Ionanofluids as Novel Fluids for Advanced Heat Transfer Applications

S. M. Sohel Murshed, C. A. Nieto de Castro, M. J. V. Lourenço, J. França, A. P. C. Ribeiro, S. I. C. Vieira and C. S. Queirós

***Abstract*—**Ionanofluids are a new and innovative class of heat transfer fluids which exhibit fascinating thermophysical properties compared to their base ionic liquids. This paper deals with the findings of thermal conductivity and specific heat capacity of ionanofluids as a function of a temperature and concentration of nanotubes. Simulation results using ionanofluids as coolants in heat exchanger are also used to access their feasibility and performance in heat transfer devices. Results on thermal conductivity and heat capacity of ionanofluids as well as the estimation of heat transfer areas for ionanofluids and ionic liquids in a model shell and tube heat exchanger reveal that ionanofluids possess superior thermal conductivity and heat capacity and require considerably less heat transfer areas as compared to those of their base ionic liquids. This novel class of fluids shows great potential for advanced heat transfer applications.

***Keywords*—**Heat transfer, Ionanofluids, Ionic liquids, Nanotubes, Thermal conductivity.

I. INTRODUCTION

THE term *ionanofluids* is defined as the suspensions of nanomaterials (particles, tubes and rods) in ionic liquids [1], [2] and it is a new term in multidisciplinary fields such as nanoscience, nanotechnology, thermofluid, chemical and mechanical engineering. Ionanofluids (INF) are basically a particular type of nanofluids (i.e., suspensions of nanoparticles in conventional heat transfer fluids) which is getting immense interest from the researchers due to their potential applications and benefits.

Since ionic liquids (IL) are the base fluids (BF) in ionanofluids, their thermophysical properties, potential benefits and applications also will be briefed before discussing about the ionanofluids. In the past decades, extensive research efforts have been devoted to ionic liquids which have proven to be safe and sustainable alternatives for many applications in industry and chemical manufacturing [3]-[12]. Their prospect and success arise mainly from their thermophysical and phase-equilibria properties, the versatility of their synthesis, and manageable to be tailored for a given application. Their solvent properties as well as heat transfer or heat storage and surface properties make this class of fluids possible to use in a high plethora of applications [5], [6]. Other advantages of ionic liquids include high ion conductivity, high volumetric heat capacity, high chemical and thermal stabilities, negligible vapor pressure, wide range of viscosity, and very good solvent properties [9]–[11]. Due to all of these fascinating characteristics they have been investigated extensively as alternatives to molecular solvents for liquid phase reactions [7]. Ionic liquids are of great interest to scientists, researchers as well as chemical companies, not only because of their remarkable properties, but also for their actual and potential applications in the chemical process industries. In the past, the values of their thermophysical properties were found to have significant effect on the design of physico-chemical processing and reaction units by influencing directly the design parameters and performance of equipments like heat exchangers, distillation columns and reactors [12]. However the optimal technological design of green processes requires the characterization of the ionic liquids used, namely their thermodynamic, transport and dielectric properties. Recently, our group has reported studies where measured data on various thermophysical properties of a wide range of ionic liquids are presented besides studying their potential application as heat transfer fluids as well as their properties measurement methods and uncertainties [2],[12]-[15]. Results from these studies indicate that ionic liquids possess promising thermophysical properties and great potential for numerous heat transfer related applications. However, the major drawback of ionic liquids at this moment is their high cost which will come down to manageable level with their industrial scale production in the future.

The innovation of *bucky gels*-nanomaterials (mostly nanocarbons) blended with ionic liquids, which can potentially be used in numerous engineering or chemical processing such as making novel electronic devices, coating materials, and antistatic materials, opens a completely new field [16], [17]. Thus, these *bucky gels* are actually nanocarbons-ionanofluids. The possibility of using ionic liquids containing dispersed nanoparticles with specific functionalization such as functionalized single-walled nanotubes (SWCNT), multi-walled nanotubes (MWCNT) and fullerenes (C60, C80 etc.) opens the door to many applications. The use of nanoparticles as heat transfer enhancers allows us to add small quantity of different types of nanomaterials to ionic liquids to prepare ionanofluids, which are highly flexible such that they can be designed in terms of molecular structure to achieve the desired properties necessary to accomplish a given task. This is possibly due to the

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complex interactions of ionic liquids and nanomaterials in the created complex emulsions. In contrast to nanofluids, ionanofluids are more flexible as their base ionic liquids can be prepared or designed for specific properties as well as for specific tasks (target-oriented). A representative picture of a ionanofluid containing MWCNT in $[C_4mim][NTf_2]$ ionic liquid is shown in Fig.1.

Fig. 1 Image of sample ionanofluids ($[C_4mim][NTf_2]$+MWCNT)

Recent studies performed by this group showed that ionanofluids containing MWCNT exhibit enhanced thermal conductivity (ranging from 2 to 35%) and specific heat capacity compared to their base ionic liquids [2], [18]. To the best of our knowledge, except researches conducted by this group, no other work on ionanofluids is available in the literature.

Based on the findings on temperature and concentration dependence of thermal conductivity and specific heat capacity, the potential applications of CNT-ionanofluids in advanced thermal management systems are evaluated in this paper. Results of a comparative study of using ionanofluids and their base fluids (i.e., IL) in heat exchanger are also reported. With these fascinating features such as high thermal conductivity, high volumetric heat capacity and non-volatile together with great flexibility of designing of ionanofluids for specific tasks and for particular properties, it can plausibly be considered that this novel class of fluids can potentially be use in advanced heat transfer applications.

II. Enhanced Thermal conductivity

Thermal conductivity of any liquid is the most important property that reveals its heat transport capability and most of the conventional fluids such as water, ethylene glycol and engine oil inherently possess poor values of thermal conductivity which greatly limit their cooling performance. Some early stage results on temperature and concentration dependence of thermal conductivity of MWCNT-ionanofluids from our group are presented and discussed in this section. The effect of concentration of MWCNT on the effective thermal conductivity of two ionanofluids in $[C_4mim][NTf_2]$ and $[C_2mim][EtSO_4]$ are illustrated in Fig. 2. It is seen that the effective thermal conductivity of ionanofluids (λ_{INF}) increases significantly (almost linear) over base ionic liquid with weight concentration of MWCNT. Fig. 3 presents thermal conductivity of $[C_2mim][EtSO_4]$-based ionanofluids as a function of temperature as well as concentration of MWCNT. Results showed (Fig. 3) that the thermal conductivity of this ionanofluid is fairly independent of temperature. The reasons for such temperature-independent nature of ionanofluids are not well understood at this moment. However, similar temperature independence of thermal conductivity of petroleum oil-based nanofluid was also reported in the literature [19].

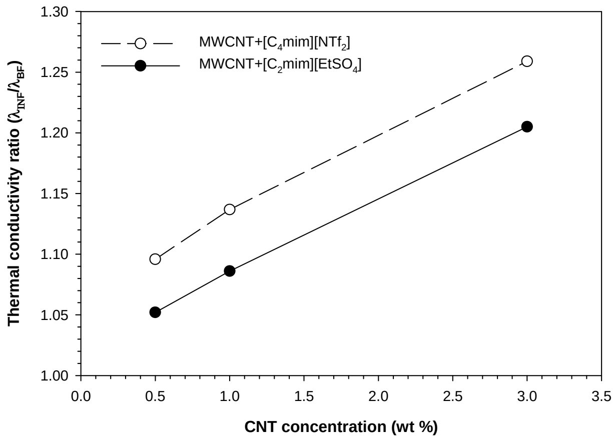

Fig. 2 Enhancement of thermal conductivity of ionanofluids as a function of CNT concentration at room temperature [18]

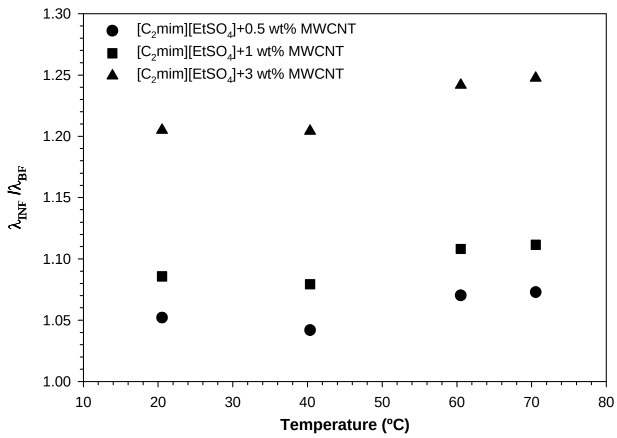

Fig. 3 Temperature-dependent thermal conductivity of ionanofluids [20]

III. Promising Heat Capacity

A. Ionic Liquids

Besides thermal conductivity, specific heat capacity of ionanofluids is of great importance for their practical applications in thermal system management and energy-based areas. The potential use of ionic liquids as heat transfer fluids particularly in heat exchanger in chemical plants and solar thermal power generation (from cryogenic temperatures up to 200 ºC) depends on the values of heat capacity, very low vapor pressures, thermal stability which have previously been presented [5] and will not be discussed here. However, comparisons of properties of ionic liquids with synthetic compounds (based on hydrocarbons, polyaromatics and siloxanes) showed that common imidazolinium systems have higher heat capacities per unit volume than the reported commercial thermal fluids such as Paratherm HE®and Dowtherm MX™ [12]. Fig. 4 illustrates that the volumetric heat capacities of several ionic liquids as well as high performance commercial heat transfer fluids (Dowtherm MX™ and Paratherm HE®) increase significantly and linearly with increasing temperature. It is noted that Dowtherm MX™ is a mixture of alkylated aromatics and Paratherm HE® is a paraffinic hydrocarbon. Similar increases in specific heat capacities of various ionic liquids with respect to temperature are also reported by Ge et al. [21]. It can be seen from Fig. 4 that the volumetric heat capacity of ionic liquids are higher than these commercial heat transfer fluids. It is, therefore anticipated that the specific heat capacity of ionanofluids will also increase with temperature.

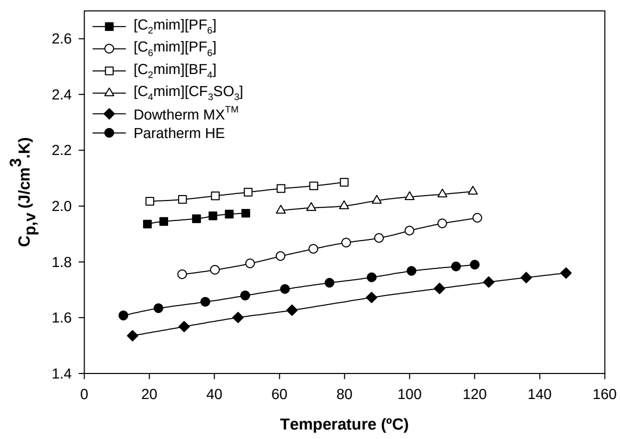

Fig. 4 Temperature dependence of volumetric heat capacity of several ionic liquids and heat transfer fluids

B. Ionanofluids

Fig. 5 depicts the effect of temperature on specific heat capacity of MWCNT-ionanofluids. As shown in Fig. 5, the specific heat of ionanofluids as well as base ionic liquid $[C_4mim][PF_6]$ increases significantly with increasing temperature. As anticipated the specific heat of ionic liquid found to increase almost linearly with temperature. However, the most interesting part of these results is that regardless of MWCNT loading there was dome-shaped jump of the specific heat capacity enhancement (a peak increase of 8% compared with base IL) at a certain temperature range (60 to 110 ºC).The reasons for such mysterious results are not well understood at this stage. There was little increase in specific heat capacity of ionanofluids with increasing loading of MWCNT. Nevertheless, any increase in heat capacity of such suspensions or fluids is of great importance for their practical applications as heat transfer fluids.

IV. Better Coolants for Heat Exchangers

Very recently a simulation study was performed to estimate the reference heat transfer area using two ionic liquids ($[C_4mim][NTf_2]$ and $[C_2mim][EtSO_4]$) and their ionanofluids containing 1 wt% of MWCNT under the same flow and other parameters in a model shell and tube heat exchanger as used in a previous study [12]. Thermophysical properties and simulated heat transfer areas for these ionic liquids and ionanofluids are shown in Table 1 [20]. It can be seen from Table 1 that maximum 2.5% decrease in reference heat transfer area (A_0) due to addition of 1 wt% of MWCNT in the base IL. This indicates that ionanofluids will perform better than ionic liquids in heat transfer devices like heat exchangers.

TABLE I
Thermophysical Properties and Reference Area (A_0) of Two Ionic Liquids and Their CNT-Laden Ionanofluids for the Shell and Tube Heat Exchanger

ILs and INFs	λ (W/m·K)	η (mPa·s)	Cp (J/kg·K)	A_0 (m^2)
$[C_4mim][NTf_2]$	0.1164	28.50	1372.44	364.63
$[C_4mim][NTf_2]$+ 1 wt% MWCNT	0.1290	31.58	1396.03	355.54
$[C_2mim][EtSO_4]$	0.1751	50.01	1614.96	383.89
$[C_2mim][EtSO_4]$+ 1 wt% MWCNT	0.1890	53.98	1642.72	376.13

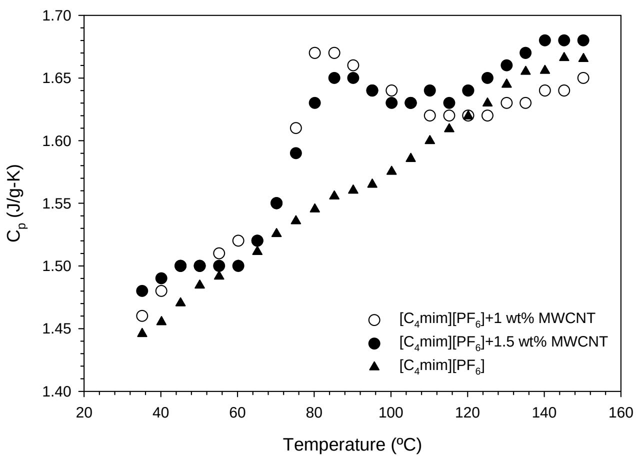

Fig. 5 Temperature-dependent heat capacity of CNT ionanofluids [12]

V. Conclusion

An overview of few important aspects of ionanofluids together with experimental findings on their thermal conductivity and heat capacity are presented in this paper. Besides presenting results on effective thermal conductivity and specific heat capacity ionanofluids as a function of temperature and concentration of MWCNT, simulated estimation of using ionanofluids as working fluids in a model heat exchanger are also reported to access their feasibility and performance in heat transfer devices.

Results showed that ionanofluids exhibit superior thermophysical properties compared to base ionic liquids and simulated results on heat transfer areas from a model study show a decrease in reference heat transfer area of a shell and tube heat exchanger due to addition of small quantity (1 wt%) of MWCNT in base ionic liquid. This indicates that ionanofluids are better heat transfer fluids for heat exchangers or other heat transfer devices than base ionic liquids. From the results presented and other findings from our pioneering researches it can be inferred that ionanofluids show great promises to be used as innovative and novel fluids in many advanced heat transfer applications. Nevertheless, more studies are imperative in order to better understand the heat transfer mechanisms as well as to exploit potential applications of this new class of fluids.

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