



HAL
open science

Shear flow behavior and dynamic viscosity of few-layer graphene nanofluids based on propylene glycol-water mixture

Samah Hamze, D. Cabaleiro, T. Mare, B. Vigolo, Patrice Estellé

► **To cite this version:**

Samah Hamze, D. Cabaleiro, T. Mare, B. Vigolo, Patrice Estellé. Shear flow behavior and dynamic viscosity of few-layer graphene nanofluids based on propylene glycol-water mixture. *Journal of Molecular Liquids*, 2020, 316, pp.113875. 10.1016/j.molliq.2020.113875 . hal-02932036

HAL Id: hal-02932036

<https://hal.science/hal-02932036>

Submitted on 22 Aug 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

1 Shear flow behavior and dynamic viscosity of few-layer graphene nanofluids 2 based on propylene glycol-water mixture

3 Samah Hamze¹, David Cabaleiro^{1,2}, Thierry Maré¹, Brigitte Vigolo³ and Patrice Estellé^{1,*}

4 ¹ Université de Rennes, LGCGM, F-35000 Rennes, France

5 ² Dpto. Física Aplicada, Facultade de Ciencias, E-36310, Universidade de Vigo, Vigo, Spain

6 ³ Université de Lorraine, CNRS, Institut Jean Lamour UMR7198, F-54000 Nancy, France

7

8 * Correspondence: patrice.estelle@univ-rennes1.fr; Tel.: +33-0223234200 (P.E.)

9

10 **Abstract:** We report the shear flow behavior of few layer graphene (FLG) based nanofluids
11 produced with a commercial mixture of water and propylene glycol and three nonionic
12 surfactants, Triton X-100, Pluronic® P123, and Gum Arabic respectively. The flow properties of
13 these nanofluids were experimentally investigated between 283.15-323.15 K and for FLG
14 content from 0.05 to 0.5 wt.%. The nanofluids were subjected to different experiments, at rest at
15 fixed temperature, under steady shear flow at fixed temperature and under temperature ramp at
16 fixed shear rate in order to evaluate their stability and behavior under shear and temperature
17 influence. These results were compared and correlated to visual aspect of the samples at the end
18 of measurements. This experimental study evidences that the temperature, the shearing and the
19 shearing duration have an important influence on the stability under shear of nanofluids in
20 function of concentration and surfactant used. Finally, for all stable nanofluids under shear, the
21 dynamic viscosity evolution of nanofluids with temperature is correlated to Vogel-Fulcher-
22 Tammann model.

23 **Keywords:** Few-layer graphene nanofluids; propylene-glycol/water; shear flow stability; shear
24 flow behavior; dynamic viscosity

25 1. Introduction

26 The progressive depletion of fossil fuels and world energy demand necessitate the development
27 of new technologies based on alternative energy sources [1,2]. Nanofluids (nanoparticles
28 dispersed in a conventional fluid) have become a research topic of immense interest worldwide.
29 They have potential applications in many important fields such as in cooling technologies or
30 advanced heat transfer, energy harvesting, medical, micro-electromechanical systems,

31 microfluidics, microelectronics, numerous thermal management systems and transportation [3–
32 10]. Most studies have mainly focused on the determination of thermal properties of nanofluids,
33 especially thermal conductivity, their modeling and their use in simulations, due to the potential
34 benefits compared to suspensions of microparticles as well as conventional fluids [3,11–20].
35 Likewise, dynamic viscosity also becomes an important property when it comes to practical
36 applications related to heat transfer and fluid flow. For instance, the pumping power, pressure
37 drop and convective heat transfer in flow systems are directly dependent to the viscosity of the
38 fluids. Consequently, the interest in investigation and analysis of nanofluid viscosity is recently
39 growing than those regarding thermal conductivity which was the topic of extensive studies for a
40 longer time [3]. Among the different types of nanoparticles used in literature, carbon-based
41 nanomaterials, especially graphene, can be excellent thermal conductivity enhancers for
42 nanofluid design, due to their excellent intrinsic thermal property compared to that of metal
43 oxide or metallic nanoparticles [21–23].

44 Available literature shows that nanofluids can exhibit either a Newtonian or a non-Newtonian
45 behavior, depending on nanoparticle shape, size or concentration [3,21,24]. Such an evaluation,
46 as well as in what extend the viscosity of the base fluid is modified with the presence of
47 graphene nanosheets, is of great interest for possible applications. With this aim, Moghaddam *et*
48 *al.* [25] investigated graphene nanosheets with size of about 15-50 nm thick dispersed in
49 glycerol. The prepared nanofluids were in the concentration range of 0.25-2.0 wt.%, and their
50 viscosity was measured at temperatures between 293.15 and 323.15 K. A non-Newtonian
51 behavior was reported by these authors and a strong enhancement in viscosity of glycerol by
52 401.49 % with the 2 wt.% loading of graphene nanosheets at shear rate 6.32 s^{-1} and at
53 temperature equal to 293.15 K was also observed. On the other hand, Sarsam *et al.* [26] prepared
54 0.1 wt.% of graphene nanoplatelets (GNP)/water nanofluids without any surfactant assistance
55 (samples labeled as “pristine” in that article) or stabilized using different surfactants like sodium
56 dodecyl benzene sulfonate (SDBS), sodium dodecyl sulfate (SDS), cetyl trimethylammonium
57 bromide (CTAB) and gum arabic (GA). Authors investigated the shear rate dependence of
58 dynamic viscosity in the range from 20 to 200 s^{-1} and at temperatures from 298.15-328.15 K.
59 Without any surfactant assistance, a slight shear thinning behavior was observed for nanofluid in
60 the region of low shear rates for all studied temperatures expect for 308.15 K. A more
61 remarkable pseudoplastic behavior was reported for the dispersions stabilized with GA (at a GA-

62 GNP ratio of 0.5:1) in the studied temperature range. Conversely, suspensions containing the
63 ionic surfactants (SDBS, SDS and CTAB) at a surfactant-nanoparticle ratios of 1:1 behaved in a
64 Newtonian manner. Additionally, the (1:1) SDBS-GNP sample showed the highest stability and
65 nearly the lowest viscosity (7.4 % higher than distilled water). And based on the average values
66 of viscosity, the water based nanofluids could be sequenced as (0.5:1) GA-GNPs >> pristine
67 GNP > (1:1) SDBS-GNP > (1:1) SDS-GNP > (1:1) CTAB-GNP. The dispersion of GNPs, with
68 thickness of about 5-10 nm and 15 μm of large dimension, in a mixture of deionized
69 water:ethylene glycol (70:30 volume ratio) using 0.75 vol.% of sodium deoxycholate (SDC) as
70 surfactant was studied by Selvam *et al.* [27]. The investigation was done for nanofluids in the
71 GNP concentration range of 0.1-0.5 vol.%. The obtained results showed that the viscosity ratios
72 (μ_{nf}/μ_{bf}) of nanofluids increased from 1.06 to 1.16 and 1.13 to 1.39 at 0.1 and 0.5 vol.%,
73 respectively. In another work, Wang *et al.* [28] investigated single layer graphene (SLG)/water
74 nanofluids that contain a special dispersant (not specified in the article). They found that the
75 viscosity decreased with increasing temperature from 278.15 to 298.15 K increases with
76 increasing concentration from 0.2 to 1 wt.% with a viscosity increment ratio between SLG
77 nanofluids and water ranging from 1.24 to 2.35 and a non-Newtonian shear thinning behavior
78 was reported. Vallejo *et al.* [29] studied functionalized GNP (fGNP) nanofluids based on water
79 and propylene glycol:water mixture at 30:70 and 50:50 wt.%. Rheological investigation was
80 performed at shear rates from 10 to 1000 s^{-1} with at different weight concentrations between 0.25
81 and 1 wt.% and in the temperature range 283.15-353.15 K. The authors obtained a non-
82 Newtonian behavior at low shear rates (up to 100) and a Newtonian behavior at higher shear
83 rates. Additionally, they found that in the case of base fluid with higher viscosity, the nanofluid
84 viscosity decrease with temperature was higher and in the case of the base fluid with lower
85 viscosity, the nanofluid viscosity increase with weight content of fGNP was higher.

86 On another hand, Vallejo *et al.* [30] investigated the rheological properties of sulfonic acid-
87 fGNP nanofluids based on ethylene glycol:water mixture 50:50 vol%. Different weight
88 concentrations of fGNPs in the range 0.25-2 % were prepared and studied in the shear rate range
89 1-1000 s^{-1} between 283.15 and 353.15 K. With increasing temperature within the tested range,
90 the measurements showed a viscosity decrease by around 82 and 80 % for the base fluid and
91 nanofluids, respectively. An increase in viscosity values was found with the increase of graphene
92 loading. For example, a viscosity enhancement of 16 % was obtained for the nanofluid with 0.5

93 wt.% of fGNPs with respect to the base fluid, independently on the temperature. In addition, the
94 studied nanofluids exhibited a shear thinning behavior at low shear rates with higher
95 pseudoplasticity for higher graphene concentration; and a Newtonian behavior was found at
96 higher shear rates.

97 In another study, functionalized fGNPs were dispersed in propylene glycol:water mixture at
98 (30:70) wt% by Vallejo *et al.* [31]. The authors prepared nanofluids with weight content between
99 0.25 and 1 % and their viscosity was tested in the temperature range 293.15-323.15 K by
100 imposing constant shear rates in the range of 1000-4000 s⁻¹. The viscosity was found
101 independent on shear rate (Newtonian behavior) and on testing time (100 s). In addition, the
102 temperature rise caused a decrease in viscosity between 31 and 57 %. On the other hand, with
103 increasing the graphene loading, the viscosity increase attained 44 and 214 % for the lowest and
104 highest fGNP concentration, respectively.

105 The rheological properties of graphene oxide (GO) and reduced graphene oxide (rGO)/water
106 nanofluids were studied by Cabaleiro *et al.* [21] at 293.15 and 303.15 K. The prepared
107 nanofluids were in the volume concentration range of 0.0005-0.1 %. The results showed a
108 Newtonian behavior for the prepared nanofluids with graphene content lower than 0.01 vol.%
109 and shear-thinning behavior was observed for higher graphene concentrations. Additionally,
110 maximum increases of 100-130 % and 70-80 % was obtained respectively for the non-
111 Newtonian GO and rGO based nanofluids. The largest increase was found for the highest
112 concentration at 303.15 K. The results regarding the relative viscosity showed an enhancement
113 by about 130 and 70% in the tested range of concentration for GO and rGO based nanofluids,
114 respectively, without any significant influence of temperature. On the other hand, the authors
115 showed that for the highest graphene content studied, rGO based nanofluids exhibited lower
116 apparent viscosities than for GO-based nanofluids, and weaker shear-thinning behaviors.

117 In this study, high quality few layer graphene (FLG) was dispersed in a commercial mixture of
118 propylene-glycol/water using three different nonionic surfactants, Pluronic® P-123, Triton X-
119 100 and Gum Arabic. The studied nanoparticle weight concentrations are: 0.05, 0.1, 0.25, and
120 0.5 %. The rheological behavior of all corresponding base fluids and nanofluids were
121 investigated at temperatures between 283.15 and 323.15 K and correlated to the visual aspect of
122 the nanofluids after shearing. The results are discussed according to the influence of

123 concentration and type of surfactant, concentration of FLG, temperature and shearing time. For
124 well-stable nanofluids under shear, the viscosity evolution with temperature and FLG
125 concentration is finally predicted by a comprehensive viscosity model. This study is the last step
126 of the thermophysical characterizations of these FLG-based nanofluids, as the stability at rest and
127 thermal conductivity [32] and the volumetric and surface tension properties [33] were recently
128 reported.

129

130 **2. Materials and methods**

131 As reported in our recent works [32,33], the nanofluids presently investigated are produced with
132 high quality few-layer graphene (3-5 layers, mean lateral size 5 μ m, average thickness 1.5 nm)
133 that was synthesized from ultrasound exfoliation of expanded graphene in water assisted by
134 tannic acid. The full morphological and structural characterization of this FLG was previously
135 performed in [32]. Graphene-based nanofluids were obtained from the dispersion of the FLG,
136 previously washed, frozen and dried after the exfoliation process, in a commercial heat transfer
137 fluid, namely Tyfocor® LS, that is a mixture of water and propylene glycol 60:40 wt.% using
138 nonionic surfactants. Hence, Triton X-100 and Pluronic® P123 provided by Sigma Aldrich
139 (Germany) and Gum Arabic by Acros Organics (France) were used as received. As also
140 explained previously [32,33], a starting suspension with 0.5 wt.% of FLG was added to the base
141 fluid, Tyfocor + surfactant (1 wt.%) and sonicated with a probe sonicator (Bioblock Scientific
142 Vibra cell 75042, 125 W with a pulse mode 2 s ON / 1 s OFF) for several cycles of 15 min to
143 avoid sample overheating. Samples with lower concentration were obtained from the dilution of
144 the starting suspension with Tyfocor alone using the same sonication procedure. The
145 surfactant:FLG ratio remain constant and equal to 2 for each FLG content that varies between 0.5
146 and 0.05 wt.%. The procedure was similarly followed for the three used surfactants. More details
147 can be found in [32]. In the following, Pluronic® P-123, Triton X-100 and Gum Arabic will be
148 referred to as P123, TrX and GA, respectively and Tyfocor is used in the text and the figures
149 instead of Tyfocor® LS, for sake of clarity.

150 **2.2 Rheological characterizations**

151 Dynamic viscosity studies were performed on a Malvern Kinexus Pro rotational rheometer
152 (Malvern Instruments Ltd., United Kingdom) equipped with a cone-plate geometry appropriate
153 to investigate low-viscosity colloidal suspensions. The measuring geometry has a diameter of 60
154 mm and a cone angle of 1° , while the gap between the cone and the plate is 0.03 mm. Stress-
155 controlled measurements were done at temperatures between 283.15 and 323.15 K with an
156 interval of 10 K. Temperature was controlled with a precision of ± 0.01 K by means of a Peltier
157 temperature control device placed below the lower surface. Special thermal clovers were used to
158 ensure constant temperature throughout the sample gap during experiments. A sample volume of
159 1 cm^3 , considered optimal for the analysis with this geometry, was placed on the lower plate and
160 a stabilization time of 5 min was allowed before experiments. Before starting the rheological
161 measurements and in order to evaluate the temperature effect on nanofluid state at rest, every
162 nanofluid was tested under controlled temperature at each single studied temperature for 10
163 minutes (+5 min stabilization time) and without shearing the sample.

164 Afterwards, two rheological analyses were performed. First, shear-viscosity flow curves were
165 collected in state regimen at shear stresses in logarithmic scale corresponding to shear rates
166 between 10 and 1000 s^{-1} . Finally, with the aim of analyzing the combined effect of both
167 temperature and shearing time on nanofluid state, samples were also subject to a temperature
168 ramp (in which temperature was continuously increased in the range from 283.15 to 323.15 K by
169 steps of 10 K) while shear rate was hold to 500 s^{-1} . This shear rate was selected based on shear
170 flow curves and corresponded to the region where Newtonian plateau was reached for all
171 samples.

172 In an original way, pictures of the samples were taken at the end of the measurements to evaluate
173 the stability of the nanofluids and to correlate the shear flow behavior with the visual aspect of
174 the nanofluids.

175 Additional details about the experimental device can be found in Halelfadl *et al.* [34].
176 Experiments for each fluid and nanofluid and studied conditions were performed at least in
177 duplicate and obtained flow curves did not show any significant difference. To validate the
178 experimental shear flow protocol described above, dynamic viscosity measurements were done
179 between 283.15 and 313.15 K for distilled water and between 273.15 and 373.15 K for Tyfocor
180 thermal fluid. As expected, the results showed a Newtonian behavior for these two fluids. To

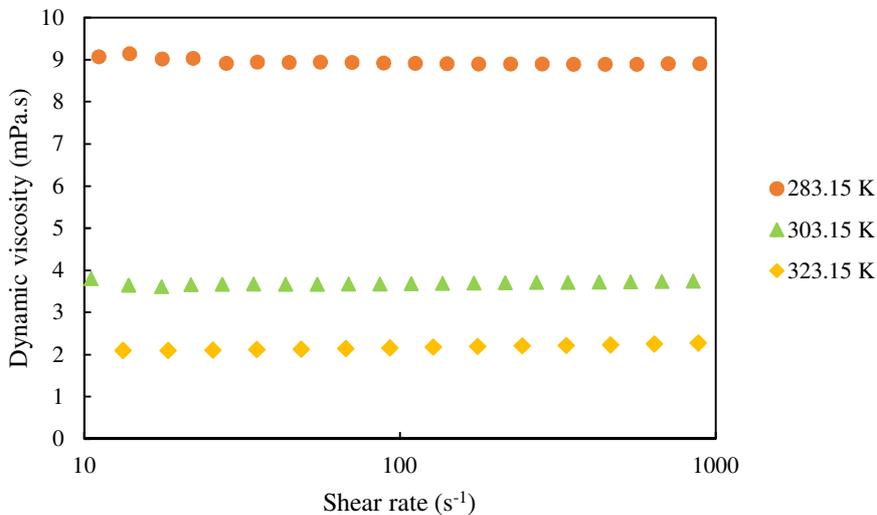
181 confirm the accuracy of the measure instrument, our experimental results were compared with
182 those reported in the literature. The absolute average deviation obtained with water was about
183 3.5% [35] and that of Tyfocor was less than 5 % [36] in the tested temperature range.

184

185 3. Results and discussion

186 3.1. Effect of surfactant on viscosity of propylene-glycol/water mixture

187 To evaluate the effect of surfactant (type and concentration) on the dynamic viscosity of
188 Tyfocor, this transport property was investigated in the temperature range 283.15-323.15 K for
189 surfactant-Tyfocor mixtures prepared at surfactant concentrations of 0.1, 0.2, 0.5 and 1.0 wt.%
190 with either Triton X-100, Pluronic® P-123 or Gum Arabic. At the investigated conditions, all
191 studied surfactant-Tyfocor mixtures (which were also used as base fluids) exhibited a Newtonian
192 behavior. As an example, Figure 1 shows the obtained flow curves for the mixture of Tyfocor
193 and 0.2 wt.% of Triton X-100 at 283.15, 303.15 and 323.15 K.

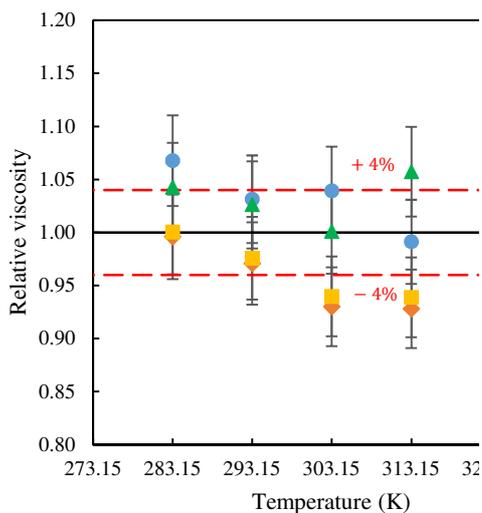


194

195 **Figure 1.** Flow curves for the base fluid Tyfocor and 0.2 wt.% of Triton X-100 at 283.15, 303.15
196 and 323.15 K.

197 Relative viscosity of the base fluids was determined in the tested temperature range as presented
198 in Figure 2. The results show that the addition of Pluronic® P-123 (all concentrations), Triton X-
199 100 (0.1, 0.2 and 0.5 wt.%) and Gum Arabic (0.1 and 0.2 wt.%) has no significant effect on the

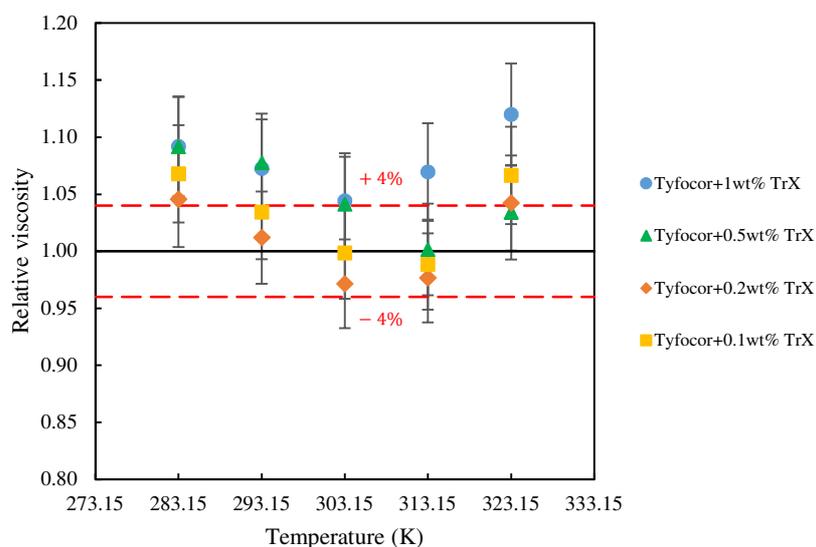
200 viscosity of the starting fluid (Tyfocor) within the experimental uncertainty. The highest
 201 concentration of Triton X-100 (1 wt.%) increased the viscosity of Tyfocor by 7.9 % on average
 202 in the tested temperature range. With Gum Arabic, the dynamic viscosity was increased by 12.3
 203 and 29.2 % after the addition of 0.5 and 1% of weight concentrations, respectively, without any
 204 dependence on the temperature.



205

(a)

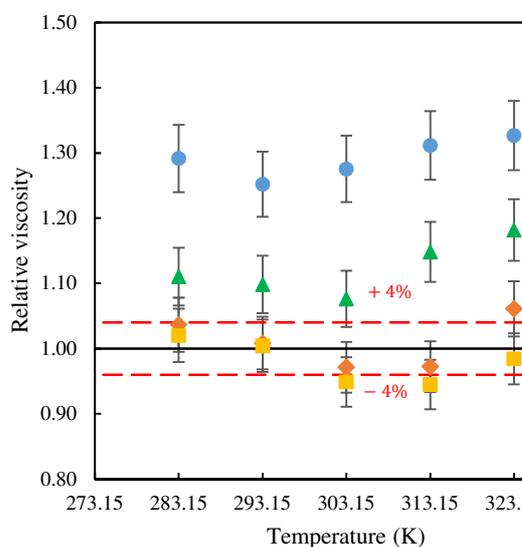
206



207

208

(b)



209

210

(c)

211

212 **Figure 2.** Relative viscosity of the studied base fluids prepared with Tyfocor with Pluronic® P-
 213 123 (a), Triton X-100 (b), and Gum Arabic (c) as a function of temperature. Solid line represents
 214 no viscosity enhancement for Tyfocor with surfactant compared to Tyfocor alone and dotted
 215 lines at +/-4% represents the uncertainty in dynamic viscosity measurement.

216

217 3.2 Effect of temperature and concentration on nanofluids behavior

218 3.2.1 Nanofluids at rest

219 All the nanofluids produced with the three different surfactants were tested between 283.15 and
 220 323.15 K, without and under shearing in order to discriminate between the temperature and the
 221 shearing effects. The observed aspects of each nanofluids after each measurement are gathered in
 222 Table 1. An example of each nanofluid state described in Table 1 is shown in Figure 3. Table 1
 223 evidences that the dispersion state of the prepared FLG nanofluids can strongly vary after the
 224 different experiments depending on the experimental protocol (no shear and shear), the type of

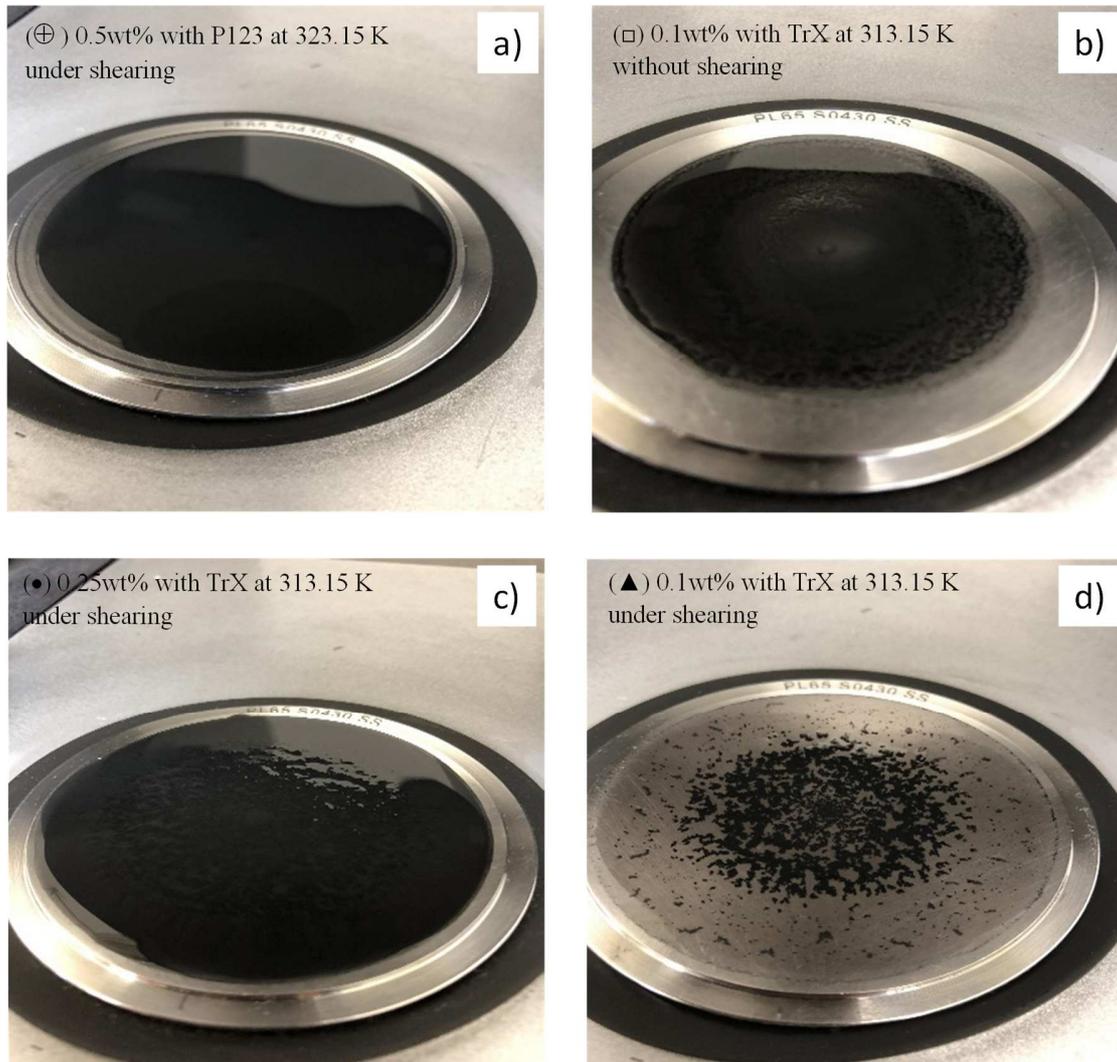
225 surfactant used, the temperature and the shearing time. Four states or aspects were mainly
 226 observed after the rheological measurements. The FLG-based nanofluids showing a dark
 227 homogeneous aspect without visible aggregates or with only few small aggregates, thus,
 228 appearing mainly as a well dispersed phase are named (\oplus) for ‘stable nanofluids’ (Fig. 3a).
 229 When black FLG aggregates are visible, the aspect is noted aggregation (\square) (Fig. 3b) and if these
 230 aggregates form a well-separated phase from the solvent, phase separation (\blacktriangle) is recorded (Fig.
 231 3d). In some cases, a homogeneous aspect is observed but in the form of a viscous gel (\bullet) (Fig.
 232 3c). Concisely, the FLG-based nanofluid samples produced with Pluronic® P-123 and Gum
 233 Arabic were rather stable at rest, while the dispersion state of the nanofluids prepared with Triton
 234 X-100 seemed much more sensitive to temperature. An aggregation phenomenon and a clear
 235 phase separation were indeed noticed when temperature increased especially for the highest FLG
 236 concentration.

237 **Table 1.** Observed states of the prepared nanofluid series at the end of the rheological
 238 measurements. Each visible aspect are noticed as (\oplus) for the stable nanofluids without or with
 239 visually observed small aggregates, (\square) for visible aggregates, (\bullet) for a gel-like aspect, (\blacktriangle) for a
 240 noticeable phase separation between FLG and the base fluid, (-) no measurement was done, (\diamond)
 241 no available photo. An example of each state mentioned in this table is shown in Fig. 3.

		T fixed, shear rate fixed at 0 s ⁻¹					T fixed, shear rate ↑					T ↑, shear rate fixed at 500 s ⁻¹				
T(K) φ _m		283.15	293.15	303.15	313.5	323.15	283.15	293.15	303.15	313.15	323.15	283.15	293.15	303.15	313.15	323.15
P123	0.05%	⊕	⊕	⊕	⊕	⊕	⊕	-	-	-	⊕	◇	◇	◇	◇	⊕
	0.1%	⊕	⊕	⊕	⊕	⊕	⊕	-	-	-	⊕	◇	◇	◇	◇	⊕
	0.25%	⊕	⊕	⊕	⊕	⊕	⊕	-	-	-	⊕	◇	◇	◇	◇	⊕
	0.5%	⊕	⊕	⊕	⊕	⊕	⊕	-	-	-	⊕	◇	◇	◇	⊕	●
TrX	0.05%	□	□	□	□	▲	□	□	▲	▲	▲	◇	◇	◇	◇	▲
	0.1%	⊕	⊕	⊕	□	□	⊕	⊕	⊕	▲	-	◇	◇	◇	▲	-
	0.25%	⊕	⊕	⊕	⊕	▲	⊕	⊕	⊕	●	▲	◇	◇	⊕	●	-
	0.5%	⊕	⊕	⊕	⊕	●	⊕	●	●	-	-	◇	◇	●	-	-
GA	0.05%	⊕	⊕	⊕	⊕	⊕	⊕	-	-	-	⊕	◇	◇	◇	◇	□

0.1%	⊕	⊕	⊕	⊕	⊕	⊕	-	-	⊕	⊕	◇	◇	◇	◇	□	
0.25%	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	□	◇	◇	⊕	□	-
0.5%	⊕	⊕	⊕	⊕	□	⊕	⊕	⊕	□	-	◇	◇	●	-	-	

242



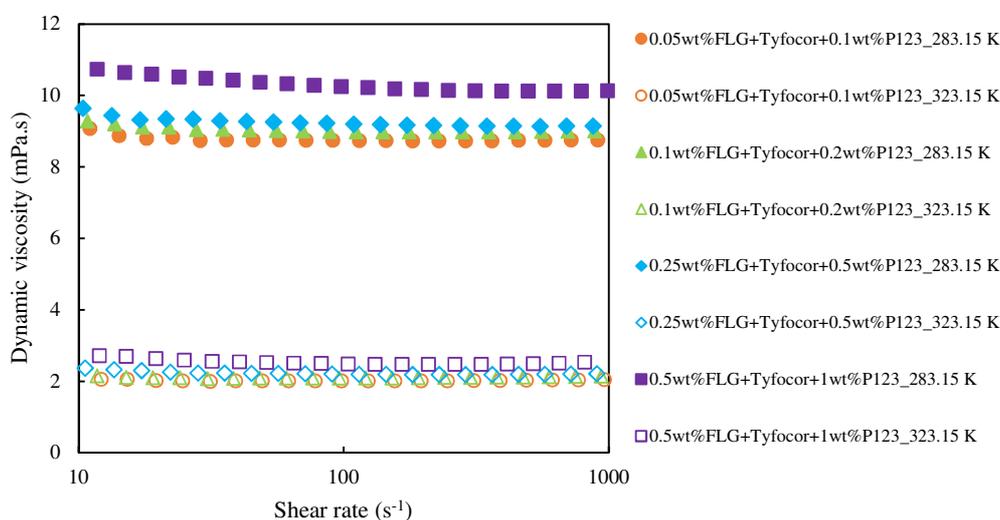
243

244 **Figure 3.** Representative examples of the different nanofluid states observed after performing
 245 the measurements: a) stable nanofluids without or with visually observed small aggregates (⊕),
 246 b) visible aggregates unseparated to the base fluid (□), c) gel-like aspect (●), and d) visible phase
 247 separation between the FLG aggregates and the solvent (▲).

248

249 **3.2.2 Nanofluid under shear**

250 The shear flow behavior of the prepared FLG-based nanofluids is discussed in the following
251 considering the type of surfactant used and the FLG concentration. With Pluronic® P-123, the
252 FLG-based nanofluids were mainly Newtonian in the investigated temperature range and they
253 exhibited a slight shear-thinning behavior at low shear rates. Such a shear-thinning trend is more
254 pronounced at 0.5 wt.% in FLG as the dynamic viscosity decreases up to 200 s⁻¹ before to reach a
255 Newtonian plateau. In addition, as noticed in Table 1, they stayed stable during all shear flow
256 measurements. From this rheological study, the dynamic viscosity was found to increase with the
257 FLG content in the nanofluids and to decrease with temperature.

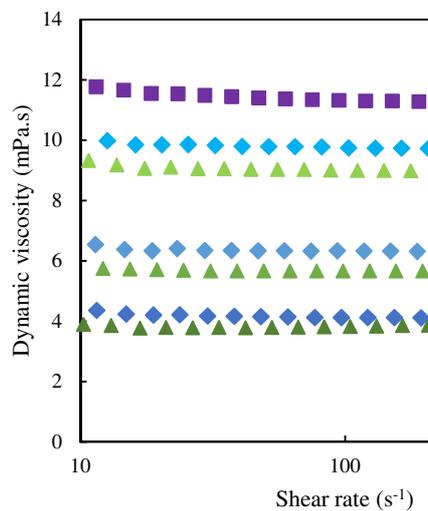


258
259 **Figure 4.** Dynamic viscosity of nanofluids with Pluronic® P-123 at 283.15 and 323.15 K as a
260 function of shear rate.

261
262 FLG-based nanofluids prepared with Triton X-100 were observed to lose their stability at high
263 temperature at rest (Table 1). Viscosity measurements with varying the shear rate between 10
264 and 1000 s⁻¹ showed the shear flow behavior of the samples at the selected temperatures. The
265 results of stable (dispersed state) nanofluids under shearing are presented in Figure 5(a), those
266 showing a gel-like appearance at end of the measurement (Table 1) are shown in Figure 5(b).
267 The stable FLG-based nanofluids behave as Newtonian fluids in the tested shear rate range with

268 a slight decrease in viscosity at very low shear rates indicating a weak shear-thinning. For the
269 other FLG-based nanofluids after a slight reduction at very low shear rates, it is observed that the
270 dynamic viscosity mainly increases with increasing shear rate indicating a shear-thickening
271 behavior. This behavior under shearing can be related to the observed gelation phenomenon and
272 the presence of a disordered structure of aggregates. This behavior seems to be sensitive to high
273 temperature and concentration. Actually, it produces for the FLG nanofluids having a relatively
274 high amount of surfactant and FLG (see also Table 1) *i.e.* 0.25 wt.% of FLG (and 0.5 wt.% of
275 Triton X-100) at 323.15 K or for the suspensions containing 0.5 wt.% of FLG (and 1 wt.% of
276 Triton X-100) at 293.15 and 303.15 K.

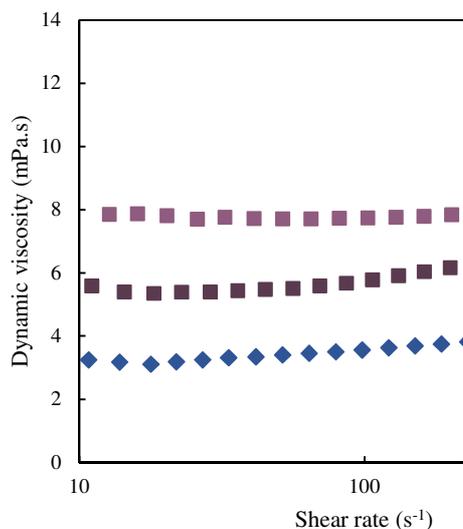
277



278

279

(a)



280

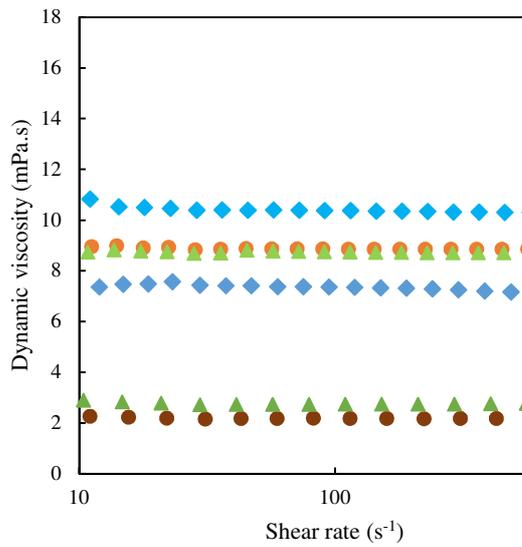
281

(b)

282

283 **Figure 5.** Dynamic viscosity of FLG-based nanofluids prepared with Triton X-100 between
 284 283.15 and 313.15 K as a function of shear rate; FLG based nanofluids showing a (a) stable or
 285 dispersed state and a (b) gel-like aspect.

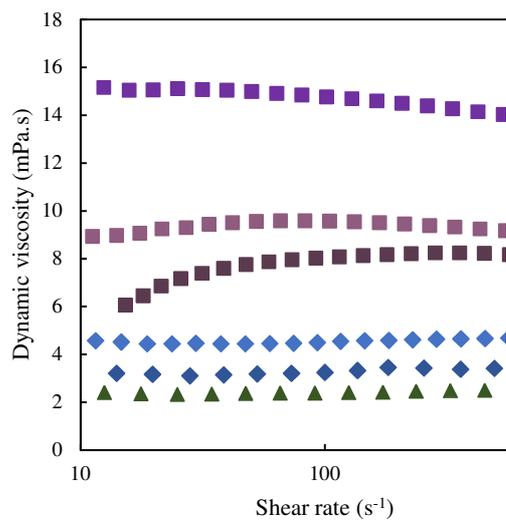
286 In the case of nanofluids prepared with Gum Arabic, they were stable with the presence of some
 287 aggregates for high FLG concentrations at high temperatures without shearing. After shearing
 288 measurements at selected temperatures, no significant change of their aspect was observed.
 289 These measurements showed different behaviors for these nanofluids, like quite Newtonian (Fig.
 290 6a and 6b), or shear-thinning and shear-thickening at low shear rates up to 200 s⁻¹ (Fig. 6b)
 291 before to reach a Newtonian plateau. For example, a slight shear-thinning behavior was obtained
 292 for 0.1 wt.% of Gum Arabic at 323.15 K, 0.25 wt.% of Gum Arabic at 303.15 K and 313.15 K
 293 and also for 0.5 wt.% of Gum Arabic at 283.15 K, respectively. A significant shear-thickening
 294 behavior was noticed for the highest concentration of FLG 0.5 wt.% (containing 1 wt.% of Gum
 295 Arabic) at 293.15 and 303.15 K at low shear rates (<200 s⁻¹). This trend could be attributed to the
 296 organization of the aggregates (see Table 1) under shear before to reach a stabilized state.



297

298

(a)



299

300

(b)

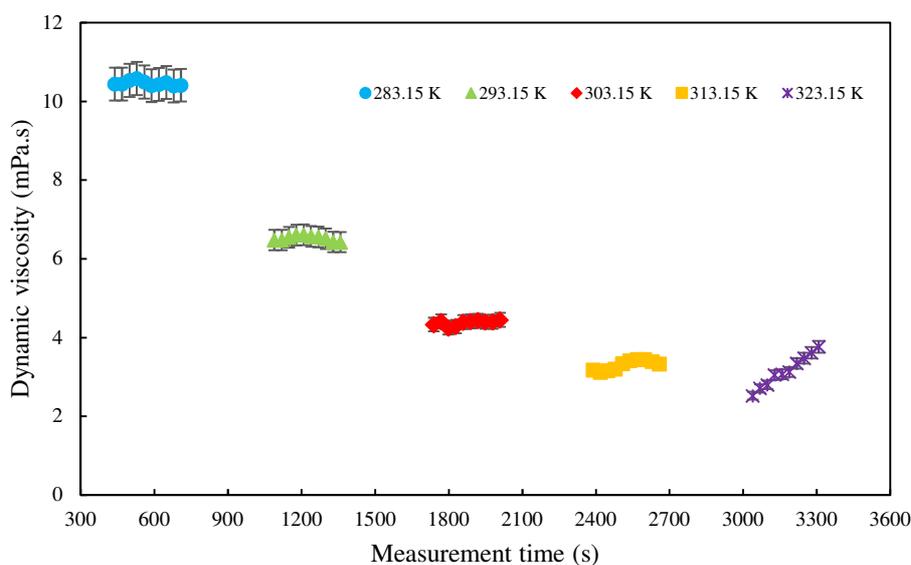
301

302 **Figure 6.** Dynamic viscosity of FLG based nanofluids prepared with Gum Arabic between
 303 283.15 and 323.15 K as a function of shear rate; (a) Newtonian and (b) non-Newtonian samples.

304 The fact that certain Newtonian fluids become non-Newtonian after the dispersion of
305 nanoparticles can be explained by the formation of possible nanoparticle-based fluid networks
306 whose structure gets modified under shear stress [30,37–39]. Accordingly, a shear thinning
307 behavior could indicate that nanoparticle networks could break once oriented in the flow
308 direction of the shear. This would lessen the interaction forces, decreasing the flow resistance
309 and, consequently, the apparent viscosity of the dispersion decreases [30,37–39]. Inversely, and
310 as mentioned earlier, shear-thickening could be attributed the presence of the disordered
311 structure of aggregates and their interaction.

312 3.2.3 Effect of shearing time and temperature

313 As explained before, a last measurement was performed with all stable nanofluids, selected from
314 the previous experiments, by applying a fixing shear rate of 500 s^{-1} (this shear rate being in the
315 Newtonian region) and increasing the temperature from 283.15 to 323.15 K with the same
316 sample.

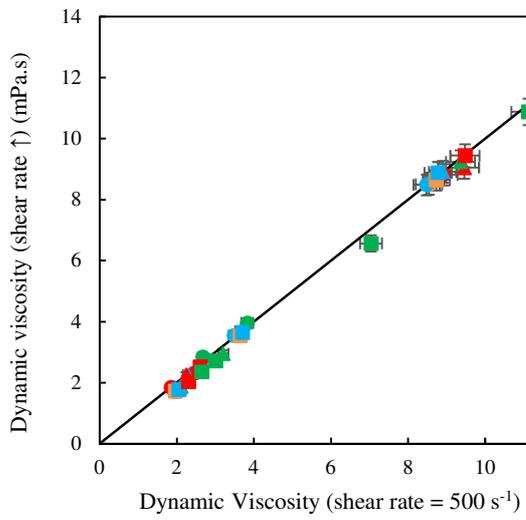


317
318 **Figure 7.** Dynamic viscosity of the nanofluid prepared with 0.5 wt.% of FLG and 1wt%
319 Pluronic® P-123 between 283.15 and 323.15 K as a function of measurement time.
320 Concerning the nanofluids prepared with Pluronic® P-123, the dynamic viscosity was stable
321 with time at all the temperatures between 283.15 and 323.15 K. However, with the highest

322 concentration of 0.5 wt.% of FLG, Figure 7 shows that the viscosity started to increase at 323.15
323 K after 3040 s from the beginning of the measurement e.g. after a total shearing time equal to
324 1200 s due to delay between each temperature change)and the sample looked like a gel at the end
325 of measurement. Another measurement performed from 283.15 to 313.15 K did not show any
326 significant change in the state of the nanofluid, which may indicate that such increase in
327 viscosity at 323.15 K may be related to the instability of the sample and change in structure.
328 Similar phenomenon was observed with the other two series, an increasing in the dynamic
329 viscosity with time related to the loss of nanofluid stability after a certain shearing time and from
330 certain temperature. Taking as an example the nanofluids prepared with Triton X-100, an
331 increasing in viscosity is observed at measurement time equal to 2390 s, 1960 s, and 499.6 s
332 (total shearing time equal to 900, 720 and 90 s) and that produces at the temperature 313.15,
333 303.15 and 283.15 K for the FLG concentrations of 0.1, 0.25 and 0.5 wt.%, respectively. With
334 Gum Arabic nanofluids, the rise in viscosity was detected at measurement times equal to 3210,
335 3190, 1220, and 656 s (that corresponds to a total shearing times equal to 1440, 1380, 450 and
336 240s respectively) which corresponds to the temperatures of 323.15, 323.15, 293.15 and 283.15
337 K for the FLG concentrations of 0.05, 0.1, 0.25 and 0.5 wt.%, respectively. From Table 1, the
338 difference between the nanofluid states observed with the three different kinds of measurements
339 evidences that the temperature, the concentration, the shearing and the duration of shearing have
340 an important role in the stability of nanofluids under shear. Based on the analysis compiled in
341 Table 1, the nanofluid samples produced with Pluronic® P-123 seem to be the most resistant
342 against shear and temperature. Nanofluids with Gum Arabic are relatively stable while
343 nanofluids containing Triton X-100 have the lowest stability. It should be finally noted that the
344 viscosities of the base fluids (mixtures of Tyfocor and surfactant) are not sensitive to this kind of
345 test and all the values were stable with time and for all the temperatures from 283.15 to 323.15
346 K.

347 **3.3 Nanofluid viscosity**

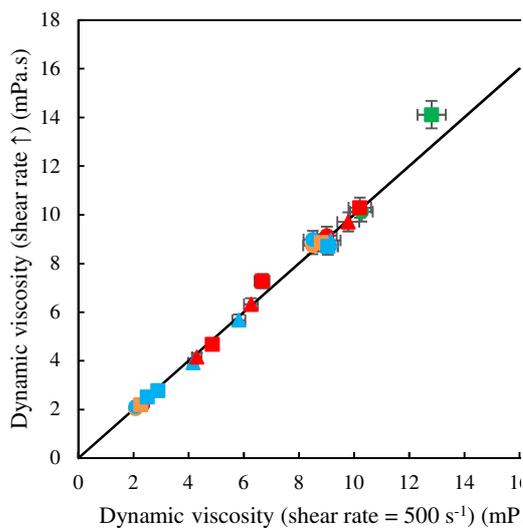
348 Now to compare the results of the two different measurements for stable nanofluids, by fixing
349 the temperature with increasing the shear rate from 10 to 1000 s⁻¹ and by fixing the shear rate at
350 500 s⁻¹ with increasing the temperature, the obtained viscosity values are represented in Fig. 8.



351

352

(a)



353

354

(b)

355

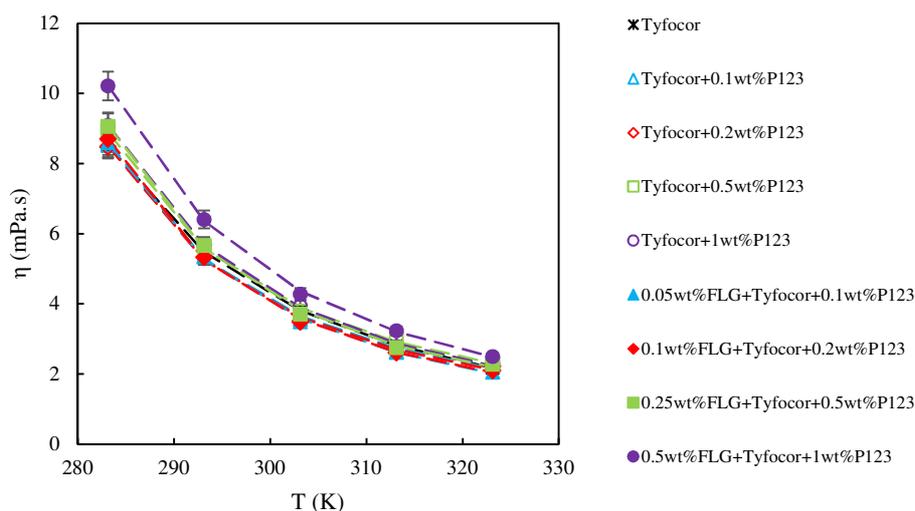
356 **Figure 8.** Comparison between the dynamic viscosity with varying shear rate and fixing it at 500
 357 s^{-1} at different temperatures for the base fluids (a) and the corresponding FLG nanofluids (b).

358

The solid line represents the bisector.

359 In figure 8, the viscosity results obtained from flow curve experiments (y-axis) correspond to the
 360 average value of data collected at shear rates higher than 200 s^{-1} (common Newtonian region for
 361 all stable nanofluids). Regarding the temperature ramps at a constant shear rate of 500 s^{-1} (x-
 362 axis), viscosity values are the average of all data that were constant during the measurement
 363 (before the rise in viscosity observed at certain temperatures as explained before). Fig. 8 shows
 364 clearly that these two different tests are compatible since they lead to values belonging quite well
 365 to same bisector (taking into account the experimental uncertainty). That is why in the following
 366 section, the considered viscosity values are the average of the results obtained with the two tests.

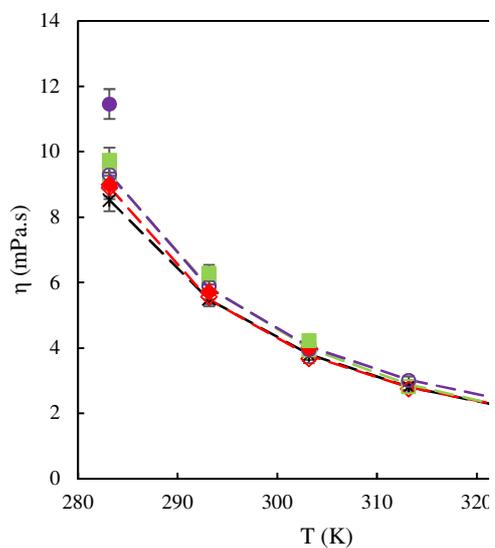
367 The effect of temperature on the viscosity of both base fluids and nanofluids is shown in Fig. 9.
 368 It is known that increasing temperature leads to decrease the viscosity of a fluid. This universal
 369 behavior in liquids is attributed to the lessening of molecular cohesive forces with increasing
 370 temperature, which reduces the shear stress and then the viscosity [40]. For all the studied base
 371 fluids and nanofluids, as expected, dynamic viscosity decreases with the increase of temperature
 372 in the range 283.15-323.15 K. The decreasing rate with Tyfocor alone and all base fluids is
 373 around 74 % from 283.15 to 323.15 K. For the nanofluids, the dynamic viscosity decreases with
 374 a similar trend as the corresponding base fluids, except for the highest concentration of FLG (0.5
 375 wt%) with Gum Arabic where it decreases from 293.15 to 303.15 K by 9 %, while this rate is 30
 376 % for the corresponding base fluid.



377

378

(a)

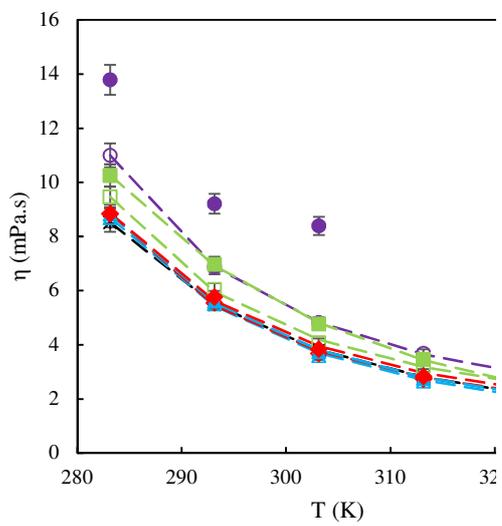


379

380

(b)

381



382

383

(c)

384

385 **Figure 9.** Dynamic viscosity of the FLG based nanofluids and the corresponding base fluids with
 386 Pluronic® P-123 (a), Triton X-100 (b) and Gum Arabic (c) as a function of temperature. The
 387 dashed lines represent the fitted values from Eq. 1.

388 One of the most used models describing the temperature dependence of viscosity is the Vogel-
 389 Fulcher-Tammann (VFT) equation [30,41–43]. This model has been previously used for
 390 graphene nanofluids [29,30,44].

$$391 \quad \eta = \eta_0 \times e^{\frac{A \times T_0}{T - T_0}} \quad (1)$$

392 where η_0 , A, and T_0 are the fitting parameters. These parameters are gathered in Table 2 for both
 393 base fluids and nanofluids (that have results at more than three temperatures). Low absolute
 394 average deviations (AADs) and standard deviations between the experimental and fitted values
 395 around 1.53 % and 0.0961 mPa.s in average were obtained, respectively.

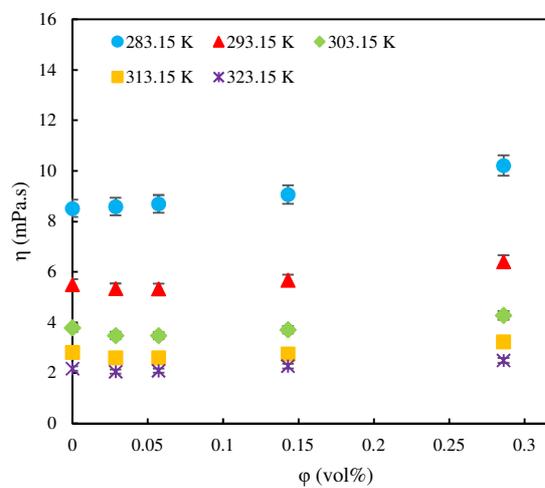
396 **Table 2.** Dynamic viscosity values (η) for base fluids and nanofluids and fitting parameters (η_0 ,
 397 A, and T_0), standard deviation (s) and AAD obtained from the VFT equation, Eq. (1).

Sft	$\varphi_{m,sft}$	$\varphi_{m,np}$	Temperature (K)					Fitting parameters and deviations				
	%	%	283.15	293.15	303.15	313.15	323.15	η_0 (mPa.s)	A	T_0 (K)	s (mPa.s)	AAD (%)
P123	0	0	8.52	5.48	3.81	2.81	2.17	0.0906	2.22	190.28	0.022	0.28
	0.1	0	8.538	5.272	3.646	2.725	2.153	0.2296	1.08	218.15	0.131	2.47
	0.2	0	8.500	5.242	3.614	2.690	2.116	0.2069	1.15	216.26	0.131	2.49
	0.5	0	8.889	5.582	3.891	2.917	2.306	0.2237	1.19	214.01	0.091	1.13
	1	0	9.094	5.669	3.895	2.870	2.228	0.1479	1.54	206.01	0.073	1.22
	0.1	0.05	8.603	5.269	3.576	2.612	2.015	0.1306	1.52	207.74	0.083	1.17
	0.2	0.1	8.710	5.257	3.567	2.624	2.044	0.1850	1.18	216.85	0.088	1.42
	0.5	0.25	9.082	5.581	3.815	2.811	2.188	0.1724	1.34	211.73	0.121	2.07
1	0.5	10.222	6.357	4.359	3.206	2.485	0.1611	1.56	205.76	0.068	0.80	
TrX	0.2	0	8.918	5.482	3.766	2.795	2.192	0.2053	1.18	215.65	0.106	1.84
	0.5	0	9.309	5.862	3.989	2.882	2.181	0.0597	2.72	183.97	0.087	1.57
	1	0	9.318	5.822	4.044	3.024	2.385	0.2271	1.20	214.10	0.092	1.29
GA	0.1	0	8.708	5.426	3.700	2.696	2.067	0.0971	1.93	198.09	0.118	1.99
	0.2	0	8.844	5.455	3.765	2.808	2.213	0.2265	1.11	217.32	0.123	2.22
	0.5	0	9.468	5.961	4.197	3.187	2.553	0.3259	0.96	220.33	0.107	1.28
	1	0	10.997	6.891	4.830	3.653	2.916	0.3552	0.99	219.72	0.032	0.42
	0.1	0.05	8.844	5.542	3.810	2.802	2.168	0.1254	1.71	202.06	0.085	1.49
	0.2	0.1	8.871	5.630	3.948	2.969	2.351	0.2210	1.24	211.95	0.195	3.40
0.5	0.25	10.971	6.926	4.813	3.436	2.512	0.0005	58.11	41.30	0.0707	0.58	

398
 399 The decrease in viscosity with increasing temperature has also been found previously with
 400 graphene-based nanofluids with water [21,45–51] and glycoled water mixtures in different
 401 proportions [23,31,44,52,53], respectively.

402 Addition of nanoparticles to a liquid was reported to induce an increase in fluid resistance to
403 flow because of the greater friction occurring within the mixture [44,54]. Thus, once a nanofluid
404 flows, to overcome this augmentation in internal friction resistance a higher energy consumption
405 is required (in comparison to the base fluid without nanoparticles) [35,54]. Hence, the addition of
406 nanoparticles in a liquid increases its viscosity. The viscosity enhancement of the studied stable
407 FLG based nanofluids under shear as function of FLG concentration and temperature is shown in
408 Fig. 10.

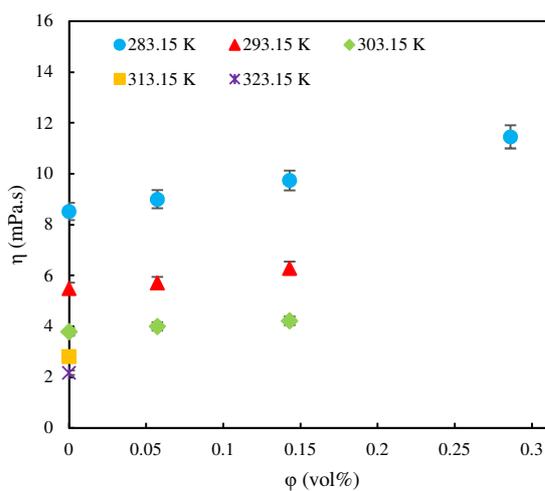
409



410

411

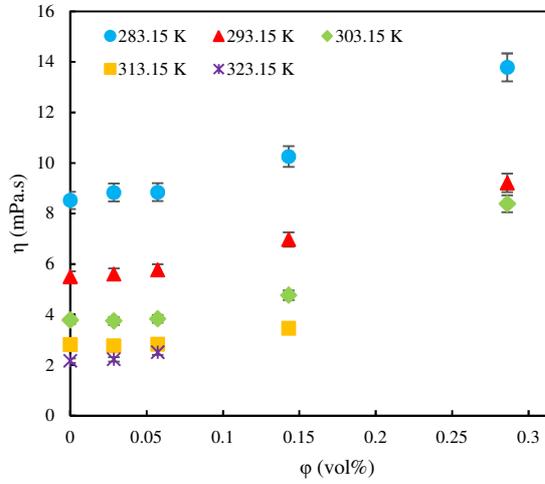
(a)



412

413

(b)



414

415

(c)

416

417 **Figure 10.** Dynamic viscosity of the FLG-based nanofluids with Pluronic® P-123 (a), Triton X-
 418 100 (b) and Gum Arabic (c) as a function of FLG volume concentration.

419 It worth noting that the volume concentration φ , used in Fig.10 is calculated from the φ_m using
 420 the following equation [32]:

$$421 \quad \varphi = \frac{\varphi_m \times \frac{\rho_{bf}}{\rho_{np}}}{\left(1 - \varphi_m \times \left(1 - \frac{\rho_{bf}}{\rho_{np}}\right)\right)} \quad (2)$$

422 where ρ_{bf} and ρ_{np} are the experimental densities of base fluids at all temperatures and the one of
 423 the nanoparticles at ambient temperature, respectively, as reported in [33]. The increase rate in
 424 dynamic viscosity (with respect to Tyfocor fluid) is maximal for the highest FLG tested
 425 concentrations. Thus, it reaches 19.9, 34.5 and 121.6 % in the case of Pluronic® P-123, Triton
 426 X-100 and Gum Arabic at 283.15, 283.15 and 303.15 K, respectively for the nanofluids
 427 containing 0.5 wt.% of FLG. From an insight of Fig.10, it can be observed that the nanofluids
 428 with Pluronic® P-123 have lower viscosities than samples containing Triton X-100 and the
 429 highest viscosities were obtained for Gum Arabic series.

430 **4. Concluding remarks**

431 This study concerned the rheological characterization of FLG-based nanofluids produced with a
432 commercial heat transfer fluid based on a mixture of water and propylene glycol and different
433 non-ionic surfactants. In an original way, nanofluid samples were subjected to different
434 experiments, at rest at fixed temperature, under steady shear flow at fixed temperature and under
435 temperature ramp at fixed shear rate, which allowed to evaluate their stability and behavior under
436 shear and temperature influence. These results were compared and correlated to visual aspect of
437 the sample at the end of measurements. These experiments were performed in the temperature
438 range 283.15-323.15 K and varying the mass content in FLG from 0.05 to 0.5 %. The difference
439 between the nanofluids states observed with the different measurement methods showed that the
440 temperature, the shearing and the duration of shearing have an important role on the nanofluids
441 stability in function of their concentration and surfactant. This also allows the best nanofluid and
442 surfactant to be evaluated in terms of stability under flow. Finally, for the stable nanofluids under
443 shear, the dynamic viscosity evolution with temperature was correlated to Vogel-Fulcher-
444 Tammann (VFT) equation.

445 **Acknowledgements:**

446 The authors would like to thank Dr. D. Bégin for providing FLG samples, Dr. N. Berrada for her
447 help in the preparation of the FLG based nanofluids and Dr. A. Desforges for fruitful
448 discussions. D.C. is recipient of a postdoctoral fellowship from Xunta de Galicia (Spain). This
449 investigation is a contribution to the COST (European Cooperation in Science and Technology)
450 Action CA15119: Overcoming Barriers to Nanofluids Market Uptake (NanoUptake).

451 **References**

- 452 [1] M. Mehrali, S. Tahan Latibari, M.A. Rosen, A.R. Akhiani, M.S. Naghavi, E. Sadeghinezhad, H.S.C.
453 Metselaar, M. Mohammadi Nejad, M. Mehrali, From rice husk to high performance shape stabilized
454 phase change materials for thermal energy storage, *RSC Adv.* 6 (2016) 45595–45604.
455 <https://doi.org/10.1039/C6RA03721F>.
- 456 [2] S. Iranmanesh, H.C. Ong, B.C. Ang, E. Sadeghinezhad, A. Esmailzadeh, M. Mehrali, Thermal
457 performance enhancement of an evacuated tube solar collector using graphene nanoplatelets
458 nanofluid, *J. Clean. Prod.* 162 (2017) 121–129. <https://doi.org/10.1016/j.jclepro.2017.05.175>.
- 459 [3] S.M.S. Murshed, P. Estellé, A state of the art review on viscosity of nanofluids, *Renew. Sustain.*
460 *Energy Rev.* 76 (2017) 1134–1152. <https://doi.org/10.1016/j.rser.2017.03.113>.
- 461 [4] S.U.S. Choi, Z.G. Zhang, P. Keblinski, Nanofluids. In: Nalwa HS, editor. *Encyclopedia of*
462 *nanoscience and nanotechnology*. Los Angeles: American Scientific Publishers; 2004. p. 757–73.
- 463 [5] S.K. Das, ed., *Nanofluids: science and technology*, Wiley-Interscience, Hoboken, N.J, 2008.

- 464 [6] S.M.S. Murshed, K.C. Leong, C. Yang, Thermophysical and electrokinetic properties of nanofluids
465 – A critical review, *Appl. Therm. Eng.* 28 (2008) 2109–2125.
466 <https://doi.org/10.1016/j.applthermaleng.2008.01.005>.
- 467 [7] K.V. Wong, O. De Leon, Applications of nanofluids: Current and future, *Adv. Mech. Eng.* 2 (2010)
468 519659. <https://doi.org/10.1155/2010/519659>.
- 469 [8] R. Saidur, K.Y. Leong, H.A. Mohammed, A review on applications and challenges of nanofluids,
470 *Renew. Sustain. Energy Rev.* 15 (2011) 1646–1668. <https://doi.org/10.1016/j.rser.2010.11.035>.
- 471 [9] S.M.S. Murshed, C.A.N. de Castro, Nanofluids as Advanced Coolants, in: Inamuddin, A.
472 Mohammad (Eds.), *Green Solvents I*, Springer Netherlands, Dordrecht, 2012: pp. 397–415.
473 https://doi.org/10.1007/978-94-007-1712-1_14.
- 474 [10] S.M.S. Murshed, C.A.N. de Castro, eds., *Nanofluids: synthesis, properties, and applications*, Nova
475 Science Publishers, Inc, New York, 2014.
- 476 [11] W. Yu, D.M. France, J.L. Routbort, S.U.S. Choi, Review and comparison of nanofluid thermal
477 conductivity and heat transfer enhancements, *Heat Transf. Eng.* 29 (2008) 432–460.
478 <https://doi.org/10.1080/01457630701850851>.
- 479 [12] S. Thomas, C. Balakrishna Panicker Sobhan, A review of experimental investigations on thermal
480 phenomena in nanofluids, *Nanoscale Res. Lett.* 6 (2011) 377. [https://doi.org/10.1186/1556-276X-6-](https://doi.org/10.1186/1556-276X-6-377)
481 [377](https://doi.org/10.1186/1556-276X-6-377).
- 482 [13] S. Özerinç, S. Kakaç, A.G. Yazıcıoğlu, Enhanced thermal conductivity of nanofluids: a state-of-the-
483 art review, *Microfluid. Nanofluidics.* 8 (2010) 145–170. [https://doi.org/10.1007/s10404-009-0524-](https://doi.org/10.1007/s10404-009-0524-4)
484 [4](https://doi.org/10.1007/s10404-009-0524-4).
- 485 [14] O. Mahian, L. Kolsi, M. Amani, P. Estellé, G. Ahmadi, C. Kleinstreuer, J.S. Marshall, M. Siavashi,
486 R.A. Taylor, H. Niazmand, S. Wongwises, T. Hayat, A. Kolanjiyil, A. Kasaeian, I. Pop, Recent
487 advances in modeling and simulation of nanofluid flows-Part I: Fundamentals and theory, *Phys.*
488 *Rep.* 790 (2019) 1–48. <https://doi.org/10.1016/j.physrep.2018.11.004>.
- 489 [15] O. Mahian, L. Kolsi, M. Amani, P. Estellé, G. Ahmadi, C. Kleinstreuer, J.S. Marshall, R.A. Taylor,
490 E. Abu-Nada, S. Rashidi, H. Niazmand, S. Wongwises, T. Hayat, A. Kasaeian, I. Pop, Recent
491 advances in modeling and simulation of nanofluid flows—Part II: Applications, *Phys. Rep.* 791
492 (2019) 1–59. <https://doi.org/10.1016/j.physrep.2018.11.003>.
- 493 [16] S.M.S. Murshed, K.C. Leong, C. Yang, Thermophysical properties of nanofluids. In: Sattler KD,
494 editor. *Handbook of nanophysics: nanoparticles and quantum dots*. Boca Raton: Taylor & Francis;
495 2010.
- 496 [17] C. Kleinstreuer, Y. Feng, Experimental and theoretical studies of nanofluid thermal conductivity
497 enhancement: a review, *Nanoscale Res. Lett.* 6 (2011) 229. [https://doi.org/10.1186/1556-276X-6-](https://doi.org/10.1186/1556-276X-6-229)
498 [229](https://doi.org/10.1186/1556-276X-6-229).
- 499 [18] S.M.S. Murshed, C.A. Nieto de Castro, Superior thermal features of carbon nanotubes-based
500 nanofluids – A review, *Renew. Sustain. Energy Rev.* 37 (2014) 155–167.
501 <https://doi.org/10.1016/j.rser.2014.05.017>.
- 502 [19] H.Ş. Aybar, M. Sharifpur, M.R. Azizian, M. Mehrabi, J.P. Meyer, A review of thermal conductivity
503 models for nanofluids, *Heat Transf. Eng.* 36 (2015) 1085–1110.
504 <https://doi.org/10.1080/01457632.2015.987586>.
- 505 [20] P. Estellé, S. Halelfadl, T. Maré, Thermal conductivity of CNT water based nanofluids:
506 Experimental trends and models overview, *J. Therm. Eng.* 1 (2015) 381.
507 <https://doi.org/10.18186/jte.92293>.
- 508 [21] D. Cabaleiro, P. Estellé, H. Navas, A. Desforges, B. Vigolo, Dynamic viscosity and surface tension
509 of stable graphene oxide and reduced graphene oxide aqueous nanofluids, *J. Nanofluids.* 7 (2018)
510 1081–1088. <https://doi.org/10.1166/jon.2018.1539>.
- 511 [22] A.A. Balandin, Thermal properties of graphene and nanostructured carbon materials, *Nat. Mater.* 10
512 (2011) 569–581. <https://doi.org/10.1038/nmat3064>.
- 513 [23] D. Cabaleiro, L. Colla, S. Barison, L. Lugo, L. Fedele, S. Bobbo, Heat transfer capability of
514 (Ethylene Glycol + Water)-based nanofluids containing graphene nanoplatelets: Design and

- 515 thermophysical profile, *Nanoscale Res. Lett.* 12 (2017) 53. [https://doi.org/10.1186/s11671-016-](https://doi.org/10.1186/s11671-016-1806-x)
516 1806-x.
- 517 [24] G. Żyła, Nanofluids containing low fraction of carbon black nanoparticles in ethylene glycol: An
518 experimental study on their rheological properties, *J. Mol. Liq.* 297 (2020) 111732.
519 <https://doi.org/10.1016/j.molliq.2019.111732>.
- 520 [25] M.B. Moghaddam, E.K. Goharshadi, M.H. Entezari, P. Nancarrow, Preparation, characterization,
521 and rheological properties of graphene–glycerol nanofluids, *Chem. Eng. J.* 231 (2013) 365–372.
522 <https://doi.org/10.1016/j.cej.2013.07.006>.
- 523 [26] W.S. Sarsam, A. Amiri, S.N. Kazi, A. Badarudin, Stability and thermophysical properties of non-
524 covalently functionalized graphene nanoplatelets nanofluids, *Energy Convers. Manag.* 116 (2016)
525 101–111. <https://doi.org/10.1016/j.enconman.2016.02.082>.
- 526 [27] C. Selvam, D. Mohan Lal, S. Harish, Enhanced heat transfer performance of an automobile radiator
527 with graphene based suspensions, *Appl. Therm. Eng.* 123 (2017) 50–60.
528 <https://doi.org/10.1016/j.applthermaleng.2017.05.076>.
- 529 [28] Y. Wang, H.A.I. Al-Saaidi, M. Kong, J.L. Alvarado, Thermophysical performance of graphene
530 based aqueous nanofluids, *Int. J. Heat Mass Transf.* 119 (2018) 408–417.
531 <https://doi.org/10.1016/j.ijheatmasstransfer.2017.11.019>.
- 532 [29] J.P. Vallejo, G. Żyła, J. Fernández-Seara, L. Lugo, Rheological behaviour of functionalized
533 graphene nanoplatelet nanofluids based on water and propylene glycol:water mixtures, *Int.*
534 *Commun. Heat Mass Transf.* 99 (2018) 43–53.
535 <https://doi.org/10.1016/j.icheatmasstransfer.2018.10.001>.
- 536 [30] J. Vallejo, G. Żyła, J. Fernández-Seara, L. Lugo, Influence of Six Carbon-Based Nanomaterials on
537 the Rheological Properties of Nanofluids, *Nanomaterials.* 9 (2019) 146.
538 <https://doi.org/10.3390/nano9020146>.
- 539 [31] J.P. Vallejo, J. Pérez-Tavernier, D. Cabaleiro, J. Fernández-Seara, L. Lugo, Potential heat transfer
540 enhancement of functionalized graphene nanoplatelet dispersions in a propylene glycol-water
541 mixture. Thermophysical profile, *J. Chem. Thermodyn.* 123 (2018) 174–184.
542 <https://doi.org/10.1016/j.jct.2018.04.007>.
- 543 [32] S. Hamze, N. Berrada, D. Cabaleiro, A. Desforges, J. Ghanbaja, J. Gleize, D. Bégin, F. Michaux, T.
544 Maré, B. Vigolo, P. Estellé, Few-layer graphene-based nanofluids with enhanced thermal
545 conductivity, *Nanomaterials.* 10 (2020) 1258. <https://doi.org/10.3390/nano10071258>.
- 546 [33] S. Hamze, D. Cabaleiro, D. Bégin, A. Desforges, T. Maré, B. Vigolo, L. Lugo, P. Estellé,
547 Volumetric properties and surface tension of few-layer graphene nanofluids based on a commercial
548 heat transfer fluid, *Energies.* 13 (2020) 3462. <https://doi.org/10.3390/en13133462>.
- 549 [34] S. Halelfadl, P. Estellé, B. Aladag, N. Doner, T. Maré, Viscosity of carbon nanotubes water-based
550 nanofluids: Influence of concentration and temperature, *Int. J. Therm. Sci.* 71 (2013) 111–117.
551 <https://doi.org/10.1016/j.ijthermalsci.2013.04.013>.
- 552 [35] J.V. Sengers, J.T.R. Watson, Improved international formulations for the viscosity and thermal
553 conductivity of water substance, *J. Phys. Chem. Ref. Data.* 15 (1986) 1291–1314.
554 <https://doi.org/10.1063/1.555763>.
- 555 [36] Tyfocor LS Technical Information available at <https://tyfo.de/en/produkt/tyfocor-ls/>, (n.d.).
- 556 [37] M. Pastoriza-Gallego, L. Lugo, J. Legido, M.M. Piñeiro, Rheological non-Newtonian behaviour of
557 ethylene glycol-based Fe₂O₃ nanofluids, *Nanoscale Res. Lett.* 6 (2011) 560.
558 <https://doi.org/10.1186/1556-276X-6-560>.
- 559 [38] S. Genc, B. Derin, Synthesis and rheology of ferrofluids: a review, *Curr. Opin. Chem. Eng.* 3 (2014)
560 118–124. <https://doi.org/10.1016/j.coche.2013.12.006>.
- 561 [39] C. Hermida-Merino, M. Pérez-Rodríguez, M.M. Piñeiro, M.J. Pastoriza-Gallego, Evidence of
562 viscoplastic behavior of exfoliated graphite nanofluids, *Soft Matter.* 12 (2016) 2264–2275.
563 <https://doi.org/10.1039/C5SM02932E>.
- 564 [40] J. F. Douglas, *Fluid mechanics*, 5th ed. Harlow, England ; New York : Pearson/Prentice Hall, 2006.

- 565 [41] G.S. Fulcher, Analysis of recent measurements of the viscosity of glasses, *J. Am. Ceram. Soc.* 8
566 (1925) 339–355. <https://doi.org/10.1111/j.1151-2916.1925.tb16731.x>.
- 567 [42] G. Tammann, W. Hesse, The dependence of viscosity upon the temperature of supercooled liquids.
568 *Z. Anorg. Allg. Chem.* 1926, 156, 245–257.
- 569 [43] H. Vogel, The law of the relation between the viscosity of liquids and the temperature. *Phys. Z*
570 1921, 22, 645–646.
- 571 [44] J.P. Vallejo, S. Gómez-Barreiro, D. Cabaleiro, C. Gracia-Fernández, J. Fernández-Seara, L. Lugo,
572 Flow behaviour of suspensions of functionalized graphene nanoplatelets in propylene glycol–water
573 mixtures, *Int. Commun. Heat Mass Transf.* 91 (2018) 150–157.
574 <https://doi.org/10.1016/j.icheatmasstransfer.2017.12.001>.
- 575 [45] P. Dhar, M.H.D. Ansari, S.S. Gupta, V.M. Siva, T. Pradeep, A. Pattamatta, S.K. Das, Percolation
576 network dynamicity and sheet dynamics governed viscous behavior of polydispersed graphene
577 nanosheet suspensions, *J. Nanoparticle Res.* 15 (2013) 2095. [https://doi.org/10.1007/s11051-013-](https://doi.org/10.1007/s11051-013-2095-2)
578 2095-2.
- 579 [46] M. Mehrali, E. Sadeghinezhad, S. Latibari, S. Kazi, M. Mehrali, M.N.B.M. Zubir, H.S. Metselaar,
580 Investigation of thermal conductivity and rheological properties of nanofluids containing graphene
581 nanoplatelets, *Nanoscale Res. Lett.* 9 (2014) 15. <https://doi.org/10.1186/1556-276X-9-15>.
- 582 [47] E. Sadeghinezhad, M. Mehrali, S. Tahan Latibari, M. Mehrali, S.N. Kazi, C.S. Oon, H.S.C.
583 Metselaar, Experimental investigation of convective heat transfer using graphene nanoplatelet based
584 nanofluids under turbulent flow conditions, *Ind. Eng. Chem. Res.* 53 (2014) 12455–12465.
585 <https://doi.org/10.1021/ie501947u>.
- 586 [48] M. Mehrali, E. Sadeghinezhad, M.A. Rosen, S. Tahan Latibari, M. Mehrali, H.S.C. Metselaar, S.N.
587 Kazi, Effect of specific surface area on convective heat transfer of graphene nanoplatelet aqueous
588 nanofluids, *Exp. Therm. Fluid Sci.* 68 (2015) 100–108.
589 <https://doi.org/10.1016/j.expthermflusci.2015.03.012>.
- 590 [49] M. Mehrali, E. Sadeghinezhad, M.A. Rosen, A.R. Akhiani, S. Tahan Latibari, M. Mehrali, H.S.C.
591 Metselaar, Heat transfer and entropy generation for laminar forced convection flow of graphene
592 nanoplatelets nanofluids in a horizontal tube, *Int. Commun. Heat Mass Transf.* 66 (2015) 23–31.
593 <https://doi.org/10.1016/j.icheatmasstransfer.2015.05.007>.
- 594 [50] M.R. Esfahani, E.M. Languri, M.R. Nunna, Effect of particle size and viscosity on thermal
595 conductivity enhancement of graphene oxide nanofluid, *Int. Commun. Heat Mass Transf.* 76 (2016)
596 308–315. <https://doi.org/10.1016/j.icheatmasstransfer.2016.06.006>.
- 597 [51] M. Hadadian, E.K. Goharshadi, A. Youssefi, Electrical conductivity, thermal conductivity, and
598 rheological properties of graphene oxide-based nanofluids, *J. Nanoparticle Res.* 16 (2014) 2788.
599 <https://doi.org/10.1007/s11051-014-2788-1>.
- 600 [52] A. Ijam, R. Saidur, P. Ganesan, A. Moradi Golsheikh, Stability, thermo-physical properties, and
601 electrical conductivity of graphene oxide-deionized water/ethylene glycol based nanofluid, *Int. J.*
602 *Heat Mass Transf.* 87 (2015) 92–103. <https://doi.org/10.1016/j.ijheatmasstransfer.2015.02.060>.
- 603 [53] M. Kole, T.K. Dey, Investigation of thermal conductivity, viscosity, and electrical conductivity of
604 graphene based nanofluids, *J. Appl. Phys.* 113 (2013) 084307. <https://doi.org/10.1063/1.4793581>.
- 605 [54] Materials Science & Technology Conference et al., Éd., Processing and properties of advanced
606 ceramics and composites V. 2013.
- 607