the corresponding volume of distilled water (base fluid). The name of each nanofluid sample (ex: M1C1, M1C2 and M1C3) in function of its functionalization degree and volumetric concentration is also in Table 2.

Table 2. Characteristics of the synthetized MWCNT/H_2O nanofluids.

Nanofluid sample	−OH [%wt]	r = L/D	Volumetric concentration φ [%]	Distilled water [mL] (±0.1 ml)	MWCNT nanoparticle [g] (±0.001 g)
M1C1			0.005	4000.0	0.420
M1C2	4%	1000	0.01	4000.0	0.840
M1C3			0.05	4000.0	4.200
M2C1			0.005	4000.0	0.420
M2C2	6%	667	0.01	4000.0	0.840
M3C3			0.05	4000.0	4.200
M3C1			0.005	4000.0	0.420
M3C2	9%	231	0.01	4000.0	0.840
M3C3			0.05	4000.0	4.200

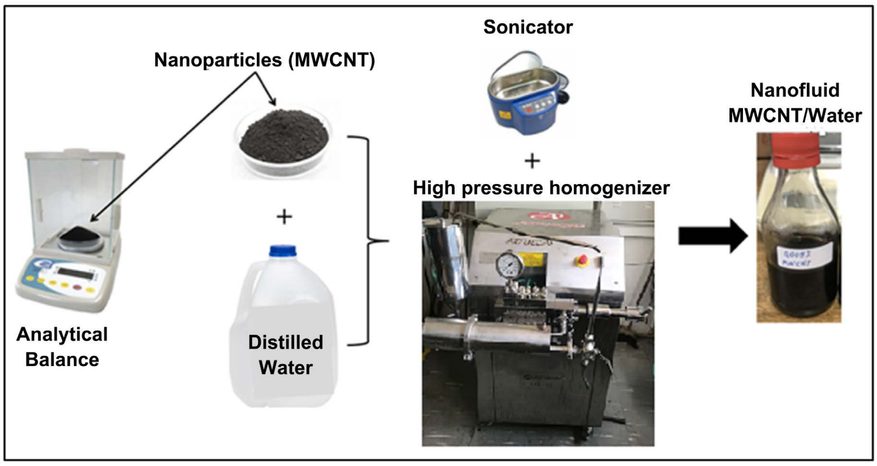

Figure 2. Two-step method to synthetize MWCNT/H_2O nanofluids samples.

After their production, part of each nanofluid sample was properly identified and packaged in small-volume flasks, placed on a flat surface and kept at room temperature as shown in Figure 3. In order to qualitatively assess their stability, a visual inspection was performed periodically to check their stability and sedimentation caused by gravity over time. The nine samples exhibited good stability; there was no nanoparticles sedimentation even after 8 months. This is due to MWCNT nanoparticles surface functionalization described by their manufacturer (CTNano). The main objective of surface functionalization is to improve MWCNT nanoparticles dispersion in polar liquids such as water, since these nanoparticles are strongly hydrophobic.

2.2. Thermal Conductivity of MWCNT/H_2O Nanofluid Samples

It was used a Linseis device, model TB-1 (Transient Hot Bridge), to measure nanofluids thermal conductivity. The equipment uses a flat heat source, which is considered an evolution of the traditional transient hot wire method, enabling

Figure 3. MWCNT/H_2O nanofluid samples qualitative stability evaluation.

faster measurement without operator interference, what reduces errors during the process. Both conductivity meter and THB-1 sensor are shown in **Figure 4**.

The traditional transient hot wire method has disadvantages, such as heat loss between electrical conductors, high sensitivity to mechanical stress, low sensitivity between output voltage and sensor temperature. THB-1sensor eliminates part of these disadvantages, due to the construction of a bridge between small electrical resistors, forming a flat conductor and increasing temperature sensitivity of the signal. The flat conductor is divided into two resistors of different lengths, resulting in a single heat source. For thermal conductivity analysis at different temperatures, a thermal container, in **Figure 5**, was installed for temperature control during experimental procedures.

To maintain fluid temperature at the desired value, a thermal bath (Microchemical MQBM-01) was coupled to the thermal container as in **Figure 6** [31]. This device allows digital temperature selection over a range of −20˚C to 150˚C, with a resolution of 0.1˚C. During the process, the cavity of this thermal container was filled with fluid. THB-1 sensor is then inserted into such cavity. The sensor receives heat from the fluid until the desired temperature is reached. Finally, THB-1 conductivity meter is directly connected to a computer, through its own software, to control test parameters and then visualize the results. The complete experimental apparatus used to determine thermal conductivity of each nanofluid sample is also presented in **Figure 6** [31]. It is composed by THB-1 Linseis conductivity meter, thermal container, MQBM-01 thermal bath and a computer with THB-1 software. Conductivity measurement is done through a transient process that depends on the measurement time. In this way, the data acquisition time and the power dissipated must be adjusted so that the software is able to calculate thermal conductivity of the sample. **Figure 7** shows the software interface for adjusting the parameters electric current and test time.

The measurement process is based on Equation (1). In it, k is the thermal conductivity of the fluid; q is the heat dissipated per unit length; ΔT is the temperature variation; and Δt is the time variation. However, the calculation can only be performed in the temperature range where the variation $\Delta T/\ln(\Delta t)$ can

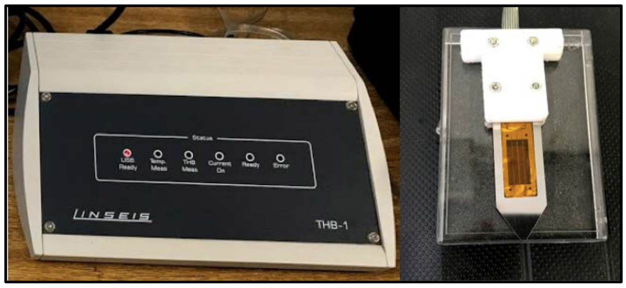

Figure 4. Conductivity meter and THB-1 sensor.

Figure 5. Thermal container and THB-1 sensor.

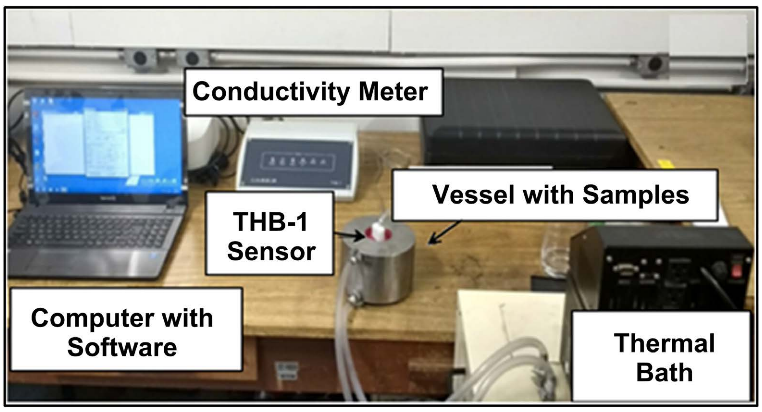

Figure 6. Experimental apparatus for measuring the thermal conductivity of nanofluids [31].

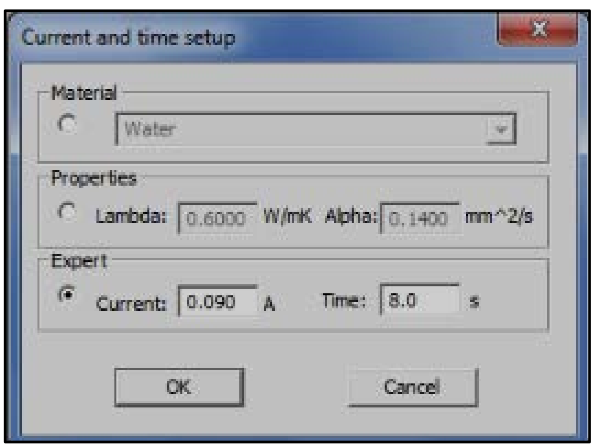

Figure 7. Parameters selection for conductivity measurement.

be considered linear. For this reason, the program presents the output signal proportional to temperature as a function of time. In addition, the derivative of this function must consequently be constant in period in order to determine k.

$$k = \frac{q}{4\pi\Delta T}\ln(\Delta t) \quad (1)$$

Finally, the main software interface shows the results for thermal conductivity of all samples, if calculation is possible. If calculation is not possible, an error is indicated, and an adjustment in time and electrical current parameters are required to enable evaluation. The optimal parameters vary according to the nature of the fluid and its temperature. Therefore, an individual adjustment was made for each sample before measurements were started. **Figure 8** exhibits the main software interface.

Thermal conductivity measurements were performed at temperatures set at 10˚C, 20˚C, 30˚C, 40˚C and 50˚C. For all fluid samples, distilled water and nanofluids, 10 measurements per cycle were performed, and the final conductivity value was the arithmetic mean of the results obtained. For calculations was considered an uncertainty inferior to 5% according to THB-1manufacturer.

To quantify a possible increment in thermal conductivity or other thermophysical property (P), the results obtained for nanofluid samples were compared with the ones for distilled water (base fluid), which were also determined experimentally. The percentage increase value (I_c) was determined by Equation (2); where, P_{nf} is the property of the nanofluid and P_{bf} is the property of the base fluid (distilled water).

$$I_c[\%] = \left(\frac{P_{nf} - P_{bf}}{P_{bf}}\right)\cdot 100 \quad (2)$$

2.3. Specific Heat of MWCNT/H_2O Nanofluid Samples

Specific heat of MWCNT/H_2O nanofluid samples were determined according to Xuan and Roetzel [32] correlation, Equation (3). It employs a classical model based on the thermal equilibrium between particles and their surrounding fluid, in addition to the volumetric concentration (φ) of the solution, the specific heat (Cp) and density (ρ) of nanoparticles (np) and base fluid (bf).

$$Cp_{nf} = \frac{\varphi\cdot\rho_{np}\cdot Cp_{np} + (1-\varphi)\cdot\rho_{bf}\cdot Cp_{bf}}{\varphi\cdot\rho_{np} + (1-\varphi)\cdot\rho_{bf}} \quad (3)$$

2.4. Dynamic Viscosity and Specific Mass of MWCNT/H_2O Nanofluid Samples

An Anton Paar rotational viscometer (model SVM 3000), **Figure 9**, was used to determine the specific mass (density) and dynamic viscosity of MWCNT/H_2O nanofluids and distilled water. Viscosity measurement is based on certain parameters such as speed and torque while density is determined according to a cell inside the equipment that operates according to "U" tube oscillation principle.

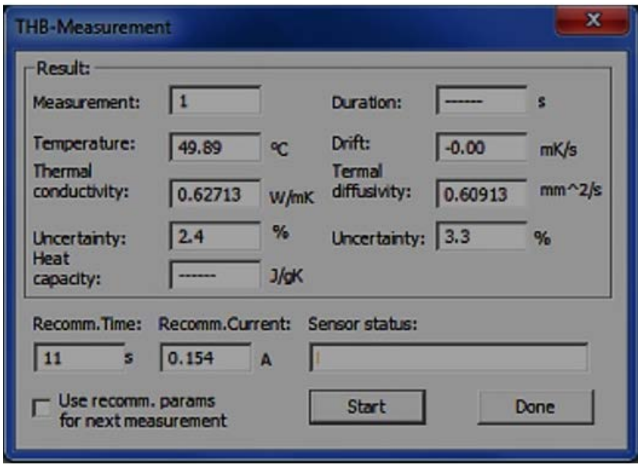

Figure 8. Visual interface (results) of the program for thermal conductivity tests.

Figure 9. Viscometer used to measure viscosity and density of nanofluid samples.

Both viscosity and density measurement cells are filled simultaneously with fluid sample [33]. Temperature control is carried out by the equipment itself, with measurements performed at temperatures of 10˚C, 20˚C, 30˚C, 40˚C and 50˚C. For all nanofluid properties tests, five replicates were performed, and the average was considered. The standard deviation was taken into account in the uncertainty analysis. The values of dynamic viscosity and density for all MWCNT/H_2O nanofluid samples and distilled water were provided by the viscometer. The viscometer has uncertainty of ±0.35% for viscosity and ±0.0005 g/cm^3 for density according to the manufacturer.

3. Results

3.1. Thermal Conductivity Results

The nanofluids were synthesized using functionalized MWCNT (–OH) nanoparticles dispersed in distilled water. The experimental results of thermal conductivity for all functionalized samples (4% wt, 6% wt, and 9% wt), in function of temperature, are presented in Figure 10. In this picture, it can be observed good agreement between experimental data of the base fluid (distilled water) and the

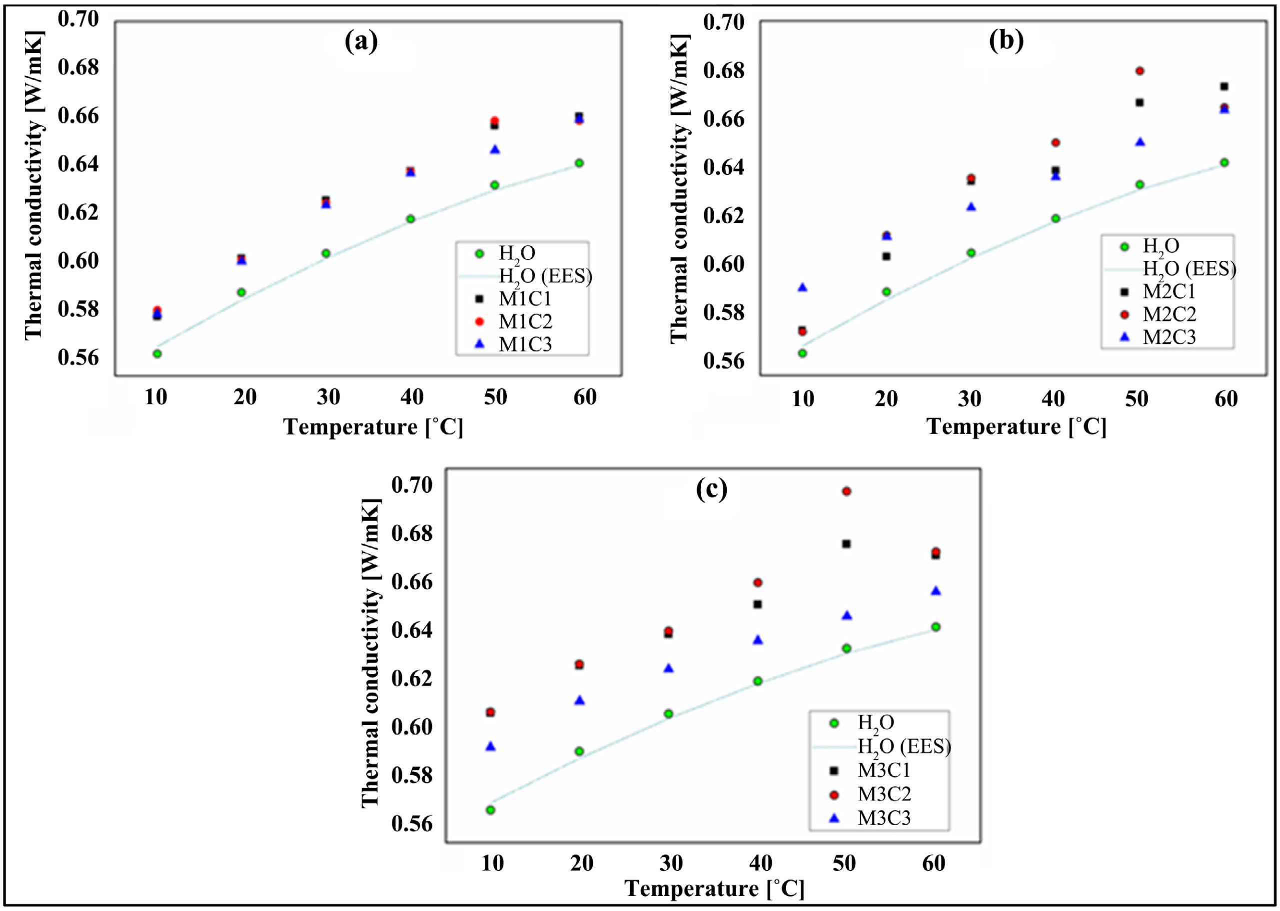

Figure 10. Thermal conductivity of functionalized MWCNT nanofluids in function of temperature.

reference data obtained from EES software, which presents a maximum deviation of 0.65% in the analyzed temperature range. Additionally, in Figure 10, there was an increase in thermal conductivity for all nanofluids concentration when compared to distilled water.

Increments in thermal conductivity of each nanofluid sample in function of temperature are presented in Figure 11. In general, there was increase in thermal conductivity. The largest increments occurred for intermediate volumetric concentration of 0.01% for the three nanofluids. They were (4.20 ± 0.13)% for M1C2, Figure 11(a), whose nanoparticle volume concentration is equal to 0.01%. For nanofluids in Figure 11(b), the highest increment obtained was (7.37 ± 0.22)% for sample M2C2, which has volumetric concentration equal to 0.01%. Finally, in Figure 11(c), the highest increment was (10.65 ± 0.32)% for sample M3C2, whose volumetric concentration is also 0.01%. In all the samples analyzed, it was observed that the volumetric concentration equal to 0.01% showed higher thermal conductivity values than the highest volumetric one (0.05%). This may have occurred due to nanoparticles sedimentation caused by its high concentration.

The average increment in thermal conductivity of samples with lower functionalization degree (4 wt%, Figure 11(a)), intermediate functionalization degree

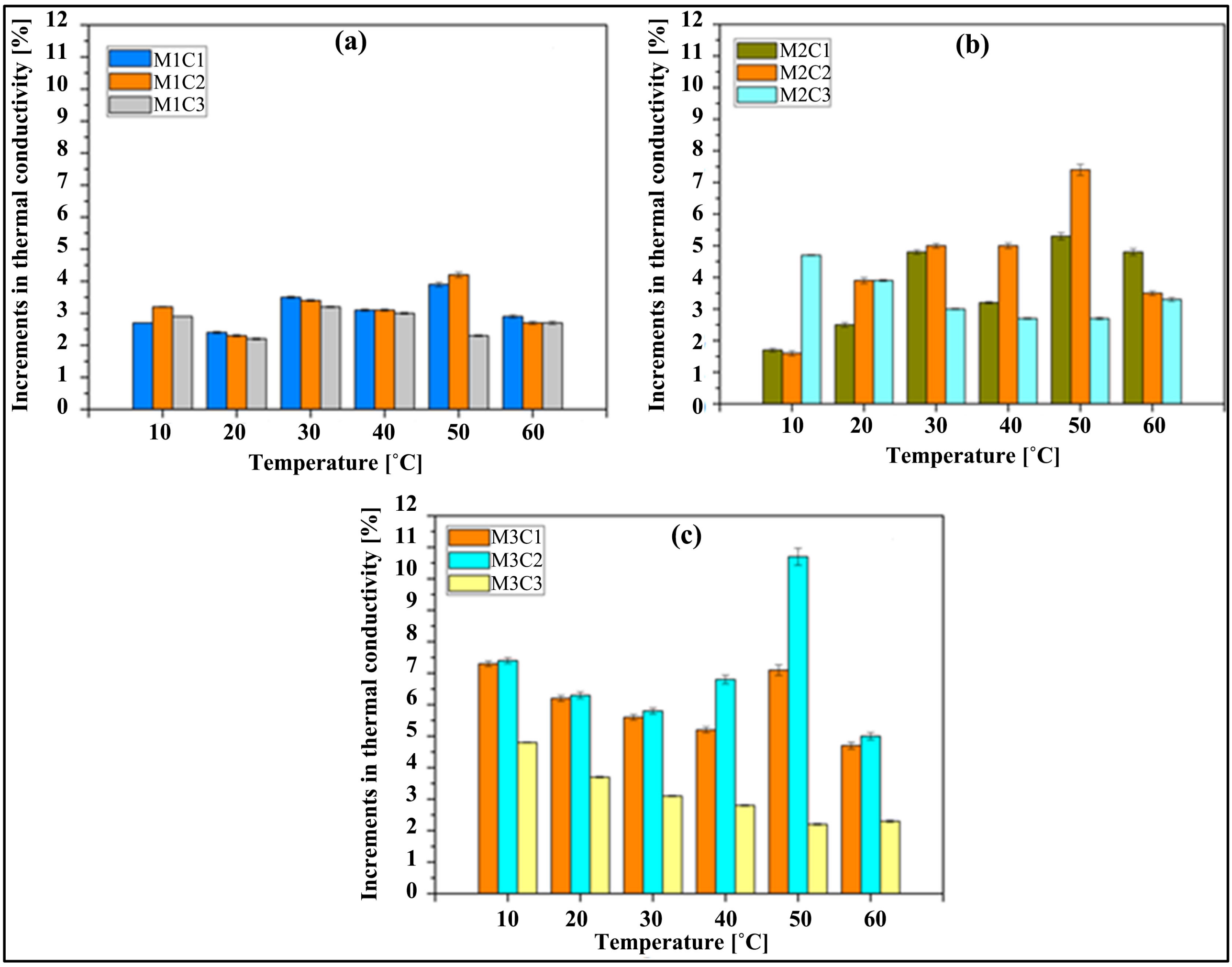

Figure 11. Increments in thermal conductivity of functionalized MWCNT nanofluids in function of temperature.

(6 wt%, **Figure 11(b)**) and higher functionalization degree (9 wt%, **Figure 11(c)**) were 2.75%, 3.82% and 4.68%, respectively. According to Yu *et al.* [34], the reasons for the increase in thermal conductivity of nanofluids is due to the high thermal conductivity of multi walled carbon nanotubes, approximately 4000 W/mK, the high surface area in the case of carboxylated MWCNT nanoparticles, and also the surface rich in hydroxyl (−OH) and carboxyl (−COOH) groups, which allow good compatibility with base fluids such as water, reducing contact resistance and improving dispersibility.

3.2. Specific Heat Results

Figure 12 shows the values of specific heat for nanofluid samples in function of temperature. They are also exhibited the values of *Cp* for distilled water. Equation (3) does not consider the morphology or the size of nanoparticles or even its functionalization degree, but their volumetric concentration previously defined in **Table 2**. Because of this, the final values of specific heat, for a certain temperature point, are the same for samples that have the same volumetric concentration

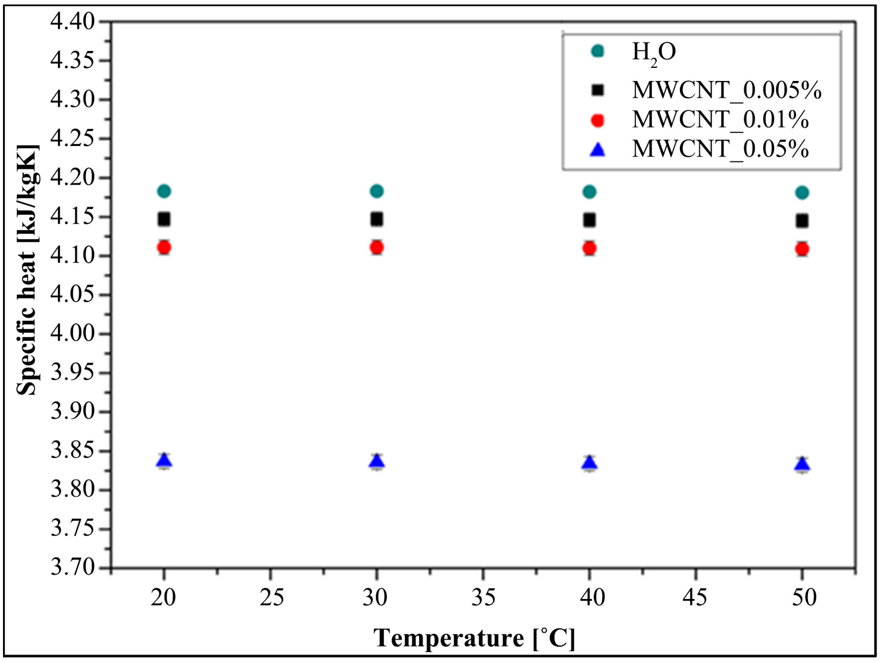

Figure 12. Specific heat of functionalized MWCNT nanofluids in function of temperature.

(ex: M1C1, M2C1 and M3C1). Additionally, for a same nanofluid sample, its specific heat remains the same because there is no considerable change in the specific heat of water in the temperature range considered, while the value of specific heat for all nanoparticles was 0.71 kJ/kgK.

According to Figure 12, it is noted that specific heat obtained for all nanofluids was lower than distilled water. It is also possible to verify that specific heat decreases with increasing nanoparticles concentration. This behavior was already expected and occurs due to the specific heat of nanoparticles being lower than water. Consequently, specific heat of the mixture will decrease with increasing volumetric concentration of nanoparticles, as reported by Murshed [35]. Similar behaviors, for other fluids like mineral oil, water/ethylene glycol mixture, and nanoparticles made of carbon nanotubes and grapheme were obtained by Gómez [36], Flores [33], Oliveira (2018) [31] and Gómez [37].

3.3. Dynamic Viscosity Results

It can be seen in Figure 13 the good agreement between experimental results and EES database on the viscosity of the base fluid (distilled water). These data showed a maximum deviation of 1.86% in the analyzed temperature range. For all samples in all temperature ranges, a decrease in dynamic viscosity was observed with increasing temperature, while an increase was observed when the volumetric concentration of nanoparticles is increased.

Increments calculated for all nanofluid samples are in Figure 14. In the case of samples with the lowest (4% wt) functionalization degree, Figure 14(a), the largest increase in dynamic viscosity was 8.6% at 50˚C. In samples with an intermediate

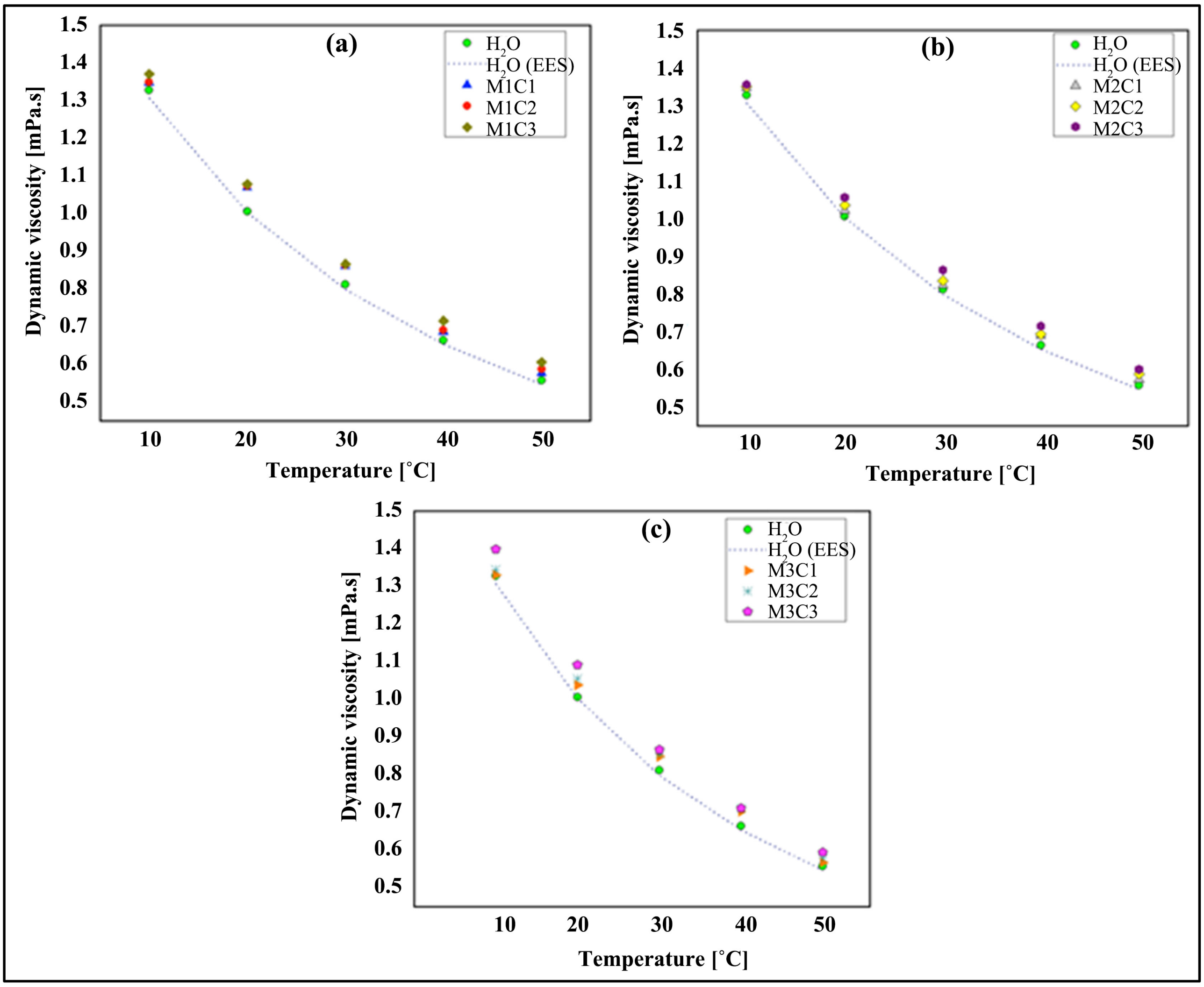

Figure 13. Dynamic viscosity of functionalized MWCNT nanofluids in function of temperature.

(6% wt) functionalization degree, **Figure 14(b)**, the greatest increase in viscosity was 7.6% at 40˚C. For samples with the highest (9% wt) functionalization degree, **Figure 14(c)**, the greatest increase in dynamic viscosity was 8.5% at 20˚C. In all samples, the highest increment value in viscosity occurred for the highest volumetric concentration of nanoparticles (0.05%).

In the present work, the highest average increment for dynamic viscosity was 5.2% for samples in **Figure 14(c)**, which are the ones with the highest functionalization degree and lowest aspect ratio (r = 231). Similar results were obtained by Hoffmann [38] when he measured the viscosity of MWCNT/H_2O nanofluids with volumetric concentration equal to 0.24%, but with different aspect ratios, showing that the nanofluid with nanoparticles with the lowest aspect ratio (r = 100), showed greater mean increment in viscosity. The aspect ratio of all nanofluid samples are in **Table 2**. The increase in viscosity of MWCNT nanofluids occurs because MWCNT nanotubes are made up of long tubes, which, when dispersed in water, form tangles, what contributes to increase viscosity.

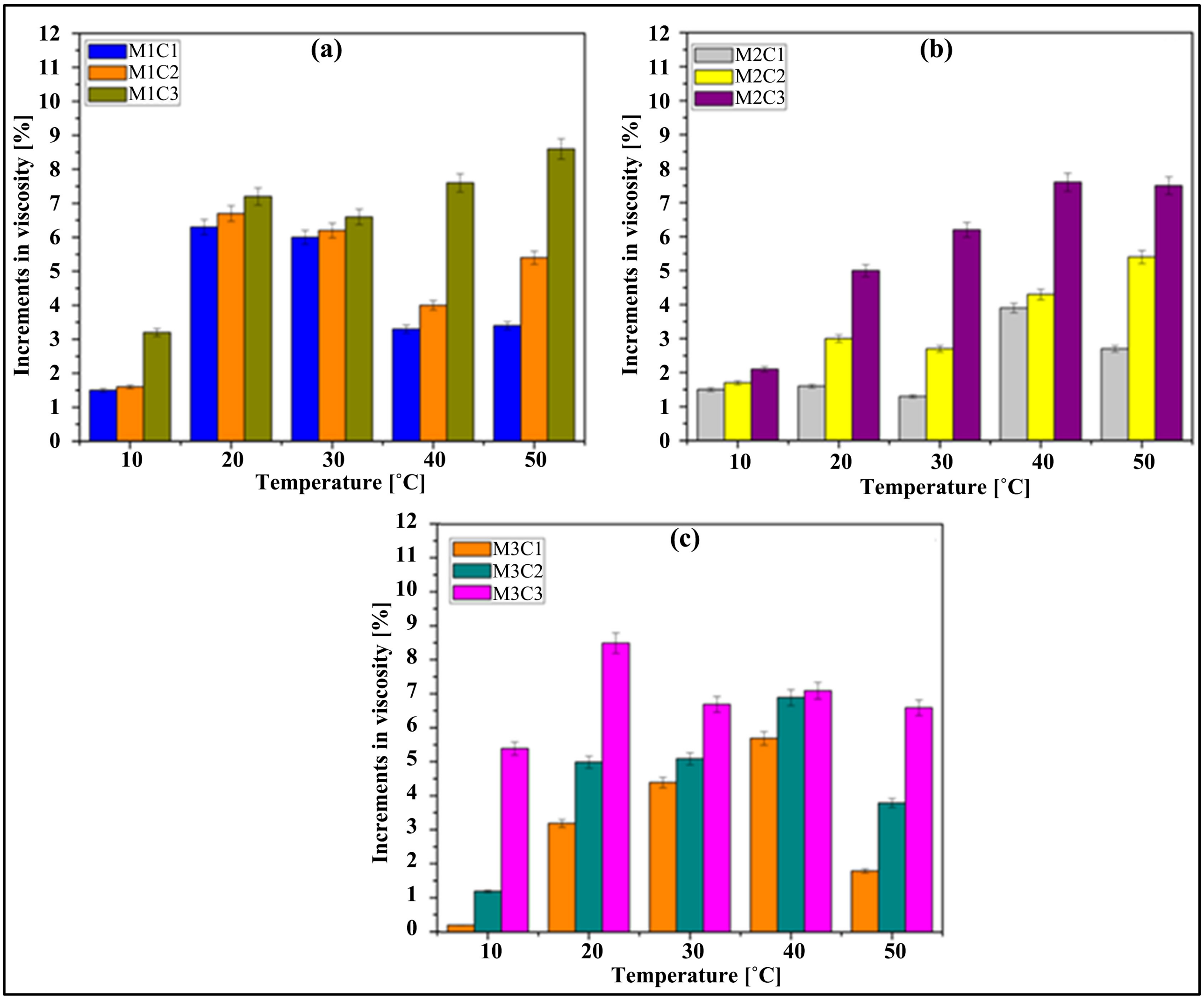

Figure 14. Increments in dynamic viscosity of functionalized MWCNT nanofluids in function of temperature.

3.4. Specific Mass Results

Specific mass (density) of distilled water and nanofluid samples were obtained experimentally with Anton Paar viscometer in Figure 9. Measurements of density were performed for nanofluid samples in a temperature range between 10˚C and 50˚C, with increments of 10˚C. In Figure 15 are presented the experimental results for MWCNT/H_2O nanofluids in function of temperature. Volumetric concentrations are those described in Table 2. As expected, it is observed that there is an increase in specific mass of all nanofluid samples due to adding nanoparticles, as can be observed in Figure 15. Additionally, an overall behavior presented in Figure 15 is the reduction in specific mass due to increasing nanofluids temperature. A possible explanation for this situation is because with enhancing temperature, the volume of a liquid tends to increase, then reducing its specific mass.

In order to promote a better visualization of the results, Figure 16 shows the increments in specific mass for nanofluid samples. In general, an increase in it

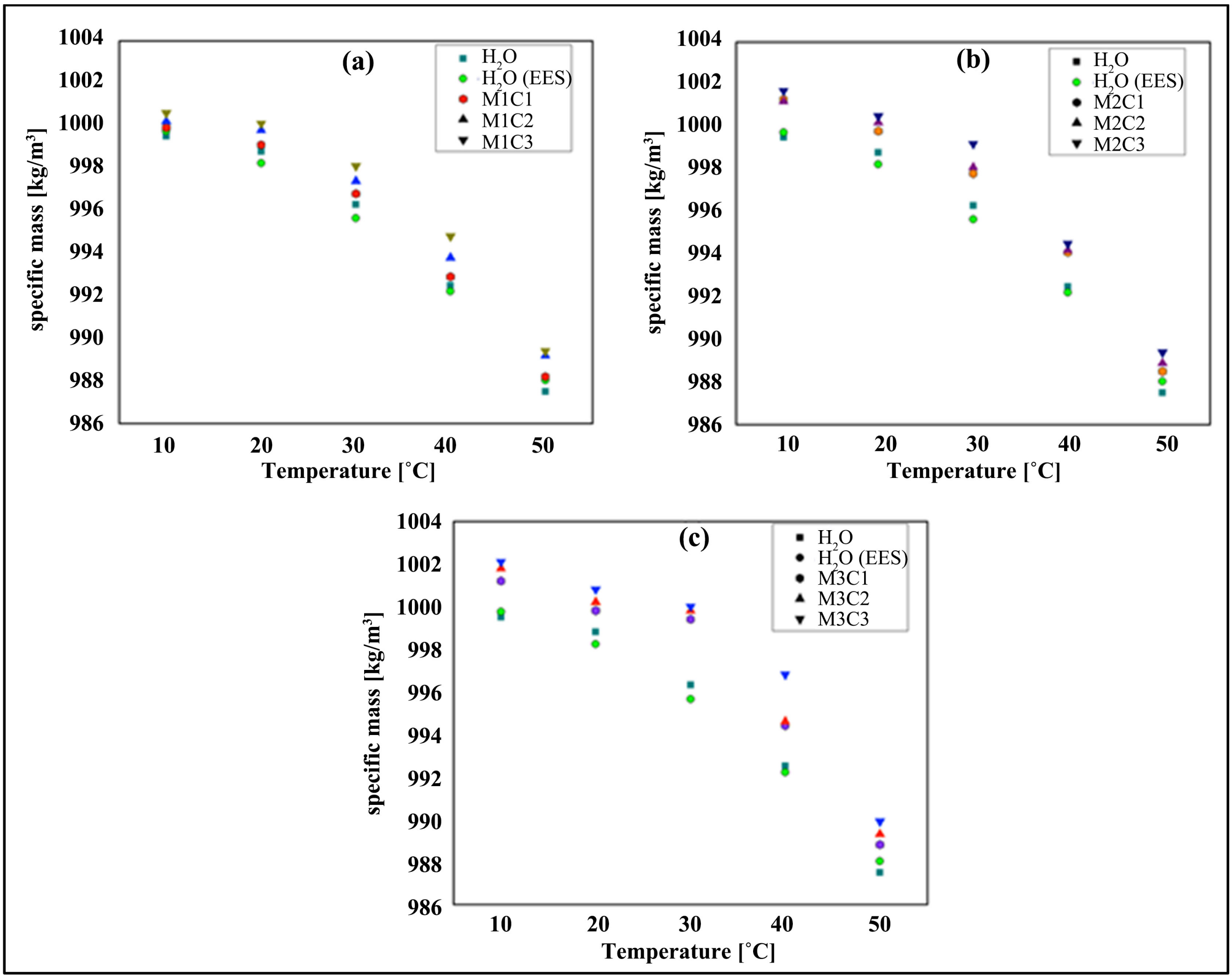

Figure 15. Specific mass of functionalized MWCNT nanofluids in function of temperature.

occurs with increasing volumetric nanoparticles concentration. The biggest increments, in relation to distilled water, always occur in the biggest volumetric concentration of nanoparticles. For samples with lower functionalization degree, Figure 16(a), the mean increment was 0.12% and while the maximum was 0.26% for 40˚C. In the case of samples with intermediate functionalization degree, Figure 16(b), the average increment obtained was 0.19% and the maximum 0.36% at 30˚C. Finally, for samples with the highest functionalization degree, Figure 16(c), the average increment was 0.25% and the maximum was 0.46% at 40˚C.

4. Conclusions

Nanofluids and nanoparticles are relevant research fields nowadays, as can be verified in recent researches [39] [40] [41] [42] covering such subject. Although the present work did not perform any analysis to evaluate the stability of the produced nanofluids, their samples remained stable even after 11 months. This fact suggests that the "two-step" method, carried out by means of a sonicator

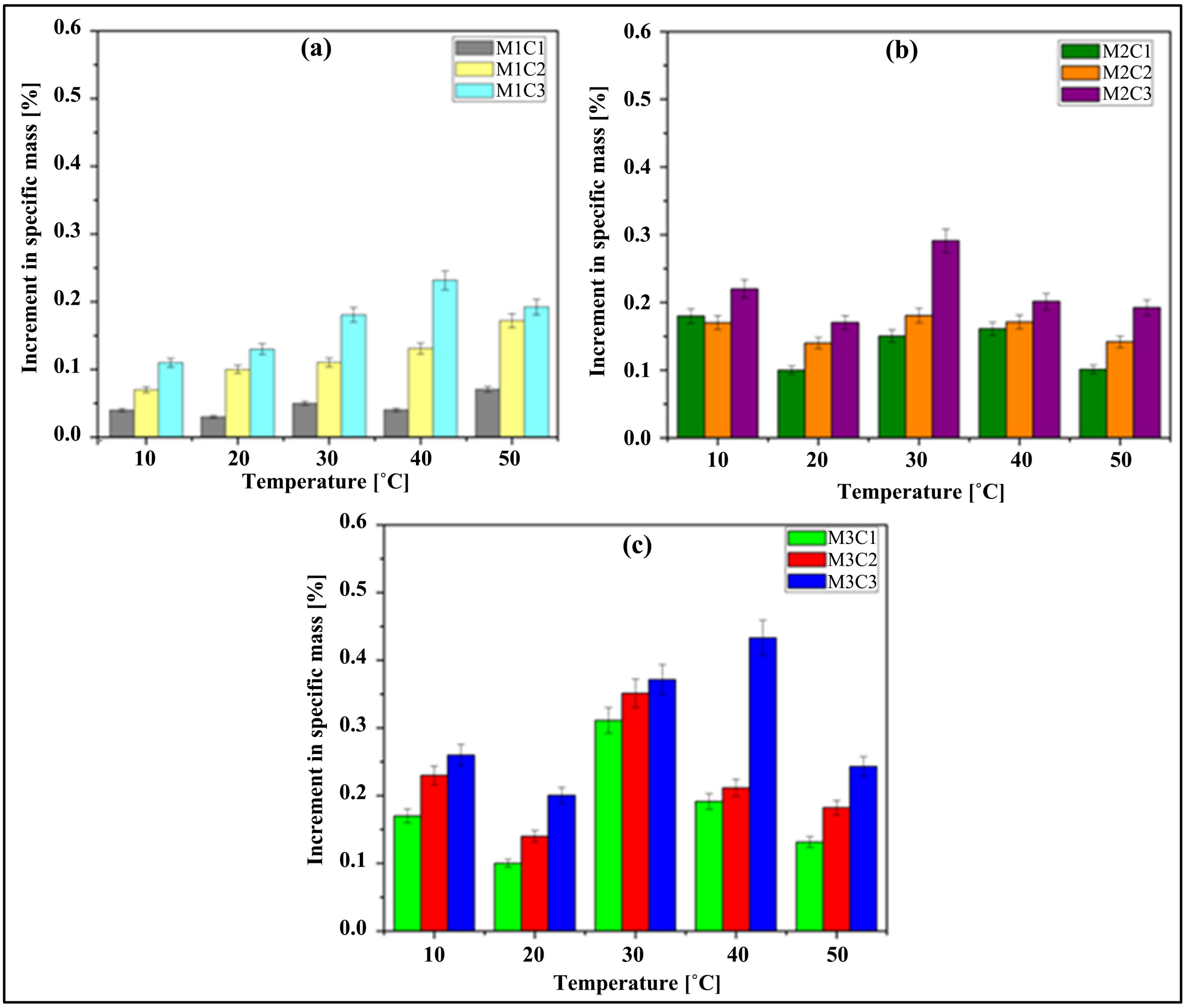

Figure 16. Increments in specific mass of functionalized MWCNT nanofluids in function of temperature.

and a high-pressure homogenizer, is suitable to produce nanofluids. Furthermore, the functionalized characteristics of MWCNT nanoparticles provided by CTNano contribute to obtain stable and homogeneous samples. Their functionalization degrees (4%, 6% and 9%) are based on the −OH group that makes such nanoparticles more hydrophilic, and so increase the stability of MWCNT/ H_2O nanofluid samples to be synthetized.

The results showed that even at low concentrations, MWCNT/H_2O nanofluids showed higher thermal conductivity than the base fluid (distilled water). The highest increment in thermal conductivity was (10.65 ± 0.32)% for sample M3C2, whose volumetric concentration is 0.01%. It was observed that samples with intermediate volumetric concentration of nanoparticles presented the highest values of thermal conductivity. The fact that samples with higher nanoparticles concentration showed lower increment may be related to nanoparticles sedimentation in function of their high concentration. The average increment in samples with lower functionalization degree (4%), intermediate functionalization degree (6%), and higher functionalization degree (9%) were, 2.75%, 3.82%, and 4.68%, respectively. Nanofluid samples with higher functionalization degree showed the largest increments in thermal conductivity.

As suggestions for future works, it would be of great relevance, studies that seek to implement analytical techniques to obtain stable nanofluids and also experimental tests to evaluate equipment wear due to nanofluid flow.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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