Critical evaluation of nanofluids and ionanocolloids as heat transfer fluids

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Abstract. Nanofluids and ionanocolloids are potential heat transfer fluids with remarkable thermophysical properties. The main difference between these two types of fluids remains in the base fluid used, which significantly impacts their performances. In this work, an attempt of a critical evaluation of the most relevant characteristics of both fluids is presented and the main challenges of their application are discussed.

1. Introduction
Technology development leads to the production of high-power devices increasingly smaller. To perform appropriately, these devices require more efficient cooling systems by replacing their conventional heat transfer fluids. The addition of nanoparticles (NPs) into fluids has been widely reported due to notable enhancement on the thermophysical properties of the base fluids [1]. The term nanofluids is used when nanoparticles are dispersed into conventional heat transfer fluids, while ionanofluids or ionanocolloids as it is considered more correct term, refers to the use of ionic liquids as base fluids [2]. Nanofluids have remarkable thermal behavior and features. However, a major challenge on their application is to obtain a stable suspension for a long period of time and over high temperatures. Due to the attractive forces of Van der Walls the nanoparticles tend to aggregate and settle down, resulting in drastic drop on the performance of the nanofluids [3]. There is a large diversity of base fluids used to prepare nanofluids, being the most used water, ethylene glycol, engine oil and acetone [4]. On the other hand, ionic liquids are molten salts that have negligible vapor pressure, high ionic conductivity and high thermal stability [1]. The immense combinations of cations and anions allow a synthetization of ionic liquids with specific required properties and, for that reason, these fluids are known as “task specific liquids”. Ionanocolloids stability is much higher than the nanofluids, but their industrial implementation may require high investment costs associated with their high viscosity and lower thermal conductivity [2]. However, they can be recycled almost infinite times, are non-flammable and safer to operate [1].

Despite the concept of nanofluids has been introduced in 1995 by Choi, at Argonne National Laboratory in USA [3], the number of publications in nanofluids for heat transfer application continues to grow exponentially. On the other hand, as it is displayed in Figure 1, the studies of using ionanocolloids in energy-related areas is much more recent and there is still a long road ahead. In this work, a critical comparison from literature articles between these two types of fluids is made taking into consideration their main thermophysical properties and stability. Both fluids are very promising options as heat transfer fluids for thermal energy applications, and their prospects and challenges are discussed.
2. Preparation methods
In relation to nanofluids and ionanocolloids, they basically differ by the base fluid used, which are the conventional heat transfer fluids in case of nanofluids (water, ethylene glycol, oil) and ionic liquids in ionanocolloids. There are two approaches for nanofluids and ionanocolloids preparation: one-step and two-step methods. In the one-step method, nanoparticles are synthesized into the base fluids. Consequently, the cluster formation is much lower, and the suspension obtained is more stable [1]. The two-step method, as the name suggests, refers to two stages during preparation: the first is when NPs are synthesized or purchased, and the latter is the addition and blending of them into base fluids. The two-step method is more appropriated to industrial usage and therefore, it is largely performed by the authors. Despite this method is economically attractive it is less stable because NPs are initially in a powder size favouring their aggregation in solution by Van der Walls attractive forces [1].

3. Results and discussion
Table 1 presents a summary of the main characteristics of nanofluids and ionanocolloids relevant for industrial heat transfer applications. When considering a best choice of a heat transfer fluid, the Nusselt number is very important because it dictates the heat transfer performance of a fluid. This dimensionless number is directly proportional to the thermal conductivity (TC) of the fluid, and for that reason this is the most important property to evaluate the efficiency of the heat transfer fluids [4].

Water is the base fluid most used for the preparation of nanofluids by the authors, while Al₂O₃ and carbon-nanotubes are the most applied nanoparticles. In general, the TC improvement is related with the TC of the nanoparticle and base fluid used, and hence, nanoparticles like metals or carbon nanotubes, which have higher values than metal oxides, promote higher improvements on thermal conductivity. Aravind et al. observed enhancements from 10 to 88 % in TC of a water-based nanofluid with the addition of 0.04 vol% of sG–f-MWNT (solar graphene-functionalized multi-walled carbon nanotubes composite) under temperatures between 293-323 K [5]. In the work of Eastman et al., nanofluids containing 5 vol% of CuO were responsible to increase TC in almost 60 % compared with the base fluid (water) [6]. The dispersion of SWCNT (single-walled carbon nanotubes) in water in concentrations of 0.05-0.25 vol% enhanced thermal conductivity up to 36 vol%, for the highest volume fraction added [7]. Regarding the ionanocolloids, it is clear that the ionic liquid type exerts significant influence on thermal conductivity and according to the cation and anion nature the TC of the base fluid may vary from 0.10 W m⁻¹ K⁻¹ [8] to 0.30 W m⁻¹ K⁻¹ [9]. In the investigation of Jozwiak et al., the addition of 1 wt.% of SWCNT increased 68 % the TC of [C₂mim][SCN] compared with the value of this pure fluid.
of 0.177 W m\(^{-1}\) K\(^{-1}\) [10]. Moreover, Nieto de Castro et al. evaluated the effect of blending 1 wt.% of MWCNT into different ionic liquids. They reported enhancements of 36, 7 and 7 % for base fluids of \([\text{C}_4\text{mim}][\text{NTf}_2]\) (0.121 W m\(^{-1}\) K\(^{-1}\)), \([\text{C}_6\text{mim}][\text{NTf}_2]\) (0.122 W m\(^{-1}\) K\(^{-1}\)) and \([\text{C}_8\text{mim}][\text{NTf}_2]\) (0.121 W m\(^{-1}\) K\(^{-1}\)), respectively [11]. The effect of nanoparticle loading follows the same trend in both types of fluids, higher concentrations led to higher thermal conductivities. However, the impact of temperature on TC is reported as positive in nanofluids [12], while for ionanocolloids there is still a large divergency in the results and no conclusions can be taken.

### Table 1. Main characteristics of nanofluids and ionanocolloids.

|                        | Nanofluids (water-based) | Ionanocolloids |
|------------------------|--------------------------|----------------|
| Time of Stability (without surfactants) | Very low                | Stable        |
| NPs most used          | \(\text{Al}_2\text{O}_3\) and carbon-nanotubes | MWCNT         |
| Thermal conductivity of base fluid | 0.6                      | 0.10-0.30     |
| TC enhancement (room temperature) | Up to 88 % [5]           | Up to 68 % [10] |
| Effect of increasing nanoparticle concentration on TC | Enhance mostly non-linearly | Enhance mostly linearly |
| Effect of increasing temperature on TC | Enhancement                | No conclusive  |
| Thermal Stability      | Low-medium temperature   | High temperatures (up to 776 K [15]) |
| Effect of increasing nanoparticle concentration on viscosity | Increase significantly | Increase moderately |
| Effect of increasing temperature on viscosity | Remarkable reduction     | Reduction      |

Maintaining a suspension of nanoparticles stable for a long period of time or to operate under high temperatures without causing degradation is not an easy task regarding the industrial application of the nanofluids and ionanocolloids. Such issue is due the high tendency of nanoparticles to clustering into the nanofluids with subsequent precipitation. Stable suspensions are obtained by various ways like sonication, addition of surfactants, functionalization on the nanoparticles surfaces or by changing the pH of the medium [12]. For instance, Xie et al. evaluated the effect of modification on the CNT surface on stability of water- and ethylene glycol-based nanofluids and observed that the suspensions remained stable after 2 months with no visible sedimentation at the bottom, whereas the untreated CNT sedimented after only 5 minutes [13]. In the case of ionanocolloids, the stability issue might be overcome by the interaction between the ions in solution and the surface of nanoparticle, that can result in the formation of an electrostatic layer that avoids their agglomeration and keep the dispersion stable for long time [1]. Other important feature of the heat transfer fluids to take into consideration is the thermal stability. It is an important requirement and is essential to determine the maximum temperature operation under the heat transfer fluid can be applied. In general, water-based nanofluids are able to operate under low-medium temperature while ionanocolloids can withstand high temperatures. Ionic liquids such as \([\text{C}_4\text{mmim}][\text{NTf}_2]\) only degrade above 732 K [14] and \([\text{C}_4\text{mpyrr}][\text{NTf}_2]\) above 776 K [15].

Viscosity is an important rheological property of the heat transfer fluids and it is closely related with the energy demanded in the process, ascribed to the pumping power required by the fluid. Ionic liquids have a large range of viscosities, that depends on their chemical structure and can go from tens to thousands mPa s\(^{-1}\) remarkably higher than the viscosity of water of 0.9 mPa s\(^{-1}\), at room temperature.

As temperature increases, the viscosity of ionic liquids drops drastically, which may represent a great advantage, since at high temperatures it can have viscosities like the conventional heat transfer fluids while possess much better thermal stability. Overall, it can be concluded that for applications at lower temperatures, viscosity is the main disadvantage of using ionanocolloids instead of nanofluids. Like the
ionanocolloids, increasing temperature also reduces the viscosity of nanofluids. Such behavior is attributed to the more intense motion of the molecules and the higher distance between them [1]. In addition, the increase in the concentration of nanoparticles is usually related to higher viscosities. Significant viscosity improvement of more than 400 % were reported after mixing 2.5 wt.% of Al₂O₃ with [C₄mpyr][NTf₂] [16]. The addition of 3 vol% of SiC resulted in 102 % enhancement of viscosity of water-based nanofluid at 301 K [17].

4. Conclusions
This work evaluated the main thermophysical properties of nanofluids and ionanocolloids for applications in thermal energy systems. In general, the addition of nanoparticles into base fluids promote considerable enhancements on their performances. Nanofluids and ionanocolloids are very different fluids and both have incredible potential as advanced heat transfer fluids. Only a careful evaluation of their features and properties will allow to obtain a better choice for a more efficient and economical process.

Acknowledgments
This work was supported by the Fundação para a Ciência e Tecnologia (FCT), Portugal through project grant number: PTDC/NAN-MAT/29989/2017.

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