

Ionanofluids: A review on its properties and thermal applications

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Abstract. The dispersion of nanoparticles (NPs) into ionic liquids results in ionanofluids (INFs) (ILs). INFs are regarded as the newest type of heat transfer fluids (HTFs). INFs are discovered to improve the fluids' thermophysical characteristics at high temperatures with negligible vapor pressure. The preparation techniques and theoretical models used to calculate the physical characteristics of ionofluids, including their density, heat capacity, thermal conductivity, and thermal applications, are summarized in this work.

Introduction

Nanotechnology focuses on creating and using objects with organizational characteristics between individual molecules and around 100 nm, where special properties emerge in contrast to bulk materials. To build tailored nanostructures and gadgets for particular uses, it entails changing molecules and atoms. Nanotechnology is growing and enabling technology for the twenty-first century, alongside the already well-established sectors of information technology and biotechnology. The convergence of knowledge in physics, chemistry, biology, materials science, and engineering at the nanoscale is the cause, and matter control at the nanoscale is significant for almost all technologies.

Because manufacturing of nanoparticles is a key component of nanotechnology, specific features are achieved at the nanoparticle, nanocrystal, or nanolayer level. The assembly of precursor particles and related structures is the most popular technique for producing nanostructures. People have been producing nanoparticles empirically for thousands of years, for as by producing carbon black [1]. Ionanofluid (INF) is defined as a nanodispersion of metallic, polymeric, inorganic, or organic solid nanoparticles dispersed in an ionic liquid (IL) [2,3]. Since Nieto de Castro's proposal of such a system, INFs have received considerable scholarly interest. Ionic liquids (ILs) are described as liquids with organic cations and organic/inorganic anions that are at room temperature. They can be used as heat transfer fluids (HTFs) because of their good thermal characteristics [2,4]. The characteristics of vapor pressure and volatility are deemed unimportant for ILs. In addition to being used as HTFs, ILs have a variety of additional uses. For instance, they are frequently employed as solvents in chemical, gas processing, coal handling, and pharmaceutical factories, among other facilities [5–10].

Nanofluids have a lot of potential for applications involving heat transmission. They are made up of tiny nanoparticles in volume and weight fractions together with base fluids like water and glycol. When operating temperatures range from -40 to 400 °C, ILs have more advantages when used as a continuous phase in nanofluids than the usual base fluids. INFs have great dissolving power for a variety of organic and inorganic substances, considerable chemical and stable thermal characteristics, and little vapor pressure [11–15]. The scientific discipline of rheology gains substantially from nanotechnology. It offers several useful tools to look at how various physical and chemical circumstances affect ionanofluid properties. To validate materials prior to manufacturing and usage on a wider range, design the appropriate machineries, and improve the

performance, such complex system necessitate in-depth rheological analysis [16,17]. Viscosity is the most important parameter to consider when looking at rheological parameters. Convective heat transfer, pressure loss, and required pumping power are all dependent on viscosity [18–20]. It is due to the requirement for optimizing internal resistance and heat transport capacities. Internal resistance increases as a fluid's viscosity increases [21].

Dynamic (also known as oscillatory) shear testing and steady shear experiments are two methods used to research rheological behavior. The majority of literature data follows the steady-shear material function, and steady shear flow is simple to manufacture. The material is subjected to a sinusoidally varying deformation in dynamic shear flow [22–24]. By employing steady shear measurements depends on viscosity or shear stress are studied. While the modulus rigidity (G'') can be determined using dynamic shear tests as a function of temperature, time, or oscillation frequency. For example, moduli G' and G'' show the material's "elastic" and "viscous" characteristics "properties, or stored and lost energy, during sample deformation, respectively [25,26]. Both rheological methods have benefits and drawbacks. The steady shear tests have several limitations in terms of sample component migration and slippage even if they require less complicated equipment. The non-destructive nature of oscillatory shear tests is due to the tiny strain/stress amplitude. They are, nevertheless, inappropriate for real-world processing applications [27,28].

The literature claims that nanodispersions exhibit complicated rheological characteristics [29]. There has already been a large amount of structured and reviewed research on the rheological properties of conventional nanofluids [6,18,20,30-44]. However, Shakeel et al. [45].'s previous research on viscosity of ionanofluids only included one review publication. Unfortunately, given of the review's broad topic scope, which encompassed the ionanofluids gels. The review by Vignarooban et al. [46] explored the thermal properties and stability of different ILS-based HTFs, including molten salts, steam, organic fluids, thermal oils, liquid metals, and air. For usage in parabolic trough collectors, Malviya et al. [47] investigated a number of ILS-based HTFs, including sodium salt, solar salt, solar grade oil, etc. Other ILS-based HTFs, including as Therminol VP-1, Syltherm 800, Solar salt, Hitec XL, and liquid sodium, have also been the focus of a theoretical investigation for Malaysian circumstances by Zaharil and Hasanuzzaman [48]. Conroy et al. [49] developed a theoretical model to investigate the hydraulic flow properties of liquid sodium, molten salt, and lead-bismuth in a concentrated solar power (CSP) receiver.

Trabelsi et al. [50] performed an optimization analysis of a solar parabolic trough power plant using the simulation software SAM, with an emphasis on the field size, storage system, and HTFs. They came to the conclusion that Therminol VPI and synthetic oil are less economically sound than molten salt. The thermal and physical properties of liquid sodium and Hitec (a blend of KN, NaN, and NaN) were assessed by Boerema et al. It has been established that future CSP can use liquid sodium in place of molten salts. Although there has been a lot of research in this field over the last ten years, more work is still required. This paper's major goal is to present a thorough analysis of ionanofluid in terms of its preparation processes, varieties, and properties. Additionally, to examine the effects of various parameters, such as thermal conductivity, viscosity, density, and specific heat, on the thermal transport characteristics of ionanofluid. The thermal uses of ionanofluids and potential thermal applications are covered in this review paper.

Preparation methods for Ionanofluids

In their review, Azmi et al. [40] discussed the processes for creating and purifying ionic liquids. One-butyl-3-methylimidazolium bis(trifluoromethyl) sulfonylimide, one-butyl-3-methylimidazolium ethylsulfate, one-butyl-3-methylimidazolium tetrafluoroborate, and one-hexyl-3-methylimidazolium tetrafluoroborate are the most often utilized ionic liquids as base liquids. Ionic liquids excel in several areas, including thermal stability, a wide operating temperature range, low freezing point, low flammability, low vapor pressure, high thermal

conductivity, and high heat capacity. The biggest drawback of employing ILs is their high viscosity, which increases the expense of pumping. By dispersing different weight/volume fractions of nanomaterials in the matching base ionic liquids, ionanofluids are created. Ionanofluids, for instance, were created by dispersing different weight percentages of Multiwall Carbon Nanotubes (MWCNT) in a variety of ionic liquids, then sonicating them for enhanced nanotube dispersion [52, 53].

Types of Ionanofluids

The creation of mixes of dispersed nanoparticles in predetermined base liquids was the basis for Choi and Eastman's initial mention of nanofluids [54]. Nanofluids are categorized into four primary classes based on the different types of nanoparticles that were employed in their synthesis: metal-based, metal oxide-based, carbon-based, and hybrid/mixed metal-based. To create nanofluids, these nanoparticles are suspended in base fluids such as water, methanol, ethylene glycol, kerosene, and transformer oil. The stability and physical properties of nanofluids must be taken into account when choosing them for any application. Nieto de Castro et al. [2] produced what are known as "ionanofluids" for the first time by dispersing nanoparticles within ILs. On the basis of their successes in improving thermal conductivity, other research projects were published in the synthesis of ionanofluids using the same techniques as nanofluids.

Properties of Ionanofluids

Because of their high thermal stability and low vapor pressure, ionic liquids offer a great deal of potential as heat transfer fluids. Additionally, they have an excellent thermal conductivity and large volumetric heat capacity (like more conventional HTFs like Dowtherm MXTM, Syltherm 800TM, and engine oil). Table 1 displays reference values for the thermophysical characteristics of various commonly used heat transfer fluids and ionic liquids at a temperature of 40 °C [55, 56].

Table 1. Reference values of various widely used heat transfer fluids and ionic liquids' thermophysical properties at a temperature of 40 °C

Liquids	λ [W/m·K]	η [mPa·s]	C_p [J/kg·K]	ρ [kg/m ³]
Water	0.631	0.653	4,179	992
Ethylene glycol	0.256	10.37	2,520	1,100
Engine oil	0.148	568.00	2,000	880
1-butyl-3-methylimidazolium bis(trifluoromethyl) sulfonylimide	0.116	28.50	1,372	1,423
1-butyl-3-methylimidazolium ethylsulfate	0.178	50.00	1,615	1,226

The higher thermal conductivity of the nanoparticles in contrast to any base fluid has been attributed to the heat-transfer characteristics of nanofluid. Since thermal conductivity is the most important feature in this context, it is well described [57–61] how to improve the thermal conductivity of nanofluids. Other essential qualities, such as density, heat capacity, and viscosity, can be changed by the addition of nanoparticles. The effects of the nanoparticles are now more complicated, and it is still need to thoroughly examine all of the mechanisms. It is commonly known that when a fluid's temperature increases, its properties can change significantly. If we exclude molten salt-based nanofluids, there are relatively few research and observations of the

thermophysical properties of nanofluids at temperatures beyond 100°C [62]. In this section, the characteristics of ionanofluids and the findings of literature searches in high-temperature regions are reviewed.

Thermal conductivity of Ionanofluids

The fact that nanofluids transmit heat more efficiently than base fluids is well-known. It has served as the subject of several literary analyses. Thermal conductivity was the subject of a thorough and insightful review by Sobti and Wanchoo [63]. Ionic liquids (ILs) have gained significant attention as environmentally friendly solvents, heat carriers, and electrolytes. Cations and anions can be made to have specific thermophysical properties and functions by changing their species. Understanding the basic thermophysical characteristics of ILs, such as their densities, viscosities, and thermal conductivities, is necessary to create ILs with the best possible thermophysical qualities. Tomida [64] presented the experimental results for the thermal conductivity of the pure IL components as well as methods for calculating the thermal conductivity of IL using correlations.

Additionally, there has recently been a lot of interest in the thermal conductivities of ionanofluids, which are made up of nanoparticles dispersed in an IL. In a study of the thermal conductivities of nanofluids with carbon nanotubes dispersed in ILs, Castro et al. provided the first description of the thermal conductivities of ionanofluids in 2010. The thermal conductivities of ILs have been shown to be rather low, matching those of ethanol and methanol. As a result, it was hypothesized that distributing nanoparticles within an IL would increase its thermal conductivity [65–67]. The impact of volume and temperature on the thermal conductivity of ionanofluids is covered in the section that follows. It also discusses the theoretical frameworks that were used to forecast the thermal conductivity of ionanofluids.

Effect of volume on thermal conductivity of Ionanofluids

Nanofluids were projected to offer superior properties over microfluids due to their large surface area to particle volume ratios. The Hamilton-Crosser model (Eq. 1) and the thermal conductivity of nanofluids are widely known to accord [68].

$$\frac{k_{eff}}{k_0} = \frac{k_p + (n-1)k_0 + (n-1)(k_p - k_0)\phi_p}{k_p + (n-1)k_0 - (k_p - k_0)\phi_p} \quad (1)$$

Where n is the particle shape parameter, k_p is the volume fraction of the dispersoid, and k_0 , k_{eff} , and k_p are the thermal conductivities of the dispersion medium, nanofluid, and dispersoid, respectively, in [W/ m.K]. Fig. 1 depicts the projected rise in k value through Hamilton-Crosser model for Ag, Al₂O₃, BaTiO₃, nanoparticles are used as the dispersoid in 1-butyl-3-methylimidazolium tetrafluoroborate ([BMIM] [BF₄]) as a typical IL.

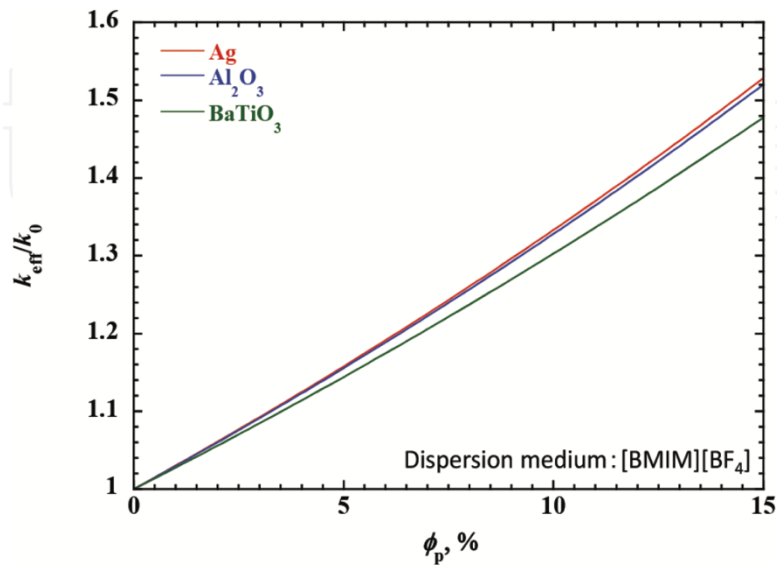


Figure 1. Relationship between the volume fraction of nanoparticles and the improvement in thermal conductivity based on the Hamilton-Crosser model at 298 K [64].

Table 2 shows k of each dispersed that was evaluated. The results show that the increase in k that occurs when the volume percentage is around 15% ($n = 3$) does not very much, even when dispersions have thermal conductivities that are significantly variably. This explains by diluting spherical nanoparticles in an IL, the thermal conductivity of the dispersed has little impact on the k resulting ionanofluid. In order to further increase the k of an ionanofluid containing spherical nanoparticles, the volume fraction of the dispersion must be increased; however, this has an impact on flowability. When using an ionanofluid as a heating medium, the minor volume proportion of nanoparticles must be used to enhance k . To dramatically increase the rate of k augment with a low nanoparticle concentration, it is essential to increase the particle diameter, n . Increasing n while lowering the slope is attainable by selecting a material with a high aspect ratio.

Table 2. Thermal conductivities of dispersoids [64].

Dispersoid	k_p , [W(mK)]
Ag	428
Al_2O_3	36
$BaTiO_3$	6

Effect of temperature on thermal conductivity of Ionanofluids

Studies have shown that temperature has a big impact on k data. The greater the impact, the higher the temperature. An increase in Brownian motion is the primary explanation for this effect [69–70]. But according to various research [71–73], the thermal conductivity of nanofluids closely mirrored the base fluid's temperature dependency. Fig. 2 displays temperature-dependent thermal conductivity data for ionanofluids containing the same concentration of MWCNT and SWCNT (1 wt%) in both water and $[C_4mim][NTf_2]$ and $[C_2mim][EtSO_4]$ [74]. At normal temperature, other $[C_2mim][EtSO_4]$ based ionanofluids showed an increase in thermal conductivity of just 8.5%,

whereas [C₄mim] [NTf₂] based ionanofluid showed an increase in *k* of up to 35.5% over its base ionic liquid.

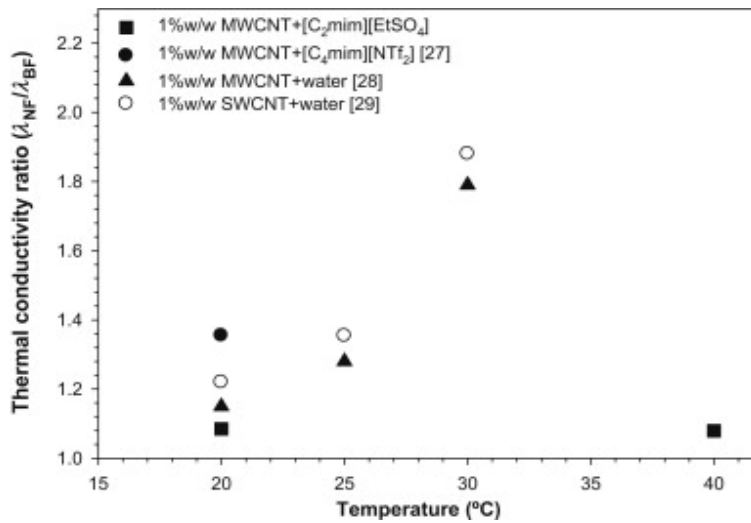


Figure 2. Effect of temperature on *k* of CNT loaded nanofluids and Ionanofluids [75]

At room temperature, [C₂mim] [EtSO₄] was found to have *k* of 0.128 W/(m. K). However, the MWCNT/water nanofluid *k* data published by Ding et al. [75] and the SWCNT/water nanofluid data presented by Amrollahi et al. [76] both exhibited increases in thermal conductivity of about 15% and 22%, respectively, at the same temperature and concentration. Fig. 2 further demonstrates that *k* of [C₂mim] [EtSO₄] based nanofluid is temperature independent, but the thermal conductivity of CNT-nanofluids increases noticeably as temperature rises.

Models to predict the thermal conductivity of Ionanofluids

Since the publication of Maxwell's treatise, various classical models have been constructed to estimate the effective thermal conductivity of suspensions of solid particles. Most researchers discovered that these classical models, including those credited to Maxwell [77] and Hamilton-Crosser [78], were not able to anticipate the anomalous thermal conductivity of nanofluids because they were designed for micro- or millimeter-sized dispersed particles. As a result, several theoretical investigations have been conducted over the past ten years to comprehend the heat transfer mechanism and create models that can precisely predict the effective thermal conductivity of nanofluids [79]. The majority of theoretical investigations, however, were restricted to spherical nanoparticles and were not well received.

Murshed et al. [80] developed a model for the prediction of *k* of cylindrical nanoparticle based nanofluids by considering the effects of particle size and the interfacial layer at the particle/fluid interface (nanolayer). In this study, both the traditional HC model and the more recent model developed by Murshed et al. are used to predict the effective *k* of ionanofluids containing MWCNT. The HC is modified version of Maxwell's model to include a form component that takes spherical and non-spherical particles' effective *k* into consideration. The volume ratio, the shape of the dispersed particles, and the *k* of the solid and liquid phases all play a role in their model. The form of the HC model is represented by Eq. 2.

$$\lambda_{\text{eff}} = \lambda_f \left[\frac{\lambda_p + (n-1)\lambda_f - (n-1)\phi_p(\lambda_f - \lambda_p)}{\lambda_p + (n-1)\lambda_f + \phi_p(\lambda_f - \lambda_p)} \right] \quad (2)$$

Where ϕ_p is the particle volume fraction, n is the form factor $n = 3$ for spherical particles and $n = 6$ for cylindrical particles, and λ_f and λ_p are the thermal conductivities of the base fluid and nanoparticle, respectively. This idea states that spherical particles show a smaller increase in thermal conductivity than non-spherical ones. It is noted that for spherical particles, the Maxwell model can replace the Hamilton-Crosser model. On the other hand, Eq. 3 represents the model created by Murshed et al. for the effective k suspensions of cylindrical nanoparticles (nanofluids), which accounts for the effects of particle size, concentration, and interfacial nanolayer.

$$\lambda_{\text{eff-nf}} = \lambda_f \frac{\phi_p \omega (\lambda_p - \omega \lambda_f) [\gamma_1^2 - \gamma^2 + 1] + (\lambda_p + \omega \lambda_f) \gamma_1^2 [\phi_p \gamma^2 (\omega - 1) + 1]}{\gamma_1^2 (\lambda_p + \omega \lambda_f) - (\lambda_p - \omega \lambda_f) \phi_p [\gamma_1^2 - \gamma^2 - 1]} \quad (3)$$

Where $\omega = \lambda_{lr} / \lambda_f$, $\gamma = 1 + (t/r_p)$, $\gamma_1 = 1 + (t/2r_p)$, r_p is the particle's radius, t is the interfacial layer's thickness, and λ_{lr} is the interfacial layer's thermal conductivity.

According to experimental and analytical investigations, the thickness of a nanolayer produced at the interface between nanoparticles and fluids is thought to be 1 nm; however, neither theoretical nor practical methods can be used to evaluate the thermal conductivity of such a nanolayer. However, the sequence and orientation of the fluid molecules that are absorbed on a nanoparticle surface led to an intermediate value of thermal conductivity for the nanolayer, i.e., $\lambda_{fr} < \lambda_{lr} < \lambda_p$. The interfacial layer thermal conductivity is therefore expressed as by $\omega > 1$, where > 1 is an empirical value that depends on the arrangement of fluid molecules at the interface as well as the composition and surface chemistry of nanoparticles.

Viscosity of Ionanofluids

The addition of particles to a liquid alters the viscosity of the combination. This effect might not be noticeable for very small particle volume fractions. As the volume fraction rises, though, the mixture's viscosity could noticeably increase. Since viscosity is a crucial characteristic that impacts friction and pumping power/pressure drop, it has been the subject of several investigations. The rheological behavior of nanofluids has been the subject of some discussion [41]. There appears to be no correlation between rheological behavior and particle concentration, and the behavior appears to vary depending on the material, according to a recent review by Okonkwo et al. [59].

Wittmar's work [81] measured the apparent viscosity of INFs having three various kinds of externally purchased and internally produced TiO₂ nanoparticles distributed in three various ILs with various alkyl chain lengths: [Emim][BF₄], [Bmim][BF₄], and [Hmim][BF₄]. The amounts were 0.05, 0.1, 0.5, and 1 weight percent. The experiments were performed with shear rates ranging from 0.1 to 1000 s⁻¹ at a temperature of 25 °C. The outcomes demonstrated that the length of the alkyl chain on the IL cation improved the viscosity and non-Newtonian characteristics of the INFs (Fig. 3). Longer alkyl chains made INFs more viscous because bigger cations had less rotational flexibility and greater van der Waals interactions [82–85]. Additionally, they inhibited Brownian motion from causing the nanoparticles to aggregate, which normally raised the stability of nanodispersion.

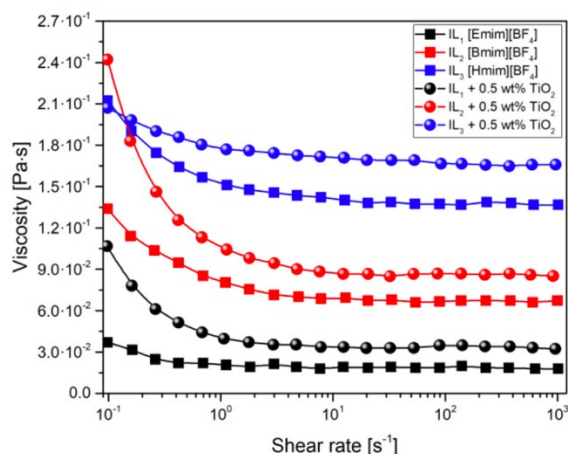


Figure 3. The figure depicts apparent viscosity as a function of shear rate for pure ILs and INFs that contain 0.5 weight percent of TiO_2 nanoparticles and have varying alkyl chain lengths on the IL cation. Data from [82] was used to make the figure.

Wittmer and Uibrich [86] looked viscosity of TiO_2 /[Emim][NTF₂] and [Emim][BF₄] ionanofluids and found higher viscosity. In contrast to prolonged treatments, shorter ultrasonic treatments for hydrophilic IL resulted in Newtonian behavior of the INFs. But in both cases, a longer ultrasound session (>1 h) had little to no effect on the stability of INFs. The stability and rheology of nanodispersion appeared to be significantly influenced by the hydrophilicity of IL. It occurs because the hydroxyl groups of IL on the surface of nanoparticles and within the IL itself form hydrogen bonds. [Emim][BF₄] produced more stable and viscous nanodispersions than [Emim][NTF₂]. It might be connected to the [87] less adaptable chains [BF₄] ionanofluid. These observations are in line with other experimental results reported in the literature [88,89], which show that base ILs with the same cation but various anions display the sequence shown below as their viscosity rises: $[\text{PF}_6]^- > [\text{BF}_4]^- > [\text{NTf}_2]^- > [\text{DCA}]^- > [\text{TCB}]^- > [\text{TCM}]^-$.

Gao et al. [88] observed the enhanced viscosity of [Bmim][BF₄] ionanofluids. Ueno et al. [89] examined viscosity of INFs dispersed in [Emim][NTF₂] and [Bmim][BF₄] that had hydrophilic and hydrophobic SNP loadings of 5, 8, 10, and 15 weight percent. The shear rates used for the rheological measurements ranged from 0.1 to 1000 s⁻¹ at a temperature of 25 °C. At the lowest shear speeds, the INFs with hydrophilic SNPs and [Emim][NTF₂] displayed significant shear thinning behavior and had a high apparent viscosity. The shear flow's destruction of the intermolecular physical connections in the flocculated silica networks is most likely what caused the non-Newtonian characteristics. The lack of silica network structure was suggested by the fact that hydrophilic SNP nanodispersions in [Bmim][BF₄] lower responsive to shear rate (Fig. 4). However, a distinct non-Newtonian behavior was showed that nanoparticles may have flocculated.

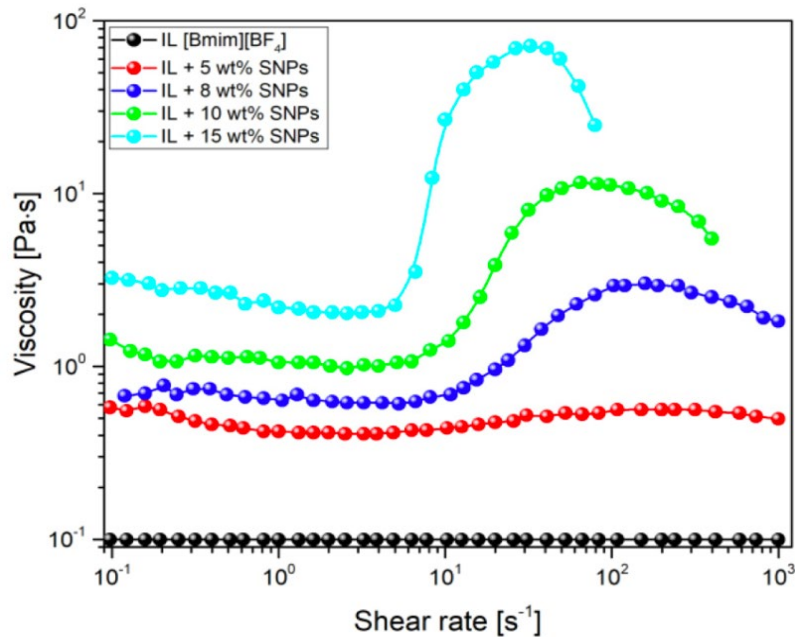


Figure 4. Viscosity of SNP ionanfluids (25 °C) [89,90].

Novak and Britton [91] investigated the shear stress and apparent viscosity of INFs with hydrophilic SNP loadings of 5 and 15 wt%, as well as two ILs, hydrophobic [P_{6,6,6,14}][NTF₂] and hydrophilic [Bmim][BF₄]. The experiments were performed with shear rates ranging from 0.05 to 1000 s⁻¹ at a temperature of 25 °C. According to the published experimental data, Newtonian fluids were all that pure ILs could be at low shear rates (<10 s⁻¹), where the addition of 15 weight percent of SNPs to [Bmim][BF₄] produced Newtonian behavior, whereas at higher shear rates (>10 s⁻¹) exhibits non-Newtonian pseudoplastic characteristics. These results were somewhat in line with those of Ueno et al. [89]. The INF also demonstrated a more complex shear-banding behavior with five wt% of SNPs in [P_{6,6,6,14}][NTF₂].

Zhang et al. [92] evaluated the stress and viscosity of Graphene/[Emim][Ac] ionanfluids and observed an enhanced viscosity. The self-lubricating characteristics of GNPs are most likely what caused this scenario [93]. The viscosity of GNPs/[Hmim][BF₄] IL was measured by Liu et al. [94] and observed higher viscosity 170 °C, when it eventually plateaued at 6.3 mPas. Additionally, it was found that at the same temperature viscosity of the INFs was marginally lower. As was previously indicated, this phenomenon was assumed to be caused by the self-lubrication of GNPs.

The viscosity of [Hmim][BF₄]/SiC ionanfluids was analyzed by Chen et al. [95]. Aggregates of nanoparticles most likely caused the increase. In the nanodispersions, free ions can be captured by aggregation of nanoparticles. The viscosity of MWCNTs/pure [Emim][DEP] IL were examined by Xie et al. [96]. The viscosity rose linearly when MWCNT concentration was raised. Additionally, it was found that when the base liquid's water content increased, viscosity drastically dropped (by as much as 75%). (Fig. 5).

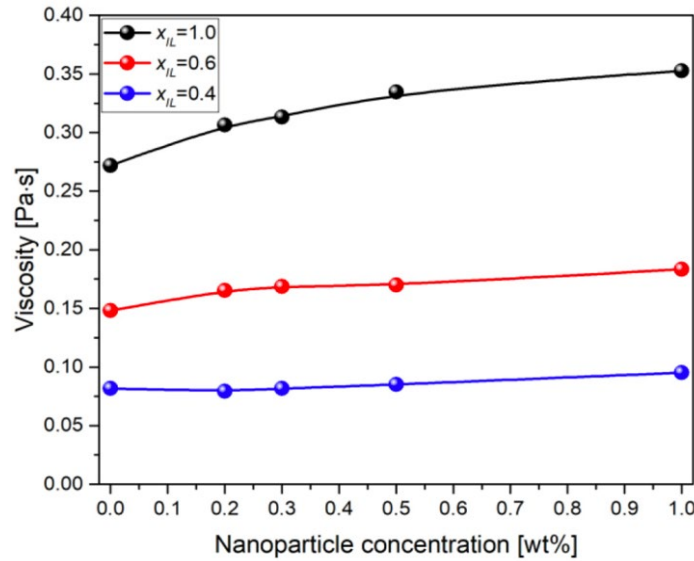


Figure 5. Viscosity of MWCNTs/[Emim][DEP] ionic liquids [96].

Density of Ionanofluids

When applied to a continuum of non-interacting particles, the traditional definitions of density and specific heat capacity give rise to straightforward equations for the mixture equivalents [58,97]. In other words, the mixture density, ρ_{nf} (kg/m³), represents an average of the volume-based component densities.

$$\rho_{nf} = \alpha_p \rho_p + \alpha_{bf} \rho_{bf} \quad (4)$$

$$c_{nf} = \phi_p c_p + \phi_{bf} c_{bf} \quad (5)$$

The terms "nanofluid property," "particle property," and "base fluid property," respectively, are denoted by the subscripts nf, p, and bf. The density and volume fraction of the specified component are, respectively, and. The specific heat capacity of the mixture, and c_{nf} (J / (K kg)), is an average of the specific heat capacities of the various components depending on mass fraction [98]. Where $\phi_p = \alpha_i \rho_i / \rho_{nf}$ is the component mass-fraction. More complex models may be used to determine the component densities and specific heat capacities. However, these models might lose precision for small particle sizes. For instance, experimental findings by Sharifpur et al. [99] demonstrate that Eq. (4) miscalculates the density. They assume that the generally used density model ignores the effect of the gap between the nanoparticles and the base fluid because of the nano layer on the particle surface. They suggest a new theory to explain this nano layer:

$$\rho_{nf,new} = \frac{\rho_{nf}}{\alpha_{bf} + \alpha_p \left(1 + \frac{d_{nl}}{r_p}\right)^3} \quad (6)$$

Where d_{nl} stands for the thickness of the nanolayer and r_p stands for the average particle diameter. Additionally, they demonstrate that their model has a superior fit with the detected experimental results. Hentschke [100] asserts that the improvement might be predominantly attributable to a different factor than the commonly believed nanolayer effect. He proposes a different theory instead, one that depends on longer-range interactions between the nanoparticles in the surrounding liquid. Adding 0.1 weight percent of SiO₂ and Al₂O₃ nanoparticles to Therminol 66 at temperatures between 280 and 320 °C did not appreciably change the fluid's density or viscosity compared to the base substance, according to a recent study by Safaei et al. [101]. There

is currently no comprehensive literature on the density and high temperature heat capacity of nanofluids.

Even if there is evidence of nanoparticle effects, such as the nanolayer, the fundamental connections in E. qs. (4) and (5) may still hold true at high temperatures, as the densities of the base fluid and the nanoparticles or nanoparticle material do typically rely on temperature [102].

$$\rho(T) = \sum_{i=0}^2 a_i T^i \quad (7)$$

Where a_i : the regression parameter (using the least-square method), δa_i is the standard uncertainty, while the fit was described using the coefficient of determination, R^2 . An experimental thermophysical characterization was carried out by Oster et al. [103]. The density was measured as a function of temperature, $T = (298.15-363.15)$ in accordance with Eq. 7 using an Anton Paar DMA 4500M densitometer (calibrated on ultrapure degassed water and dry air, relative standard uncertainty of density $u_r(T) = 0.1\%$, relative standard uncertainty of temperature $u_r(T) = 0.01$ K, approximately 1.5 cm^3 of sample volume, three independent measurement repetitions.

The densities of multi-walled carbon nanotubes, boron nitride, and graphite nanoparticles were measured before determining the Ionanofluids density [104]. Despite not having been previously reported, those for mesoporous carbon were computed using the empirical formulas as stated in Eq. 8, in a manner akin to that followed for carbon nanotubes, boron nitride, and graphite [105]:

$$\rho_{NP} = \frac{\rho_{IL+NP} - \rho_{IL}(1-w_{NP})}{w_{NP}} \quad (8)$$

The subscripts IL and NP stand for ionic liquids and nanoparticles, respectively, where w stands for the mass fraction. Eq. 8 can be used to evaluate density.

Heat capacity of Ionanofluids

Although the specific heat capacity may also decrease, adding nanoparticles usually improves a fluid's thermal conductivity. Its cooling capacity is severely limited. The alteration or improvement of thermophysical properties must be balanced in order to use a nanofluid during the application. For effective and clean heat transfer systems, higher heat-capacity heat transfer fluids are required. Researchers have suggested a variety of techniques, such as increasing surface energy, for improving specific heat capacity. They raised the heat resistance at the interfaces between the liquid molecules surrounding the nanoparticles and themselves, resulting in the formation of a semisolid liquid layer. In a recent study using molecular dynamics simulations, Carrillo-Berdugo et al. [104] attribute some of the specific-heat enhancement of nanofluids to strong chemisorption interaction of the fluid molecules at the nanoparticle surfaces.

Understanding specific heat capacity is essential for figuring out other heat transfer factors, flow characteristics, and enthalpy estimations when modelling different processes, it is well acknowledged. Fig. 6 demonstrates that MWCNT-ionanofluids have a higher specific heat capacity than base ionic liquids (i.e., $[\text{C}_4\text{mim}][\text{PF}_6]$) from room temperature to 115°C , and that this specific heat capacity grows with temperature between 60°C and 90°C [106]. The most noteworthy feature of these findings is that there is a dome-shaped spike in the specific heat capacity within a specific temperature range ($60-110^\circ\text{C}$), independent of MWCNT loading (peak increase of 8% compared with base ionic liquid). It is yet unknown why these puzzling consequences exist.

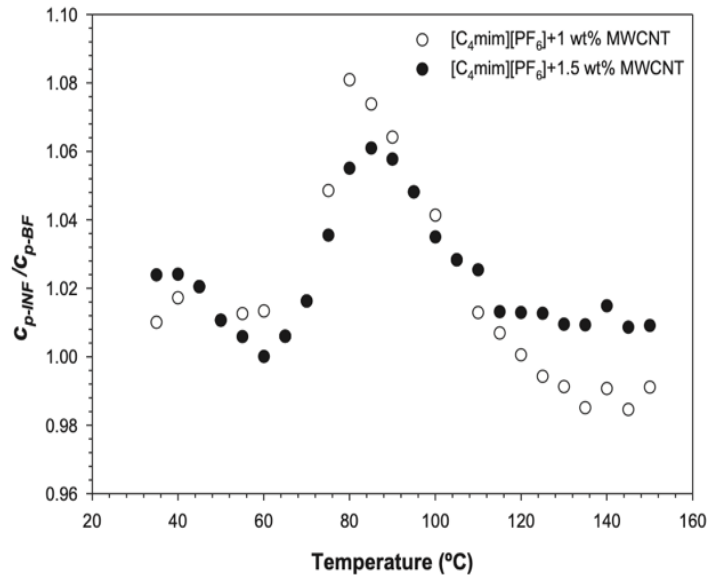


Figure 6. The specific heat of Ionanofluids [106].

Oster [103] measured the isobaric heat capacity, c_p by using differential scanning calorimeter (DSC) apparatus, Q100 TA Instruments, in the temperature range of 298.15-363.15 K (modulated differential scanning calorimetry technique, MDSC, calibrated on synthetic sapphire, CAS: 1317-824, TA Instruments, ultrapure in accordance with the reference standards NIST SRM 720) and checked with 1hexyl3hexyl3methylimidazolium bis(trifluoromethylsulfonyl)imide as a classified ionic liquid NIST standard [107]. It was performed under nitrogen gas flow = $50 \text{ cm}^3 \text{ min}^{-1}$, heating rate $dT/dt = 3 \text{ K min}^{-1}$, amplitude = $\pm 0.5 \text{ K}$, modulation period = 60 s . The calibration and post-calibration method findings determined that the standard temperature uncertainty was 0.01 K , and the relative standard uncertainty of measurement was $u_r(T) = 3\%$. With a 5% repeatability, three independent measurement repeats were carried out. DSC equipment Q100 TA Instruments are used in this study, This does not permit this testing, although the outcomes are consistent with earlier studies. Therefore, the data from our earlier research is utilized for pure ionic liquids. They used a second-order Eq. 9 to correlate the specific heat capacity to temperature like Eq. 7.

$$c_p(T) = \sum_{i=0}^2 a_i T^i \tag{9}$$

Where a_i : the regression parameter (using the least-square method)

δa_i is the standard uncertainty

While the fit was described using the coefficient of determination, R^2

Thermal applications of Ionanofluids

In the past few decades, there has been significant progress in the understanding and application of ionic liquid. In-depth research has been done on ionic liquids [107–117], which has shown them to be competitive replacements for a variety of industrial and chemical manufacturing applications. Their potential and success are influenced by phase equilibrium, thermophysical characteristics, and synthesis flexibility, among other factors. These fluids can be used in a number of applications due to their solvent properties, capacity to transmit or store heat, and surface characteristics [118]. Ionic liquids also have large volumetric heat capacities and great chemical and thermal stabilities.

Additionally, they have a wide range of viscosities, good solvent characteristics, and low vapor pressures. These are merely a few extra benefits.

- Enhanced thermal stability and heat transfer.
- Clog-free microchannel cooling.
- Downsized systems.
- Reduced pumping power.

Ionic liquid has come a long way in the last few decades, both in terms of understanding and practical use. Ionic liquids have been the focus of in-depth study [107–117] and have proven to be competitive substitutes for a range of industrial and chemical manufacturing applications. Phase equilibrium, thermophysical properties, and synthesis adaptability all contribute to their potential and success. Due to its solvent qualities, ability to transmit or store heat, and surface properties, these class of fluids can be used in a variety of applications [118]. Additionally, ionic liquids have excellent chemical and thermal stabilities as well as high volumetric heat capacities. Additionally, they exhibit good solvent properties, a wide variety of viscosities, and minimal vapor pressures. These are only a few additional advantages.

Because of their exceptional qualities, they have been widely investigated as molecular solvent replacements for liquid-phase operations. Because of their outstanding qualities and their current and potential applications in the chemical process industries, ionic liquids are of great interest to scientists and chemical corporations. It has been found that the values of their thermophysical properties greatly affect the design of physicochemical processing and reaction units by directly affecting the design parameters and operation of apparatus such heat exchangers, distillation columns, and reactors [119]. There are numerous recent studies [120-122] that give data on various thermophysical characteristics of various ionic liquids. These studies also look at measurement methods, measurement errors, and potential use of these fluids as heat transfer fluids. According to the results of these experiments, ionic liquids have enormous promise for a variety of applications, particularly as novel heat transfer fluids. However, for the optimal technical design of the green process, the characterization of the used ionic liquids, namely their thermodynamic, transport, and dielectric properties, is required.

The discovery that "bucky gels" can be produced by mixing carbon nanotubes and room-temperature ionic liquids opens up a brand-new field and has the potential to be applied in numerous engineering or chemical processes, such as the development of novel electronic devices, coating materials, and antistatic materials [52, 53]. The "bucky gels" are ionanofluids, which are emulsions or mixes of ionic liquids and nanomaterials, mostly nanocarbons, that are rich in CNTs (tubes, fullerenes, and spheres). There are many possible applications for ionic liquids that contain dispersed nanoparticles that have been functionalized in certain ways, such as functionalized single-walled carbon nanotubes (SWCNT), multiwalled carbon nanotubes (MWCNT), and fullerenes (C60, C80, etc.). By utilizing nanoparticles as heat transfer enhancers, it is possible to create ionanofluids, which are highly flexible and may be customized (target-oriented) in terms of molecular structure to gain the ideal attributes required to fulfill a certain task. The complicated interactions between ionic liquids and nanomaterials in the ensuing complex emulsions may be to blame for this. Ionic liquids, the building blocks of ionanofluids, are more versatile since they may be manufactured or created for particular characteristics and functions.

In contrast to their basic ionic liquid counterparts, MWCNT-containing ionanofluids exhibit higher thermal conductivity (from 2% to 35%) and specific heat capacity, according to recent study by Nieto de Castro and colleagues [121, 122]. These ionanofluids have excellent characteristics, such as high thermal conductivity, large volumetric heat capacity, and nonvolatility, which enable the development of novel heat transfer fluids. Ionanofluids can be used to make new pigments for solar collector paint coatings that have higher solar absorbance and thermal emissivity than base

paint. Further than the investigations carried out by this group, there is no other ionanofluids study available in the literature.

Future scope of research studies

The following are the potential areas of future research involving ionanofluids:

- To completely characterize the effect of nanoparticles on base ionic liquids, empirical correlations, conventional numerical methods, and experimental observations must be used more frequently. Therefore, first-principle techniques such as density functional theory (DFT) or molecular dynamics (MD) simulation tools may be used to precisely assess the impact of nanoparticle size, shape, and concentration on the characteristics of ILs-based nanofluids.
- New IL-based nanofluids' thermo-physical properties and thermal performance can be characterized with artificial intelligence based on machine learning at a low computational cost. A deep learning or machine learning model can be trained and validated using the results of a molecular dynamics simulation.
- But given the available training data and computational resources, machine learning techniques must be carefully selected.
- To fully characterize the thermal performance of ILs-based nanofluids in full-scale solar thermal power systems, it is necessary to conduct experimental benchmarking. It is necessary to characterize the thermophysical characteristics and thermal performance of ILs-based nanofluids under suitable operating conditions, i.e., the high temperature of a solar thermal power plant.

Conclusion

The development of ionanofluid as a heat transfer fluid for thermal applications was summarized in this publication. It covers thermophysical parameters (thermal conductivity, viscosity, density, and heat capacity), the meticulous manufacture of ionic liquid, measurements process, theoretical and empirical correlation, heat transfer applications of ionanofluids, and potential areas for further research.

The following finding and suggestions were made as a result of the detailed examination of ILs-based nanofluids:

- The density of IL-based nanofluids has not been the subject of many studies. The density of ILs-based nanofluids increases in comparison to base ILs because much denser nanoparticles are added to the base fluid. Density decreases slightly as temperature rises.
- In their particular heat, IL-based nanofluids display scattered behavior with different nanoparticles. Nanofluids based on graphene and SWCNTs have a lower specific heat than the foundation ILs. High heat capacity is displayed by nanofluids made of multi-walled carbon nanotubes (MWCNTs). To better understand the behavior of specific heat detraction or enhancement, a thorough experimental research of the heat capacity of ILs-based nanofluids is required. Specific heat is one of the most significant thermophysical parameters for any heat storage medium.
- All of the studies revealed that the thermal conductivity of ILs-based nanofluids was higher than that of base ILs and that it rose with the concentration of nanoparticles. The increase in thermal conductivity was attributed to the interfacial layer of base ILs into the nanoparticles and the interaction between ions and nanoparticles.
- However, further investigation is required to completely comprehend the rise in thermal conductivity of ILs-based nanofluids.

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