

Investigation of Thermophysical Properties of Io Nanofluids Containing Multi-Walled Carbon Nanotubes and Graphene

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ABSTRACT: Thermophysical properties of base ionic liquid ($C_{10}H_{19}F_6N_2P$) (IL) and Io NanoFluids (INF) containing different contents of (0.05, 0.1, and 0.5 wt%) MultiWalled Carbon NanoTubes (MWCNTs) and Graphene (Gr) were measured experimentally. INF exhibited augmentation in thermal conductivity, viscosity, and heat capacity with respect to the base fluid. Maximum thermal conductivity breakthrough was detected at 39%, 48% of MWCNT-IL, and 0.5wt% of Gr-IL, respectively. Eventually, the experimental viscosity and thermal conductivity data were fitted with the existing theoretical models. The findings highlighted that the viscosity of MWCNTs-IL and Gr-IL was in unison with the particle aggregation effect (Krieger-Dougherty model) and both INF effective thermal conductivity are prognosticated by the interfacial layer approach with sufficient accuracy.

KEYWORDS: Ionic liquids; Io Nanofluids; Rheological behavior; Thermal conductivity; Heat capacity; Theoretical model.

INTRODUCTION

Nowadays, technological energy optimization of resources has been evidently emphasized, and ionic liquids with exceptional characteristics have drawn significant attention in the realm of heat transfer fluid [1, 2]. Ionic liquids because of their unique essence, prompt scientists to manage novel heat transfer fluids by variation of the cation-anion structure to attain escalated physiochemical fingerprints [3]. These fluid classes are thoroughly environmental-friendly; recyclable and not combustible at ambient temperature; low vapor pressure,

high thermal stability and high heat capacity [4, 5]. All these features make it the appropriate heat transfer fluid applier at low pressure and even under vacuum contingencies [6]. Ionic liquids are safe and sustainable substitutes for numerous industries and chemical manufacturers. They have been flourishing due to their distinguishing traits over and above thermo-physical, phase-equilibrium, synthesis versatility, and devisable for a specific application.

Consequently, ionic liquids' heat transfer capabilities,

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heat storage capacity and dominant surface properties have caused these fluids brackets to be ultrapractical in a wide range of applications. As an exemplar, *Joseph et al.* [7] utilized iron oxide nanoparticles to develop electroactive INF with elevated dielectric constants. They declared that the charge-discharge process yield even after 100 cycles was superior to 94%. *Deba et al.* [8] dispersed ZnS nanoparticles in imidazolium ionic fluids to elaborate apt correlations among phase transition, viscosity, and ion diffusivity.

Ionic liquids have been contemplated as heat transfer modifiers for many years. As reported by the literature [9, 10], ionic liquids can be exploited as a superb candidate for thermal energy storage in open systems owing to their low vapor pressure, they will not be cooled by the evaporation process [11]. Thereupon, ionic liquids are the best fluid for the sake of employment in conventional solar power generation units and heat exchangers on account of their raised thermal conductivity and heat capacity [12,13]. In contrast to the typical heat transfer fluids, ionic liquids have a hulking heat transfer area. Miscellaneous research has affirmed that to some extent addition of carbon or metal-based nanoparticles into the ionic liquids can noticeably boost the thermal properties, which establish for them an immeasurable working domain in all cooling and heating operations [14]. It has been recited that the INF substantiates heat properties advancement of the base fluids by limited nanoparticle dispersion. The cutting-edge explorations in this area have been proclaimed by *Nieto de Castro et al.* [15], which thriving have delved into the temperature dependency of thermal conductivity of imidazolium-based ionic liquids relative to MWCNTs scattering extent in the base fluid, they rendered that dispersing MWCNTs improved the base fluid thermal conductivity. Their article delineated the linear interrelation of temperature efficacy on thermal conductivity as $K=a_1+a_2T$ and the equation constants (a_1 , a_2) are presented in their article for diverse nanoparticles and ionic fluids.

Moreover, dispersing various kinds of nanoparticles in ionic liquids has been defined as a term for INF which have been harnessed in distinct areas such as nanoscience, thermofluid, chemical, and mechanical engineering [16]. Carbon-based nanoparticles regarding their soaring electrical, mechanical, and thermal properties

are the best alternative to be applied as dispersant additives in base fluids[17, 18], also ionic nanofluids have been advised as smart lubricants [19]. CNT and Gr nanoparticles have extremely high thermal conductivity around 5000 to 6000 W/m.K which makes them a promising choice for nanofluid thermal modification [20]. Furthermore, in recent years, carbon-based nanoparticles have been manipulated as a nano additive to promote conventional fluids like water [21], ethylene glycol [22], and engine oil [23]. Stability plays a key role in nanofluids; dispersed nanoparticles must linger stable for a prolonged time, not having any sedimentation [24]. There are various confirmed methodologies to produce a stable nanofluid *via* adding surfactants, chemical treatments, and functionalization [25]. The main goal of this inquest is carving out a stable INF without using a surfactant for the sake of rheological behavior evaluation, thermal conductivity, and heat capacity measurements of INF bearing MWCNTs and Gr. Besides thermophysical properties measurements, their dependency on temperature and concentration using ionic liquid of 1-Hexyl-3-methylimidazolium hexafluorophosphate ($C_{10}H_{19}F_6N_2P$) were explored. The rheological behavior, thermal conductivity, and heat capacity were probed within the temperature ranges of 20-90 °C, 10-70 °C, and 25-345 °C, respectively. In addition, the experimental data were assimilated with the common theoretical models and plausible explanations were presented to argue the enhancement of thermophysical properties.

EXPERIMENTAL SECTION

Materials

MWCNTs and Gr nanoparticles were purchased from the Research Institute of Petroleum Industry (RIPI), Iran, and were functionalized with the acid treatment method [26]. Properties of MWCNTs and Gr are summarized in Table 1.

The INF [C6Mim][PF₆] was purchased from the Research Institute of Chemistry and Chemical Engineering of Iran (RICCE). The characteristics of the [C₆Mim][PF₆] are summarized in Table 2.

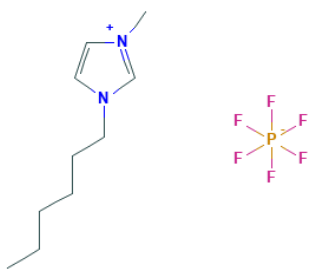
Equipment and methodology

The thermal conductivity of INF were surveyed using a KD2 Pro thermal properties analyzer (Labcell Ltd., UK) using a single needle sensor (1.3 mm diameter and 60 mm length). This sensor holds a heating element and a thermal

Table 1: Properties of MWCNTs and Gr.

properties	MWCNTs	Graphene
surface area(m ² /g)	>40	>814
Appearance	Cylindrical	Flat sheet
Diameter(nm)	90-120	60-80
purity	>95	>97
Density(g/cm ³)	2.1	2.267
Thermal conductivity(W/m.K)	6000	5300

Table 2: Properties of the [C6Mim][PF6] ionic liquid[27].

C10H19F6N2P	Molecular formula
[C6Mim][PF6]	Abbreviation
	Structure
-73.5 °C	Melting point
1.297 g/cm ³	Density at 293.15 K

resistor, which should be inserted vertically in the sample to assure minimal free convection, and it also performs relied on the hot-wire technique (error $\pm 5\%$). A thermal bath (Haake C25) was employed for constraining the specimen temperature. Prior to measurement set off, the KD2 Pro was scaled by standard samples, glycerol [23]. The specific heat capacity (C_p) of samples was quantified by a spanned differential scanning calorimeter (DSC-111, Setaram, France) with an accuracy of $\pm 2\%$. Successively, the rheological properties, density, and viscosity were also measured. The Brookfield digital viscometer (model: LV DV-II pro) with an accuracy of $\pm 1\%$ was also utilized to quantitate the effective viscosity. The Pycnometer or specific gravity bottle was employed to evaluate the density of INF (ASTM D153). In this regard, the Pycnometer was weighted in three cases empty, IL filled, and INF filled. All measurements were taken in the temperature range of 20-50°C and particle concentration of 0.05-0.5% wt. In addition, it is worth

mentioning that all measurements were performed at least three times to eliminate unpredicted errors; then, the average value has been reported.

INF preparation

Stability is one of the most crucial factors in nanofluid applications [28]. All the investigations aim at utilizing INF in industrial usages within nano-colloidal solutions that endure stability for a long time. In order to make a stable INF the MWCNTs and Gr nanoparticles were adjoined to IL 1-Hexyl-3-methylimidazolium hexafluorophosphate without any surfactant by using an ultrasonic cell disrupter system for 10 minutes using a 130 W, 20 kHz probe, and subsequently, the nanoparticles were dispersed in base fluid without any sedimentation.

The stability of fabricated INF was measured by taking dynamic digital pictures in a specified time period [19]. Fig. 1 illustrates the time dependency of formulated MWCNTs-IL and Gr-IL at the fabrication onset and then verified following four months. As it is crystal-clear, both specimens expose stability without any precipitation. For confirmation of solution stability, the extra methodology was employed *via* capturing microscopic images at successive times [29]. Microscopic images of INF were taken *via* the dispersion of INF droplet on a taintless glass, and then the scattering of particles was detected. As Fig. 2 depicted, nanoparticles were dispersed uniformly without a noticeable alteration in aggregation size at the end of four months. If the casted INF had been unstable, the aggregation's size should have been multiplied, then, due to gravity force, the suspended particles should have been precipitated down. By the way, the constant aggregation size proved that solution had agreeable stability to follow up the experiments. The stability of prepared INF was also explored by the dynamic light scattering (DLS) test in Fig. 3. This figure attests no perceptible variation in the particle aggregation size in both INF following one month. The DLS test has also brought to light that cluster size exposed constant value; consequently, it can demonstrate the super stability nature of the formulated INF. Principally, as long as nanoparticles were functionalized with carboxylic groups, the particles were able to develop links with base liquid molecules that facilitate stability without any size increment and settlement. Thereupon, the prepared INF were definitely stable for more than four months, and they have an auspicious prospect for industrial applications.

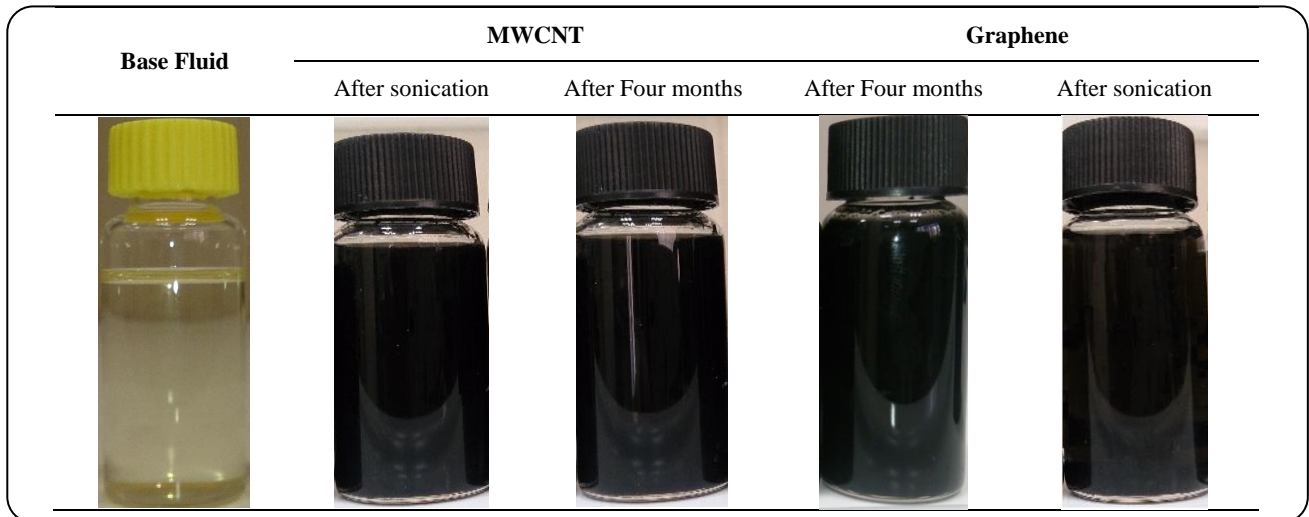


Fig. 1: Stability of prepared MWCNTs-IL and Gr-IL after sonication and after four months.

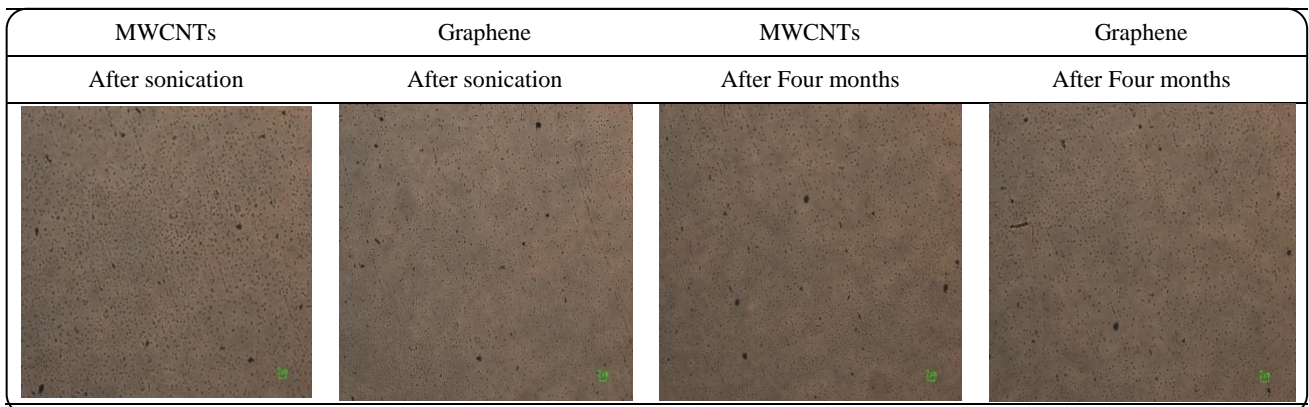


Fig. 2: Optical image of MWCNTs-IL and Gr-IL.

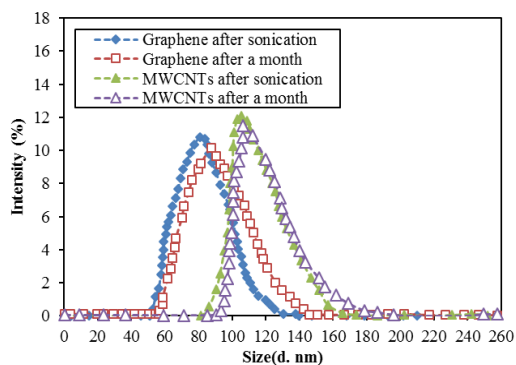


Fig. 3: DLS measurements on MWCNTs-IL and Graphene-IL after sonication and a month.

RESULTS AND DISCUSSION

Results of the effective density, viscosity, thermal conductivity, and specific heat capacity of MWCNTs-IL

and Gr-IL versus temperature and nanoparticle concentration will be argued in this section. Correspondingly, the effective viscosity and thermal conductivity of INF will be collated with frequent theoretical models afterward.

Density measurement

Fig. 4 illustrates the density variations that correspond to the particles concentration (0.05, 0.1, and 0.5 wt%) and temperature (20, 30, and 50 °C). The results spot that INF has a bit higher density than the base fluid in all particle concentrations for both MWCTs-IL and Gr-IL, however increasing trend of density is very insignificant in all measurements which signifies slight fluctuations even at higher nanoparticles concentration (0.5 wt%). The density has been changed by approximately 0.1% and 0.08% at particles concentration of 0.5 wt% and 20°C for MWCTs-IL

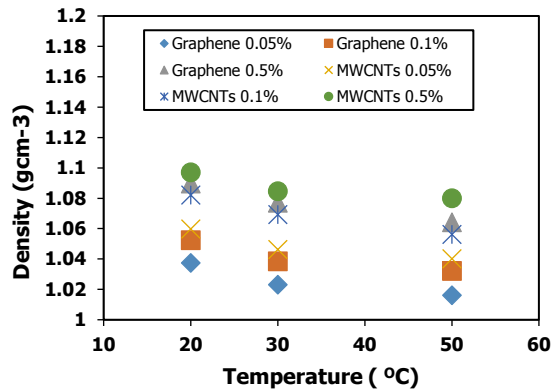


Fig. 4: Variation of density as a function of temperature at different particles concentration.

and Gr-IL, respectively. Whereas, Gr has lower bulk density rather than MWCNTs, the INF that is synthesized by Gr nanoparticles exhibits lower density. By dispersing nanoparticles in base fluids, particles are placed between the layers of the fluid without causing volume unit variation, but nanoparticles induce the mass increase regarding bulk density change of solid particles, and consequently, fluid density increment is detected. It is notable that temperature results in effective density diminishment, as temperature raises prompted the particles' Brownian motion augmentation, the INF volume escalated; consequently, the density has been boosted

Viscosity measurement

INF viscosity is one of the valuable parameters, which should be probed in experimental studies considering its role to affect the heat transfer properties and fluid pressure drop. Fluid viscosity relies on various parameters including base fluid viscosity, nanoparticles concentration, nanoparticles shape and size, the surface-to-volume ratio of nanoparticles, operating temperature, and nanoparticles aggregation extent [30, 31]. As viscosity plays a pivotal role in this investigation, the viscosity of INF was explored as a function of temperature and nanoparticle concentration. Fig. 5 depicts the base fluid and INF viscosity changing trend with respect to the temperature and nanoparticle concentration. Boosting temperature heightens viscosity abatement as a result of interlayer particles' infirm force and molecular adhesion factors, various investigations presented comparable results [32-34]. Furthermore, enhancing nanoparticle loading leads to INF

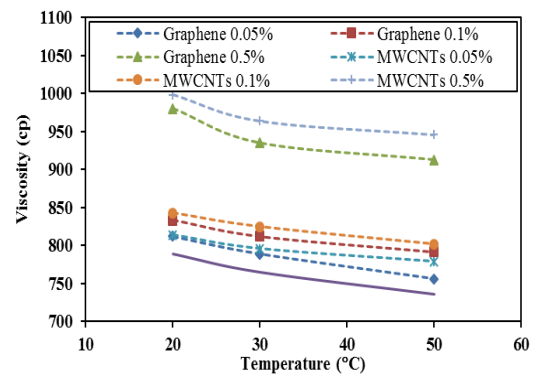


Fig. 5: Variation of viscosity as a function of temperature at different particles concentration.

viscosity improvement. Since the solid particles tend to accumulate by attractive forces, repulsive forces hinder the aggregation process. In any way, repulsive forces are the prevailing stimulus in lower nanoparticle loadings. The addition of nanoparticle contents expedited stronger attractive forces generation, in consequence, nanoparticles stick firmly together and form clusters, ordinarily, nanoparticle concentration increases lead to viscosity uptick. In spite of the fact that the viscosity rise is remarkable at higher nanoparticle concentration, low nanoparticle content reflects negligible amounts. For instance, the viscosity of MWCNTs- IL, and Gr- IL surged 26% and 24% relative to the base fluid at 20°C and 0.5 % wt, respectively. Temperature increment brings about the particles' Brownian motion soaring and weakening the intermolecular and the inter-particle's adhesion forces. At a concentration of 0.5 wt%, for MWCNTs-IL the viscosity declined from 998 cp to 941 cp and for Gr- IL abated from 980 cp to 913 cp at a temperature range of 20-50 °C. Fig. 5 also highlights the contrasts MWCNTs-IL and Gr-IL viscosity and reveals that MWCNTs-IL discloses higher viscosity in connection with Gr- IL. Moreover, MWCNT nanoparticles due to their cylindrical structure may tie to each other and consequently can raise the viscosity of MWCNTs- IL with regard to Gr- IL.

In the following, the experimental results of viscosity increment were assimilated with several common theoretical routines considering nanoparticle concentration.

Einstein's model [35] was deliberated as the foremost calculating viscosity model of INF at low fractions of spherical nanoparticles (<0.02).

$$\frac{\mu_{\text{Io Nanofluids}}}{\mu_{\text{ionic liquid}}} = (1 + 2.5\varnothing) \quad (1)$$

Likewise, Einstein's model was modified by Brinkman for high nanoparticle concentrations [36].

$$\frac{\mu_{\text{Io Nanofluids}}}{\mu_{\text{ionic liquid}}} = \frac{1}{(1 - \varnothing)^{2.5}} \quad (2)$$

Subsequently, Einstein's model was modified by Batchelor by considering the Brownian motion of nanoparticles [37].

$$\frac{\mu_{\text{Io Nanofluids}}}{\mu_{\text{ionic liquid}}} = 1 + 2.5\varnothing + 6.2\varnothing^2 \quad (3)$$

Where \varnothing is denoted as the nanoparticle volume fraction? Fig. 6 demonstrates the failed model in the prediction of experimental measurements which prognosticate lower effective viscosity relative to experimental results. This model just took into account the nanoparticle concentration as an effective parameter and the other effectual factors as an agglomeration of nanoparticles have been not contemplated. Furthermore, *Nielson* [38] made a huge effort to harness the power-law model for the high nanoparticle concentration and reflect the agglomeration packing fraction in his model.

$$\frac{\mu_{\text{Io Nanofluids}}}{\mu_{\text{ionic liquid}}} = (1 + 1.5\varnothing) e^{\frac{\varnothing}{1 - \varnothing_m}} \quad (4)$$

\varnothing_m denotes the maximum particle packing fraction and is assumed to be 0.605 in most of the investigations. As can be judged from Fig. 6, this model failed to estimate the experimental measurements. Likewise, *Krieger-Dougherty* [39] by involving the maximum packing fraction and variable packing fractions effect demanded to development of a nanofluid viscosity model.

$$\frac{\mu_{\text{Io Nanofluids}}}{\mu_{\text{ionic liquid}}} = \left[1 - \frac{\varnothing_a}{0.605} \left(\frac{a_a}{a} \right)^{1.2} \right]^{-1.5125} \quad (5)$$

\varnothing_a refers to the effective volume fraction of aggregates as presented in Eq (6), a_a and a are the average radii of the aggregates and primary nanoparticles; respectively, D denotes the fractal index whose typical value is 1.8 for nanofluids.

$$\varnothing_a = \varnothing \left(\frac{a_a}{a} \right)^{3-D} \quad (5)$$

As Fig. 6 illustrates, the experimental viscosity of both INF (MWCNTs and Gr) were fitted with the Krieger-Dougherty (K-D) model at the aggregation factor of $a_a/a=16-18$. As the Krieger-Dougherty (K-D) model predicted, the nanoparticles have a great tendency to aggregate, on account of this affinity the INF viscosity escalated, but other parameters like the ionic liquids interplays and nanoparticles surface area should be regarded as a hyper-efficient factor to precisely predict INF viscosity

Effective thermal conductivity

Thermal conductivity is recognized as one of the crucial factors in the heat transfer capabilities of fluids, in this research the thermal conductivity of IL and INF were measured against temperature (10-50°C) and particle concentration (0.05-0.5wt%). Fig. 7 illustrates the experimentally recorded thermal conductivity of IL and INF (MWCNTs and Gr) versus temperature and concentration. As Fig. 7 obviously depicts, nanoparticle concentration addition gives rise to the thermal conductivity in both INF over the measured temperature range. The results exhibit a convincing association between temperature and thermal conductivity enhancement. In the following an exemplar is presented to serve as a pattern to be imitated of thermal conductivity behavior, at 20°C and 0.5%wt, the thermal conductivity of MWCNTs-IL and Gr-IL improved about 40% and 34% with respect to the base fluid, and by further rising temperature to 50 °C, the thermal conductivity of both fluids reaches to 148% and 139% of enhancement, respectively.

The thermal conductivity correlating relationship (linearity and nonlinearity) corresponding to temperature and nanoparticles loading originated from base fluid nature and nanoparticle freshness [40]. Enhancement of thermal conductivity of INF can be spelled out using high thermal conductivity of MWCNTs and Gr in connection with the base fluid. Dispersing limited amounts of the MWCNTs and Gr in the base fluids preferentially interplay with non-polar domains related to the alkyl chains which are developed by micro-clusters and ultimately result in heat transfer characteristics of INF. In brief comparison, MWCNTs-IL has displayed higher thermal conductivity

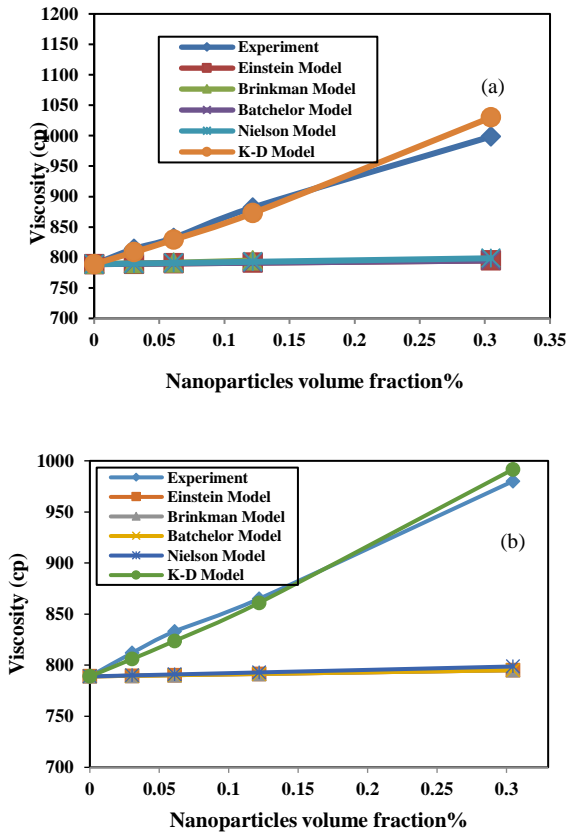


Fig. 6: Variation of experimental and theoretical (a) MWCNTs-IL and (b) Graphene-IL viscosity as a function of particles volume fraction.

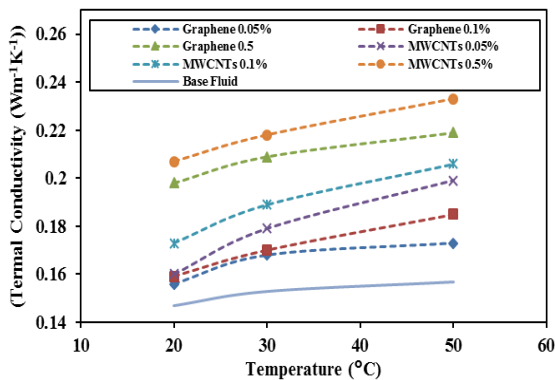


Fig. 7: Variation of thermal conductivity of INF with the temperature at different particle loading.

in all temperatures and nanoparticle concentrations. The main active mechanism on which the thermal conductivity increment of INF relied are the nanoparticles' Brownian

motion, the intrinsic heat transport nature of the nanoparticles, the liquid multilayer structure at the liquid/nanoparticle interface, and the nanoparticle cluster structure and its spatial shape [41, 42]. Accordingly, MWCNTs because of its cylindrical shape may act as a thermal bridge to transport heat efficiently between fluid layers and also heighten the Brownian motion compared to the Gr-IL.

For comprehending the accurate active mechanism of thermal conductivity uptick of INF, the measured thermal conductivity of MWCNTs and Gr were collated with theoretical models. In the first place, Maxwell [43] elaborated to predict the thermal conductivity of spherical nanoparticles nanofluid, Eq. (7).

$$\frac{\mu_{IoNanofluids}}{\mu_{IonicLiquid}} = \frac{K_n + K_{bl} - 2\phi(K_{bl} - K_n)}{K_n + 2K_{bl} + \phi(K_{bl} - K_n)} \quad (7)$$

k_n and K_{bl} refer to the thermal conductivity of nanoparticles and base fluid. ϕ is the nanoparticle volume fraction. Fig. 8 data confirm that this model was incapable to predict the experimental observations with adequate precision, as this model just takes into account the nanoparticles volume fraction and thermal conductivity of the base liquid and nanoparticles as the key factors. Later, Bruggeman [44] strived to present a new model which additionally considers the nanoparticles cluster formation, Eq. (8).

$$\mu_{IoNanofluids} = \frac{1}{4}((3\phi - 1)K_n + (2 - 3\phi)K_{bl}) + \quad (8)$$

$$\frac{K_{bl}}{4} \sqrt{\Delta}$$

$$\Delta = (3\phi - 1)^2 \left(\frac{K_n}{K_{bl}} \right)^2 + (2 - 3\phi)^2 + \quad (9)$$

$$2(2 + 9\phi - 9\phi^2) \left(\frac{K_n}{K_{bl}} \right)$$

The nanoparticles aggregation tendency was factored into the relations to predict the effective thermal conductivity[45], and the aggregation factor ($a_a/a=16-18$) was considered analogous to the viscosity prediction models, so the Maxwell model can be amended with the aggregation factor:

$$\frac{\mu_{IoNanofluids}}{\mu_{IonicLiquid}} = \frac{K_a + 2K_{bl} - 2\phi_a(K_{bl} - K_a)}{K_a + 2K_{bl} + \phi_a(K_{bl} - K_a)} \quad (10)$$

Where K_a is the aggregates thermal conductivity which is calculated by the below correlation (Eq.11):

$$\frac{K_a}{K_{b1}} = \frac{1}{4} \left[\left(3\phi_{in} - 1 \right) \frac{K_n}{K_{b1}} + 3(1 - \phi_{in}) - 1 + \left[\left(\left(3\phi_{in} - 1 \right) \frac{K_n}{K_{b1}} + 3(1 - \phi_{in}) \right)^2 + 8 \frac{K_n}{K_{b1}} \right]^{1/2} \right] \quad (11)$$

Where $\phi_{in} = \left(\frac{a}{a} \right)^{3-D}$ is the solid aggregate volume fraction. In comparison with the Maxwell model, the aggregation model estimated higher thermal conductivity (Fig. 8), but the aggregation model still was ineffective to predict the experimental thermal conductivity of both INF. Afterward, *Murshed et al.* [35] by adding the nanoparticles' interfacial layer effects in base fluid endeavored to proclaim the effective thermal conductivity of nanofluids.

$$K_{IoNanofluids} = \frac{(k_n - k_{lr})\phi k_{lr}[2\gamma_1^2 - \gamma^2 + 1] + (k_n + 2k_{lr})\gamma_1^2[\phi\gamma^2(k_{lr} - k_{b1}) + k_{b1}]}{\gamma_1^2(k_n + 2k_{lr}) - (k_n - k_{lr})\phi[\gamma_1^2 + \gamma^2 - 1]} \quad (12)$$

Where K_{lr} is the thermal conductivity of the interfacial layer which $K_{b1} < K_{lr} < K_n$; here $K_{lr} = 0.35$. γ and γ_1 are evaluated according to the equations 13-14 demonstrate.

$$\gamma = 1 + \frac{h}{a} \quad (11)$$

$$\gamma_1 = 1 + \frac{h}{2a} \quad (12)$$

Where h is the interfacial layer thickness of $h=2$, and $a=15$ nm. As Fig. 8 revealed, the interfacial layer model was successful to predict the effective thermal conductivity of both INF with passable error. The interfacial layer model predicted the experimental thermal conductivity satisfactorily with arbitrary interfacial layer thickness and thermal conductivity, but it should be noted that other effective factors like nanoparticles surface interactions with IL play a key role to outline the impeccable mechanism of thermal conductivity escalating trend which anticipated by addition of nanoparticles into IL.

Effective specific heat capacity

The heat capacity variation extent of fluids, which are rooted in nanoparticles in addition to the base fluid, takes

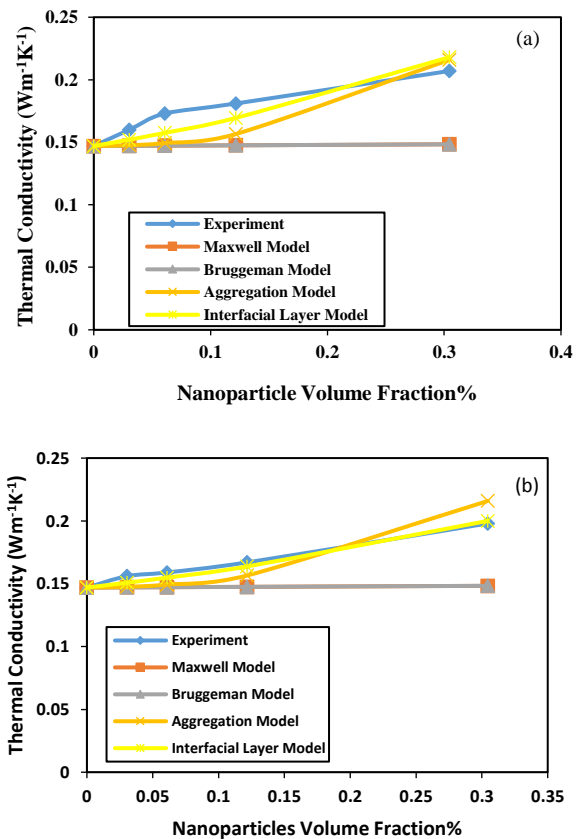


Fig. 8: Variation of experimental and theoretical (a) MWCNTs-IL and (b) Gr-IL thermal conductivity as a function of particles volume fraction.

huge amount of attention. So comprehensive effective specific heat capacity measurements were needed to conduct for better MWCNTs-IL and Gr-IL thermal properties recognition. The heat capacity of IL and INF (0.5 wt% MWCNTs and Gr) were measured over a wide range of 25-345°C temperatures with a span of 10°C. Fig. 9 illustrates the effective heat capacity versus temperature. As it is crystal clear, INF has a higher heat capacity compared to the base fluid, and also the heat capacity of both INF linearly varied by changing temperature. The average enhancement of the effective heat capacity of MWCNTs-IL and Gr-IL are approximately 19% and 12%, respectively. Although in most previous research incorporating nanoparticles diminished heat capacity commonly, a similar trend is observed in several investigations in which INF heat capacity soared relative to the nanoparticles concentration [15, 46, 47]. However, the theoretical models predict heat capacity reversely for INF

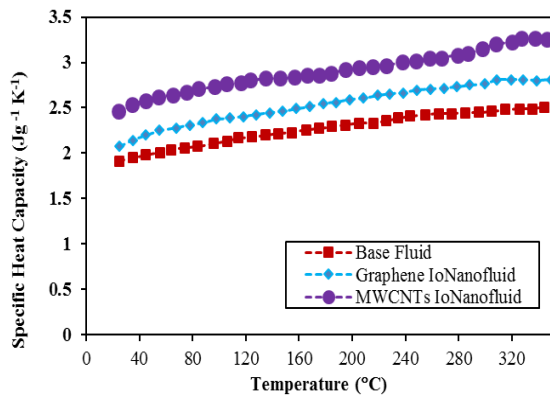


Fig. 9: Specific heat capacity IL, MWCNTs-IL, and Gr-IL as a function of temperature.

which signifies abatement with respect to the base fluid [48]. The complex interaction between a solid particle's surface area and IL may exhibit a meaningful role in enhancing INF heat capacity. Nanoparticles have a high surface area which provides excess accessible sites for heat adsorption and consequently leads to improved heat capacity due to the nanoparticles' involvement in the solutions. In spite of that, it should be noticed that specific heat capacity increment or decrement utterly depends on intrinsic properties of nanoparticles such as size, shape, surface area, and base fluid type. In this regard, a professional simulation or calculation should be executed to dig out the precise interpretation of the heat capacity changes mechanism which is expected by the addition of nanoparticles into the base fluid.

CONCLUSIONS

To sum up the current study reports on the MWCNTs and Gr particles when scattered uniformly in IL 1-Hexyl-3-methylimidazolium hexafluorophosphate ($C_{10}H_{19}F_6N_2P$) to produce thermally efficient and stable INF, the results offered that the formulated INF were thoroughly stable for over four months. Rheological properties including density and viscosity were explored conforming to the temperature and particles concentration. These research's main deductions entail the following details. The density and viscosity improvement in the low content of nanoparticles warrant little attention, but raising concentration is able to bring about viscosity escalation substantially. The effective viscosity was also correlated with several applicable theoretical models; accordingly;

the Krieger-Dougherty model by taking for the particle aggregation sway passably estimated the experimental viscosity. Moreover, the thermal conductivity performance for both Ionic nanofluids was probed experimentally. The results signify that thermal conductivity improved by 26–48% for MWCNTs-IL and 10-39% for Gr-IL at a particle mass fraction of 0.5%.wt. The experimentally recorded thermal conductivity was also matched with the common theoretical model. The result displayed that the thermal conductivity of both INF was precisely surveyed by the interfacial layer model. The INF heat capacity highlighted a higher value in comparison with the base fluid. The typical increment amount of the effective heat capacity of MWCNTs-IL and Gr-IL are 19% and 12%, respectively. Nanoparticles surface interplay effectively with IL-charged sections, these interactions play a groundbreaking role in thermo-physical augmentations. All these obtained results declare that the super-stable MWCNTs-IL and Gr-IL as promising nanofluids with improved thermal properties that can take the place of current industrial operating fluids in the heat transfer mediums.

Nomenclature

T	Temperature
h	Heat transfer coefficient
k	Thermal conductivity

Greek symbols

μ	Fluid dynamic viscosity
ϕ	Volume fraction of particles

Subscripts

eff	Effective
bl	Bulk liquid
n	Nanoparticles
lr	Interfacial layer

Abbreviations

MWCNTs	Multiwalled carbon nanotubes
INF	Ionic nanofluids
DLS	Dynamic light scattering
DSC	Differential scanning calorimeter
Gr	Graphene
IL	Ionic Liquid

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