COB-2021-1935
PHASE CHANGE MATERIAL ENHANCED WITH CARBON-BASED HYBRID NANOPARTICLES

Thiago da Silva André
Cabral Antônio Cabral dos Santos
Cleiton Rúbens Formiga Barbosa Júnior
Universidade Federal da Paraíba, João Pessoa, Paraíba
thiagoandreengmec@hotmail.com
carloscabralsantos@yahoo.com.br
cleitonformiga@gmail.com

Abstract. Phase change material is a sustainable energy alternative to reduce electrical energy demand One of the applications of the phase change material (PCM) is in refrigeration systems, as it absorbs latent heat from stored products when there is no supply of energy that keeps them frozen and keeps the internal temperature, inside the cold space, constant for a period. In this perspective, this research developed four PCMs based on water plus alcohol. The first is a mixture of water and glycerol, which will act by lowering the melting point of water, with a freezing temperature below zero degrees, to be applied in freezers or cold rooms. The others are PCM (water + glycerol) enhanced with carbon-based nanoparticles (NP) chitosan functionalized: multi-walled carbon nanotubes (MWCNT) and graphene oxide (GO). The amount of nanoparticles was 0.1 kg / m3 in each NePCM, with variations in the percentages of NP, 75% of MWCNT + 25% GO (NePCM-AG1), 50% of MWCNT + 50% GO (NePCM-AG2) and 100% MWCNT (NePCM-AG3), were so named. Furthermore, the thermophysical properties evaluated were density, thermal conductivity, dynamic viscosity and stability. In general, nanoparticles contributed to an increase in the thermal conductivity value, on average 1.5%.

Keywords:: NePCM, thermal conductivity, cooling, latent thermal energy.

1. INTRODUCION

The rational use of energy is the goal of modern society, because moving forward without observing the impacts caused to the environment is not a sustainable path, given the limitation of natural resources. In Brazil, currently, 16.81% of the energy matrix comes from non-renewable energy sources: oil, natural gas, coal, and nuclear (ENEEL, 2021).

The electrical consumption in refrigeration systems (refrigerators and freezers) accounts for a significant portion of the amounts spent, 4% of the world energy consumption, which causes the production of more than 450 million tons of CO_2 (Sonnenrein et al., 2020). This rising cost will require a balance between supply and demand since more investments in energy generation, transmission, and distribution are needed to meet the demands.

In light of this, several techniques have been applied to improve refrigeration systems, examples are the development of more efficient compressors, increased heat transfer in evaporators and condensers, thermal insulation, door tightness, and the implementation of new refrigeration cycles (Mastani Joybari *et al.*, 2015).

The use of thermal energy storage presents itself as an alternative to meet the challenges of sustainable growth (Ebadi *et al.*, 2018) The possibilities are sensitive thermal energy storage (STA), latent thermal energy storage (LTA), and chemical thermal energy storage (CTA).

Sensible thermal storage systems work by heating (increasing the energy) or cooling (reducing the energy level) a solid or liquid material, without a phase change. Latent thermal storage systems operate by storing/releasing stored/absorbed energy with a phase change of the material. Chemical thermal energy storage, on the other hand, is the result of chemical reactions to store or release heat.

In this perspective, the LTA will be adopted in this research, and this form of heat, the latent heat, is present in the phase change of the material, storing or releasing energy. The advantages of LTA, about STA and CTA, lie in the greater capacity for energy absorption and lower temperature variations.

So-called phase change materials, PCM, are widely employed in latent thermal energy storage. In situations where the local temperature of the refrigerated space is higher than the melting point of the PCM, this material absorbs energy, keeping the local temperature constant for a period; otherwise, when the ambient temperature is lower than the melting point, the phase change material releases the energy stored in it, without temperature variations for a period.

PCMs are functional when you are looking for an economy in electricity consumption. At peak charging times, the freezing system is turned off, then the phase change material comes into play (Geete *et al.*, 2018). The temperature of the refrigerated space tends to rise after the refrigeration is turned off; the PCM absorbs the heat from the environment, changing phase, but keeps the local temperature constant as long as the phase change process continues.

In addition, the PCMs also act as temperature maintainers, minimizing the effects of fluctuations, which can result from power outages, door openings, or instability in the refrigeration system (Fuqiao Wang et al., 2007).

Food, vaccines, and medicines require low temperatures to preserve their properties, longer shelf life, and control microbial agents. In this logic, temperature maintenance is essential for the chemical and physiological stability and quality of such products (Gin et al., 2011; Khan et al., 2017).

Water is the universal PCM and is widely used when it comes to energy accumulation under low-temperature conditions, i.e., cooling, and freezing products, foods, etc.(Fangxian Wang et al., 2017). Its solidification/freezing point is 0°C, therefore, it is necessary, for temperatures lower than that, to additive the PCM with a material that provides melting point reduction. Therefore, alcohols have been used for this purpose and glycerin will be the additive to be incorporated into the water, reducing its solidification point (Beatriz et al., 2011).

However, one of the disadvantages of using water and other PCM is the low thermal conductivity, a property that directly influences the heat transfer rate (Kibria et al., 2015). Thus, the increment of nanoparticles (NP) in phase change materials can result in the increase of thermal conductivity, these are the so-called NePCM, PCM enhanced with nanomaterials (Colla et al., 2017; Elias and Stathopoulos, 2019; Sharma et al., 2016; Warzoha et al., 2015).

Among the existing nanoparticles, carbon-based, carbon nanotube, multi-walled carbon nanotube, single-walled carbon nanotube, graphene, and graphene oxide exhibit higher intrinsic thermal conductivity values, 1000-6000 W/m/K (Bahiraei et al., 2017), when compared to the other NPs.

The aim of this research is to develop two water-plus-glycerin-based PCMs additive with MWCNT (multi-walled carbon nanotubes) and GO (graphene oxide) nanoparticles, to be employed in cooling systems.

2. THEORETICAL FOUNDATION

A brief description of the fundamentals of the phase change materials will be presented as well as the nanomaterials and three of the four properties studied, thermal conductivity, dynamic viscosity, and stability.

2.1 PCM

Phase change materials store energy in latent form, i.e., when transitioning phases, solid-liquid, liquid-gas, they absorb or release heat, with temperature maintenance. In practical terms, the solid and liquid phases are the most operational, because the volume change is practically nil.

When a PCM is heated, the change from solid to liquid takes place, the melting. In this process, the phase-changing material absorbs heat from the environment and releases the heat stored in it.

On cooling, the PCM changes from liquid to solid, solidification. In the transition, the phase change material releases heat from the environment and stores heat from its surroundings.

There are three categories of PCM: the organic ones, which include paraffin and non-paraffins; the inorganics, composed of the groups of hydrated and metallic salts; and, finally, the eutectic group, a union of two different materials, which can be the junction of the subgroups presented.

The advantages of organics are high melting temperatures, high latent heat value, low subcooling value, phase change without segregation. The disadvantages are low thermal conductivity and energy density; flammable, expensive, and incompatible with some plastic casings.

Inorganics have a high energy density, low melting point temperatures (-60°C), higher thermal conductivity, no segregation when switching between phases, low cost, not reactive, flammable or corrosive (for most materials); disadvantages are high subcooling values, toxicity (not high) and low nucleation degree.

Eutectic PCMs have the following benefits: accurate melting temperatures (small temperature variation expected), higher energy density than the organic type, no segregation, and uniform phase change. On the other hand, information about physical properties is limited and some have a strong smell.

In selecting a PCM, a balance is sought between physical, chemical, kinetic, thermal, and economic properties. After repeated cycles, namely several phase changes, the maintenance in the property values should be negligible.

The high energy density (physical property), no subcooling (kinetic property), no degradation of the material (chemical property), abundance, and recycling (economic aspect) among others are intended when using PCM.

2.2 Nanomaterials

These are materials with dimensions (at least one of them) in the range of 1 to 100 *nm*. Ultrathin films, nanoparticles, and quantum wires are species of nanomaterials. Nanoparticles (NP) have nanoscale dimensions in three directions, nanoscale films in two directions, and nanowires in one. The NP nanoparticles will be applied in this study.

To obtain nanoparticles, several techniques have been employed, including chemical vapor deposition, physical vapor deposition, atomic layer deposition, mechanical milling, plasma synthesis, and laser pyrolysis among others.

Nanoparticles can be classified as metal, ceramic, polymeric, semiconductor, lipid-based, and carbon-based, these being the ones with the highest thermal conductivity value.

The thermal conductivity [*W/mK*] of some NP follows: alumina (40), copper oxide (76.5), magnesium oxide (54.9), silver (429), aluminum (238-273), gold (310), copper (401), iron (75-80), MWCNT (1000-5000), GO (1000-5000) silicon carbide (490).

Dispersion of NP in phase change materials tends to enhance some properties. Thus, increasing thermal conductivity and the amount of stored energy (latent heat), reducing subcooling, decreasing the time for phase change, and, in some cases, increasing the specific heat are effects obtained or expected by increasing the nanoparticles in PCM.

On the other hand, there may be a reduction in property values after several cycles, an increase in dynamic viscosity, and a reduction in accumulated energy as NPs are added to the PCM.

2.3 Thermal Conductivity and Dynamic Viscosity

Thermal conductivity is directly related to the heat transfer rate, i.e., the higher the conductivity value, the higher the rate of heat transport.

In NePCMs, thermal conductivity is linked to factors such as shape, size, amount, and type of nanoparticles. Smaller NPs offer a greater increment. Regarding quantity, larger fractions tend to raise the heat transfer rate. Platelet-type NPs, compared to the others, provide the best contribution to thermal conductivity.

Inserting nanoparticles into the PCM tends to raise the dynamic viscosity value, which, inflow applications of this material, such as pumping, can generate the undesired effect, i.e., higher energy expenditure in the system to promote fluid displacement.

The amount of nanomaterial and temperature influence the dynamic viscosity value. Under higher temperature conditions, the viscosity decreases in NePCM.

2.4 Stability

Sedimentation happens when adding nanomaterials into a fluid. Poor dispersion of the NPs can make the application of the material impossible (Barbosa Junior, 2021).

In this logic, several strategies are used to provide better integration of the nanoparticles to the PCM. Surfactants are chemical agents and have a disaggregating effect, however, it affects, among others, the thermal conductivity and viscosity of the NePCM (Almeida, 2015).

Adding other nanoparticles in order to promote synergy with the main NP, aiming at dispersion in the PCM was applied by (Mu et al., 2019). Otherwise, a second nanoparticle assists in the stability process of the NePCM.

Functionalization of NPs is also usual when better integration with other materials is desired (Sá, 2015; Holanda, 2017) since nanoparticles are generally hydrophobic. After functionalization, the NPs become hydrophilic, making dispersion in aqueous media possible.

Another possibility is in the mode of NePCM preparation. The one-step method, in which the production and dispersion of the NPs, in the fluid, happen at the same time, shows better stability of the dispersed NPs compared to the two-step technique, production and dispersion happening in separate stages (Sajid and Ali, 2018).

3. MATERIALS AND METHODS

This section will describe the materials that make up the PCM and NePCM and the methodology for carrying out the experimental tests.

3.1 Materials

Distilled water is the PCM used in this research. Among the reasons are a high intrinsic latent heat value, high energy density, and chemical stability. Moreover, besides being found in abundance in nature, it is easy to obtain, low cost, and has the possibility of being reused (Shao *et al.*, 2017).

In applications where freezing of materials is required, which in turn occurs in refrigerators and freezers at temperatures below 0°C, water solidifies and exhibits high undercooling (Amaral *et al.*, 2017), thus a limitation of the use of this PCM in such conditions; however, this limitation is balanced by virtue of the other properties mentioned above.

Since this is a material to be applied in cooling systems and in environments with temperatures below zero degrees, the melting point of water, it is necessary to add an antifreeze so that the melting point of water, the PCM in this case, is lowered. Glycerin, 99.5% purity, commercial name glycerol (C3H8O3) from the manufacturer Insofar, was used for

this purpose (Beatriz *et al.*, 2011). This is an organic compound of the alcohol group, non-toxic, colorless, miscible in water, and, in Brazil, is a byproduct of biodiesel production (Jatobá et al., 2016).

For an increment of thermal conductivity, the main goal of adding nanomaterials in PCM, two nanoparticles were selected. The first, MWCNTs, multi-walled carbon nanotubes, of SIGMA manufacture. These NPs have a very high intrinsic thermal conductivity (4000 *W/m/K*) value compared to other NP groups. In addition, the nanopowders are found commercially, thus facilitating the NePCM production process, as no synthesis and subsequent characterization will be required.

The second nanoparticle employed is graphene oxide (GO). Its primary function is to act as a stabilizer for the MWCNTs, as noted by (Mu *et al.*, 2019), so it will be applied in smaller or equal proportions to the MWCNT NPs. The GO NPs were obtained in the Textile Engineering laboratory of the Federal University of Rio Grande do Norte.

Since the carbon-based nanoparticles, MWCNT and GO, are hydrophobic, they were functionalized to become hydrophilic since PCM is water. Chitosan powder, being a functionalizing agent, was applied for this purpose. This biopolymer comes from the shell of crustaceans such as shrimp, employed to better disperse the carbon NPs and, in turn, make it more stable when in an aqueous medium (Holanda, 2017).

3.2 Methods

Based on works from Almeida (2015), Sá (2015) Azevedo (2016), Sousa (2017), Holanda (2017), Holanda (2018) Barbosa Junior (2019) NePCM was fabricated following eight steps (Figure 1): (a) composition of the PCM, (b) measuring the volume of the PCM, (c) weighing the mass of the PCM, (d) weighing the nanoparticles of the PCM, (e) functionalizing the NPs, (f) adding the functionalized NPs to the PCM, (g) defragmentation and (h) dispersion.
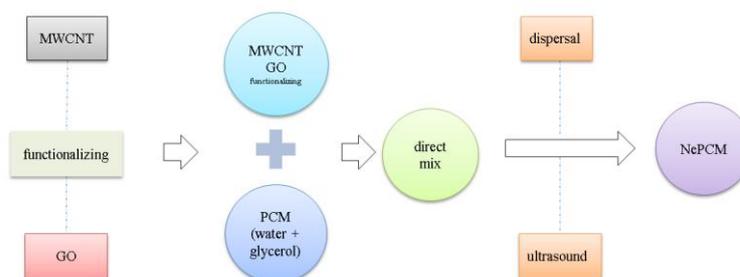

Figure 1. NePCM preparation steps.

The auxiliary equipment in the composition of the PCM was a precision digital balance (Tecnal manufacture, with a resolution of 0.0001g), graduated beakers, graduated beaker, the crucible, stainless steel pallet, graduated pipette, analog magnetic stirrer (maximum temperature 350 °C and maximum RPM 950), ultrasonic bath with frequency 40 kHz (manufacturer SACCH).

First, the PCM was formulated. To this end, distilled water and glycerol, antifreeze, were mixed in a magnetic stirrer for 30 minutes at 650 RPM rotation. The glycerol fraction inserted was based on the expected freezing point of the PCM. It was estimated -5 °C for this point, due to applications in refrigeration systems, therefore, with the help of SecCool software, the amount of glycerol, in mass percentage, to be added in distilled water, indicated by SecCool, is 19%, in other terms, for every 1 ml of water, 0.15 cm3 of glycerol is added.

Then the percentage of nanoparticles to be introduced into the PCM is defined, thus forming the NePCM. There will be three nano-enhanced phase change materials. For each NePCM, the total fraction (MWCNT + GO) of NP is 0.1 kg/m3, arranged as follows: the NePCM-AG1 is formed by 75% MWCNT and 25% GO; the NePCM-AG2 is formed by 50% MWCNT and 50% GO; the NePCM-AG3 has 100% MWCNT. As already mentioned, it will be investigated, among others, whether the GO NP aids in the dispersion of the MWCNT NPs.

The nanoparticles are hydrophobic and to address this issue we resorted to functionalizing the NPs. A 100 cm3 solution of chitosan was produced for this purpose. This liquid is formed by one gram of chitosan powder, added to 99 cm3 of water and 1 ml of acetic acid; in a becker, the solution goes through magnetic stirring, with rotation of 700 RPM, for two hours, finally, it is filtered twice with filter paper (Sá, 2015), thus finalizing the preparation of the solution.

With the solution completed, the next step is the addition of nanoparticles. In this perspective, the mass of NPs is measured on precision scales and subsequently placed in a beaker with 10 cm3 of the chitosan solution (Sá, 2015; Holanda, 2017). This mixture goes into an ultrasound bath for 2 hours and then is magnetically stirred for 1 hour. After this process, functionalization is achieved.

Then 40 *cm³* of the PCM (water + glycerol) is poured into the container that features the nanoparticles functionalized in the chitosan solution. The reason for this action is because the chitosan solution is composed of 99% distilled water.

The mixture is again placed in an ultrasonic bath (defragmentation) for another 2 hours, followed by magnetic stirring (dispersion) for another 1 hour. After these steps, the NePCM development is finished. Each sample has 50 ml of nanoaprimed phase change material.

The thermal conductivity was measured using a conductivity meter, the KD2-PRO from Decagon Devices. The selected probe is the KS-1 and this can have a measurement uncertainty of ±5%. The NePCM is poured into a container and placed under the action of a thermostatic bath (Brookfield TC-550). This bath has the function of oscillating the temperature of the NePCM, for thermal conductivity analysis in various ranges, namely from 15°C to -5°C, varying every 5°C the collection of values. The NePCM has its temperature monitored by a thermocouple, located at the base of the receptacle that contains the material. In addition to this thermocouple, the conductivity meter itself measures the temperature by means of the probe, indicating its value on the display. Once the desired temperature was reached, a 15 minute stabilization period waited for thermal conductivity measurement. The configuration of the equipment is as shown in Figure 2.
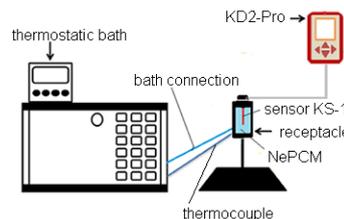

Figure 2. Arrangement of equipment for measuring thermal conductivity.

The dynamic viscosity was measured using a rheometer (manufactured by Brookfield, model DVLVIII-Ultra) plus a coaxial shear sensor, SC4-18, a receptacle for small amounts of material (8 cm3) and a thermostatic bath, manufactured by Brookfield, model TC-550, as shown to Figure 3. All this equipment is connected to a desktop computer for the collection and storage of results, using the Rheocalc software (Brookfield version 3.3).
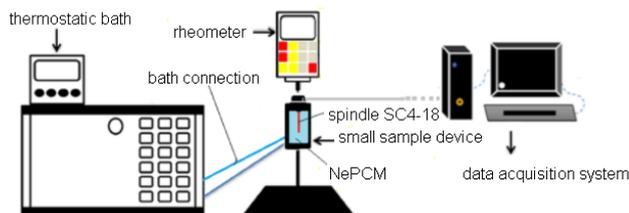

Figure 3. Arrangement of equipment for measuring thermal viscosity.

The stability in the nanoparticles in the phase change material was analyzed using the Zeta potential assay, Zeta Plus Analyser Brookhaven Instruments Corporation Equipment, Figure 4. This technique measures the value of the electric charge, in mV, on the surface of the NPs when they are in a liquid medium (Azevedo, 2016; Souza, 2017). It is an indication of the degree of electrostatic repulsion between the particles and in turn the stability of the suspension. Thus, when the charge value indicated by the Zeta potential is in the range of -25 mV to 25 mV, the material is said to present instability (Sincero and Sincero, 2003; Sá, 2015; Holanda, 2017). The NePCM samples were placed in a polymeric material receptacle, inserted into the camera located inside the equipment. Ten measurements are taken, that is, 10 cycles are performed, and the Zeta potential value is obtained by calculating the average of the measured values. The ambient temperature was 27,5 °C and the hydrogen potential (PH), adjusted by HCl and NaOH solutions in the equipment, was 7, neutral.
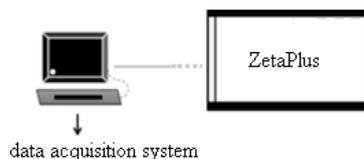

Figure 4. Equipment ZetaPlus.

The density of the materials, both base PCM and NePCM, was measured using a 10 cm3 pycnometer (estimated error 1%). This glass container has a fixed volume measure and, with the help of a digital scale (as specified above), the pycnometer + material set is weighed and, by calculating the density, i.e., mass by volume (of the material only, disregarding the mass of the container), its measure is obtained. Beforehand, it is necessary to calibrate the pycnometer volume and after performing the procedure, the real volume value of the glassware is 12.05 cm3.

It is noteworthy that in the tests when the temperature of -5°C was reached, the three NePCM were still in the liquid state. Therefore, it is concluded that a chitosan solution, in addition to functionalizing as NP, contributes to a decrease in the melting point of nano-enhanced PCM. The melting point will be investigated in future work.

4. RESULTS AND DISCUSSIONS

The results of the experimental tests for density, thermal conductivity, stability, and dynamic viscosity are presented below.

4.1 Density

The tests to measure this property took place in an environment with a temperature of 26.5 $°C$. The reason for the measurement is to know if, after adding the nanoparticles, the NePCM had its density significantly increased.

Table 1. Density (kg/cm^3)

NePCM-AG1	NePCM-AG2	NePCM-AG3	PCM
1,0416	1,0402	1,0388	1,0329

From Table 1, as already expected, the PCM presents the lowest density value. The NePCM-AG1, formed by 75% MWCNT and 25% GO, with an overall percentage of 0.1 kg/cm^3, indicated the highest value compared to the other NePCMs and, comparatively speaking, approximately 1% denser than PCM. When we consider the pycnometer error, we notice for the three NePCMs an equal value for density, but higher than that of the PCM. The reason for this is the mass increment from the nanoparticles.

4.2 Thermal Conductivity

The thermal conductivity is directly related to the heat transfer rate, that is, the higher the conductivity value, the higher the rate of heat transported. First, the conductivity of the PCM was measured. The experiments were repeated five times in each temperature range, with an allowed variation of ± 0.5 $°C$. The average values, in $W/m/K$, are shown in Figure 5.
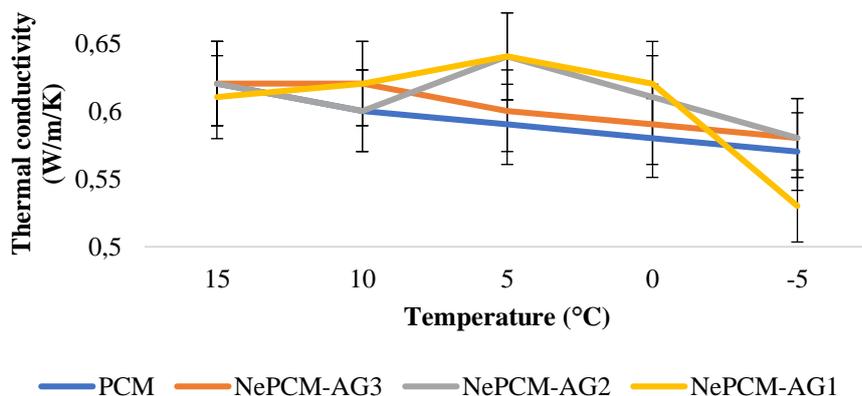

Figure 5. Thermal conductivity (PCM) x Temperature.

Figure 5 points out a decrease in the value of the average thermal conductivity with decreasing temperature. It is worth noting that the PCM at -5$°C$ was still entirely in the liquid state.

When comparing PCM with NePCM-AG1 it can be seen from Figure 5 that at temperatures from 10$°C$ to 0$°C$ the thermal conductivity of NePCM was higher. At 10$°C$ (3.12% higher); at 5$°C$ (8.68% higher) and at 0$°C$ (5.69%).

NePCM-AG2 recorded an increase in thermal conductivity at 5°C, 0°C and -5°C. At 5°C (1.58% increase); at 0°C (4.06%) and at -5°C (0.62%).

In all the temperatures measured, NePCM-AG3 indicated a superior thermal conductivity value compared to PCM. From Fig. 5, we see an increase of 0.71% at 15°C, 3.22% at 10°C, 2.94% at 5°C, 0.78% at 0°C, and 2.16% at -5°C.

As with PCM, as the temperature decreases, so does the thermal conductivity of the nano-enhanced materials. For each temperature range, one of the NePCMs, either AG1, AG2, or AG-3, stood out indicating the highest conductivity record. At 15°C, 10°C, and -5°C, the highest thermal conductivity value is indicated by NePCM-AG3; at 5°C and 0°C, NePCM-AG1 stands out.

It can still be extracted that in NePCMs with a larger amount of MWCNTs, compared to GO, the thermal conductivity measurement is also higher. The reason for the achievement is in the intrinsic value of this property in the MWCNT-type NPs.

The largest and smallest increment in the value of conductivity and their respective materials stand out: NePCM-AG3 at the temperature of 5°C, 8.68% and, the smallest occurred at -5 °C, 0.62%.

4.3 Dynamic Viscosity

The dynamic viscosity, with a unit in *cP* (centiPoise), was measured as a function of temperature, the same applied in the thermal conductivity test. The experiments were repeated 10 times in each temperature range (estimated error 5%). The average values are shown in Figure 6.
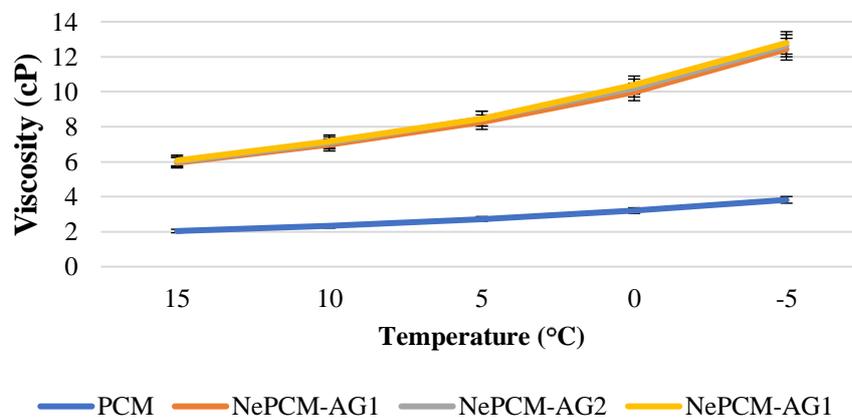

Figure 6. Viscosity x Temperature.

From Figure 6, an increase in dynamic viscosity is observed as the temperature decreases. All NePCMs had the value of this property much higher than the PCM.

At 15 °C, NePCM-AG1 indicated an increase, relative to PCM of 291%; NePCM-AG2, 294%; NePCM-AG3, 297%.

At 10 °C, all three NePCMs had the conductivity increased when compared to PCM, otherwise 300%, 305%, and 309%, respectively, NePCM-AG1, NePCM-AG2, and NePCM-AG3.

The increases in viscosity at the 5°C temperature were approximately 302% for NePCM-AG1, 309% NePCM-AG2, and 310% for NePCM-AG3, in comparative terms.

There was also superiority in the dynamic viscosity values at 0°C. NePCM-AG1, 311%; NePCM-AG2, 318% and NePCM-AG3, 335% compared to PCM.

Even at the sub-zero temperature, -5°C, the measurement of this property was higher than the base PCM. Percentages were 325%, 331%, 335% for NePCM-AG1, NePCM-AG2, and NePCM-AG3, in that order.

NePCM-AG1 stands out among the three nano-enhanced materials. It presented, in all temperature ranges, the highest dynamic viscosity values, in parallel to the other two, and consequently to PCM.

When adding carbon-based nanoparticles to water-plus-glycerol-based PCM, and this material has applicability with movement employing flow in ducts or pipelines, one should be aware that the pumping system will be more demanded, due to a significant decrease in the fluidity of NePCM.

4.4 Stability

After producing the NePCMs, they were tested on their stability through Zeta Potential. Ten points are collected, and then the average is taken. The experiment takes place at ambient temperature. The results are shown in Figure 7, Figure 8, and Figure 9.
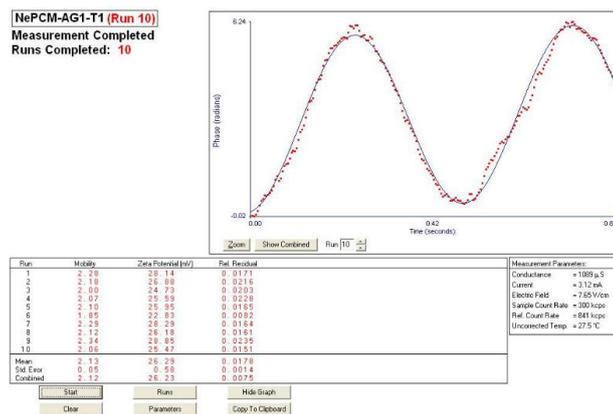
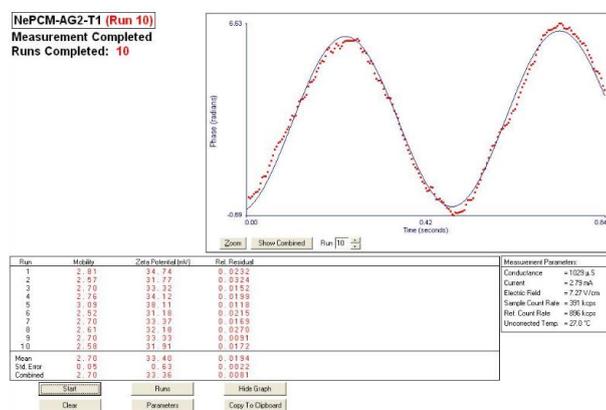Figure 7. Zeta Potential NePCM-AG1, screenshot.

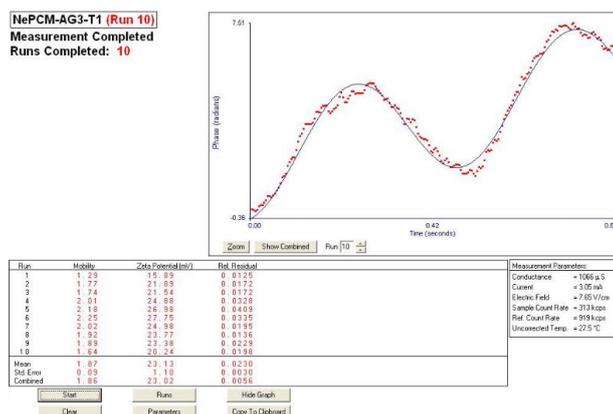Figure 8. Zeta Potential NePCM-AG2, screenshot.

Figure 9. Zeta Potential NePCM-AG3, screenshot.

The zeta potential performed was calibrated to collect 10 readings and thus take the average, given in mV. Of the three NePCMs, the NePCM-AG3 indicated an average zeta potential of 23.13 mV, which, according to (CINCERO; CINCERO, 2013) expresses instability in the material, i.e., the nanoparticles are agglomerated. The NePCM has MWCNT NP, only.

The NePCM-AG1, consisting of 75% MWCNT and 25% GO, showed, according to the Zeta Potential value, stability, 26.29 mV. Stability is also observed in NePCM-AG2, formed by 50% MWCNT and 50% GO, whose average Zeta Potential value was 33.40 mV. This non-agglomeration is a result of the effect of the graphene oxide nanoplates, since these acts, among others, as a physical separation agent for the MWCNTs.

In comparative terms, NePCM-AG2 is the most stable NePCM, since it presented the highest Zeta Potential value, corroborating the positive influence that a larger amount of GO has on the dispersion of MWCNTs.

It is important to inform that the Zeta Potential tests were performed as soon as the process of making the NePCMs was finished, otherwise, the samples were not at rest.

The thermal conductivity and dynamic viscosity tests For stability, 10 readings are collected and an average is taken, which is representative of the zeta potential

5. CONCLUSION

The present research confirms its investigative hypothesis: the nanoparticles contributed to an increase in the value of the thermal conductivity of PCM. NePCMs show a better thermal response to the heat transfer process, from the perspective of thermal conductivity.

Although it increased the value of thermal conductivity, this increase, overall, was small, 1.5%. This value is an average of the conductivities measured for all temperature ranges, compared to the PCM. NePCM-AG3 stands out because, in 4 of the five temperatures evaluated, it indicated a higher thermal conductivity value than the PCM. The explanation for this lies in the fact that this NePCM has only MWCNT with NP.

In terms of stability, NePCM-AG2 is the most stable nano-enhanced PCM, and therefore plausible for real application in refrigeration systems. NePCM-AG1 also pointed to stability.

The dynamic viscosity and density are higher in all NePCMs in parallel to the PCM. NePCM-AG1 is the most viscous and dense among all NePCMs.

Finally, when weighing the evaluated properties, density, thermal conductivity, dynamic viscosity, and stability NePCM-AG2 is the most suitable for use in latent energy thermal storage systems at low temperatures in the range of 5°C to -5°C.

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