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Advances in Rheological Behavior of Nanofluids and Ionanofluids – an Editorial Note

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Abstract: This editorial note is dedicated to the Virtual Special Issue about the “Advances in Rheological Behavior of Nanofluids and Ionanofluids”. After a brief presentation of the objectives of this VSI, the contributions published in the Journal of Molecular Liquids are introduced.

Keywords: Nanofluid; Rheology; Dynamic Viscosity; Viscoelasticity; Magneto-rheology; Experiments, Modelling

Since their introduction in the early 1990s, nanofluids have been an attractive material both in the field of basic and applied sciences, in particular for energy and heat transfer applications. Their physical properties differ from those predicted by classical theoretical models, and the possibility of using them in many fields of industry has led to a wide development of these materials and their characterizations in an attempt to understand the mechanisms of physico-chemical processes occurring at nanoscale and responsible of their properties. Among those properties, one can notice the influence of rheological properties including the viscosity, thixotropy, visco-elastic structure, ... that need to be known and understand for applications involving fluid flow due to their influence in pressure drop and pumping power of energy systems. Rheological properties are also closely related to the stability, the structure and interaction of nanoparticles within the base fluid, their degree of dispersion and aggregation. So, they can contribute to the understanding of physical and structural properties of nanofluids that could explained thermal properties evolution.

Thus, the aim of the virtual special issue entitled ”Advances in Rheological Behavior of Nanofluids and Ionanofluids” was to address the current knowledge and future prospects in the rheological behavior and flow properties of nanofluids/ionanofluids with the objectives to give a improved picture of their rheological properties and viscosity evolution in relation with

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the structure, size, shape, nature, concentration of nanoparticles, type of base fluids, temperature and understand the phenomena involved at nanoscale and molecular levels and that are beyond this evolution.

Among the large number of papers submitted for possible publication – showing both the interest of the scientific community for the nanofluid topic and the impact of the Journal of Molecular Liquids in this field – 21 articles have been published after careful evaluations and regular review process. These articles are briefly introduced in the following.

Three “state-of-the art” papers are a part of this VSI collection. Jozwiak and Boncel reviewed and analysed the recent studies on ionanofluids rheology [1]. Since the ionic liquid-based nanofluids are relatively new group of the nanofluids, such review paper could bring the overview of this issue to the readers. Beside this comprehensive literature overview, the authors also addressed future perspectives that could be used in systematic study on ionanofluids. Another review paper focused on graphene based-nanofluids [2]. Due to the unique properties of graphene, the nanofluids containing this material are one of the most often examined materials recently. In Hamze *et al.* [2], graphene-nanofluids rheology and viscosity are comprehensively reviewed, considering in particular the type of graphene derivatives. Rheological behavior of nanofluids is interesting not only from the point of view of the fundamental sciences, but also plays important role for potential application of these nanomaterials. Ali *et al.* [3] summarized recent developments in using nanofluids in oil recovery systems. In particular, they emphasized that rheological behavior of materials used in this process must be strictly controlled.

Several experimental contributions were published. A first series of papers was mainly dedicated to the shear flow behaviour of nanofluids and the investigation of their dynamic viscosities. A full thermophysical experimental characterization of MWCNT in PEG-400 nanofluids was performed by Marcos *et al.* [4], including rheological profile showing shear-thinning behaviour of these nanofluids. It was shown in this work the temperature dependence of dynamic viscosities of nanofluids well predicted by VFT equation. The modified Maron-Pierce equation, that takes into account the presence of aggregates, was able to correctly describe the evolution of dynamic viscosities with MWCNT content. A shear-thinning behaviour was reported by Ilyas *et al.* [5] for ultrastable diamond-thermal oil nanofluids that was correlated to Power law equation. In addition to proper prediction of dynamic viscosity

with temperature by VFT equation, the authors proposed a generalized two-variable correlation for modelling dynamic viscosity evolution with volume fraction and temperature. Ilyas *et al.* [6] also investigated the rheological behavior of hybrid nanofluid with different concentrations of diamond nanoparticles and graphene nanoplatelets dispersions in oil, and using a non-ionic surfactant. Similarly, a two-variable correlation is used to predict the evolution of dynamic viscosity of hybrid nanofluids with nanoparticles and temperature. Solar salt-based nanofluids containing SiO₂ nanoparticles were investigated by Navarette *et al.* [7] studying the impact of nanoparticles production methods on both stability and dynamic viscosity evolution of nanofluids. A classification was provided, from Newtonian to non-Newtonian nanofluids and enhancement in dynamic viscosity following the production method linked to the nanoparticles size distribution. The dynamic viscosity and stability under shear of few layer graphene based nanofluids were studied by Hamze *et al.* [8] in function of graphene content, temperature and surfactant type. The dynamic viscosity evolution, leading to Newtonian or non-Newtonian behaviour, was correlated to stability and visual aspect of samples after shear, and its evolution with temperature was well predicted by VFT equation. Moreover, the rheological behavior of Al₂O₃-pure coconut oil nanofluids was investigated by Sujith *et al.* [9] who reported shear-thinning properties for those nanofluids, such a trend being sensitive to nanoparticle content and temperature.

A second series of articles reported the viscoelastic properties of nanofluids, which are generally less studied than shear flow behaviour. First, Saez *et al.* [10] investigated hydrophilic gel containing graphene quantum dots and showed that the initial linear viscoelastic behaviour of gel is modified by the graphene because of the interactions between the polymer chains of the carbopol gels and the graphene quantum dots. In addition to dynamic viscosities, Żyła [11] evaluated the viscoelastic structure and thixotropy behaviour of nanofluids made of low fraction of carbon black nanoparticles in ethylene glycol. In particular, the transition from Newtonian to viscoelastic material with a yield stress for nanofluids in function of nanoparticle content is highlighted. Garcia and Saraji [12] investigated the rheological behavior of Al₂O₃ nanoparticle-enhanced viscoelastic surfactant solutions at high frequencies and various temperatures. Originally, the reported linear behaviour is well predicted by Continuous Maxwell model with a weak influence of nanoparticles on viscoelastic properties of the solutions. The shear and dynamic rheological properties of silica polymer nanofluids have been investigated by Chaturvedi and co-workers [13] for CO₂ capturing applications. Different particle sizes and concentrations were tested as

well as temperature change. A shear-thinning non-Newtonian behavior and viscoelastic nature was reported for all nanofluids, such a behavior being mainly influenced by concentration in nanoparticles and temperature.

Another series of papers are dedicated to magneto and electro-rheology of nanofluids, this kind of studies are pretty rare. There are also few papers that describe the thixotropic behavior of nanofluids in the available literature. Yang *et al.* [14] presented that thixotropy and magnetic field could lead to unusual magnetorheological behavior of the oil-based ferrofluids. This unusual behavior causes build-up of microstructures in the sample volume and their destruction with high value shear rate. He *et al.* [15] studied MnFe₂O₄/MgAl-LDH nanocomposites. They detailed the synthesis procedure of this composite and presented its characterization. They showed that fundamental rheological properties of this material (*i.e.* viscosity, loss and storage moduli) changes when magnetic field is applied. Magnetorheological behavior of MWCNTs/CoFe₂O₄ dispersed in silicone oil was described by Wang *et al.* [16]. Again, viscosity and viscoelastic structure of this nanofluid submitted to various values of magnetic field was presented and discussed. On the other hand, the influence of electric field on the rheological behavior of nanofluids was presented by Vu *et al.* [17] and Kutalkova *et al.* [18]. In Ref. [17], the authors described core-shell structured poly(*o*-toluidine)-decorated rice husk silica-based bio-composite and describes their rheological properties for various values of electric field up to 2 kV mm⁻¹. The paper by Kutalkova *et al.* focuses on the electrorheological behavior of silicon oil-based nanofluids containing high fractions of sepiolite nanoparticles. They showed that solid gel-like structure could be observed in these materials and applying electric field makes this structure stronger. Finally, the electro-rheological behavior of vanadium electrolyte-based electrochemical graphene oxide nanofluids was described by Aberoumand *et al.* [19]. This paper is particularly interesting, while those materials were designed for redox flow battery, they could find numerous applications in energy storage sector.

The last papers mainly focused on simulations development. The dynamic viscosity of carbon nanotubes water-based nanofluids was successfully modeled by Molecular Dynamics Simulations utilizing Green-Kubo method and considering both the influence of temperature and nanotubes content in the work of Razmara *et al.* [20]. As a main contribution, the impact of direction of SWCNT alignment on viscosity was highlighted and a new

viscosity model was proposed. Another Molecular Dynamic Simulation work focused on the impact of Al₂O₃ nanoparticles dispersed in super critical CO₂ generally used in Enhanced Oil Recovery. This numerical study was performed by Mahdavi *et al.* [21] using two force fields and charge optimization many body methods for investigating the influence of nanoparticle morphology and size, temperature on viscosity and self-diffusion coefficient of nanofluids.

We hope that the main results and critical discussions issued from these papers will be useful for the community. Finally, we are grateful to all the authors for their contributions and to all the reviewers for their diligent and valuable efforts in expertizing the submissions. Moreover, we would also thank the editors of Journal of Molecular Liquids for agreeing to publish this virtual special issue, especially Prof. Artur J.M. Valente (Editor-in Chief) for his support and input. Last but not least, we encourage the scientific community in pursuing theoretical, experimental and numerical studies in the field of nanofluid rheological properties, as many challenges and open questions still remain to explore and, we hope, to be solved.

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