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Current research and future applications of nano- and ionano-fluids

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Abstract. An overview of several important aspects of nanofluids and ionanofluids, their background, as well as key experimental findings on their thermophysical properties is presented in this study. While nanofluids are prepared by dispersing nanoparticles in traditional heat transfer fluids, ionanofluids are engineered by dispersing nanoparticles in ionic liquids only. Some representative results of various thermal features and properties of both fluids are also briefly discussed. Although there are inconsistencies in experimental data from various groups, nanofluids possess significantly higher thermal conductivity, convective heat transfer coefficient and boiling critical heat flux compared to their base fluids and these properties further increase with increase concentration of nanoparticles. On the other hand, based on results from very limited studies ionanofluids are found to show superior thermophysical properties compared to their based ionic liquids. In addition, numerical results on heat transfer areas from a model study indicated that ionanofluids are better heat transfer fluids for heat exchangers or other heat transfer devices than ionic liquids. Future research direction and applications of these novel fluids are also outlined. Review reveals that both nanofluids and ionanofluids show great promises to be used as advanced heat transfer fluids and novel media for many thermal management systems as well as green solvent-based applications.

1. Introduction

Both nanofluids and ionanofluids represent new classes of heat transfer fluids. While the term nanofluids was coined by Steve Choi in 1995 [1], the concept of ionanofluids has recently been devised by Nieto de Castro and co-workers [2]. Nanofluids are prepared by dispersing nanometer-sized particles in traditional heat transfer fluids such as water, ethylene glycol and engine oil. On the other hand, ionanofluids that encompasses multiple disciplines such as nanoscience, thermofluid, chemical and mechanical engineering are engineered by suspending nanoparticles in ionic liquids (ILs) only. Since the inception of nanofluids in 1995, they have attracted great interest from the researchers worldwide due to their superior thermophysical properties and potential applications in numerous important fields such as microelectronics, micro-electromechanical systems, microfluidics, transportation, manufacturing, medical, and HVAC systems [3-5]. The overwhelming interest on nanofluids can be evidenced from reported exponential growth of annual research publications on nanofluids as shown in figure1. According to Web of Knowledge searched results (figure1), total 1323 nanofluid-related publications, which include all types of journal and conference articles, patent, news, letter and other, have appeared during the past 10 years (from January 1, 2001 to December 31, 2011)

and the average ISI citations per published item is as high as 10.24. There are more than 300 research groups and companies worldwide who are involved with nanofluids research [6].

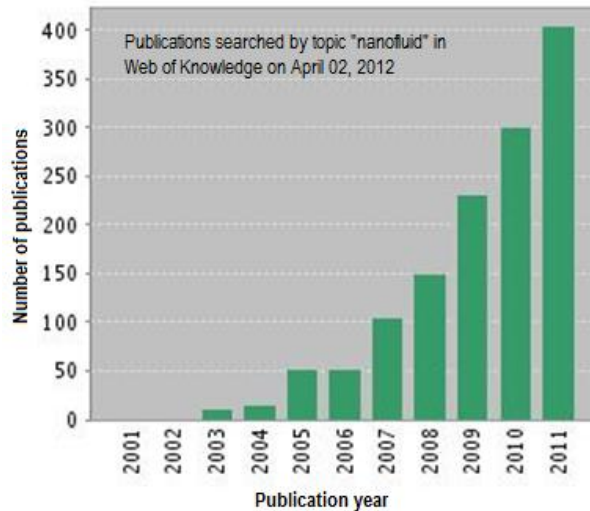


Figure 1. Annual publications on nanofluids.

On the other hand, as a recent topic ionanofluids research is still in its early stage and plenty of potentials to be explored. Recent studies of this group [7-8] showed that ionanofluids containing multi-walled carbon nanotubes (MWCNT) exhibit significantly higher thermal conductivity and specific heat capacity compared to their base ionic liquids and they further increase with temperature and loading of MWCNT.

Compared to studies on thermal conductivity, few works have been reported on boiling, convective heat transfer characteristics and other important aspects of nanofluids although such features are very important in order to exploit them as the next generation coolants. Although extensive research efforts have been made during the last decade, there remain inconsistencies and controversy in results and heat transfer mechanisms of nanofluids [3-5]. However, it is undisputed that nanofluids exhibit substantially enhanced thermal conductivity, convective heat transfer coefficient, and boiling critical heat flux and these clearly evince their potential as advanced coolants in the future. Thus, it is of great importance to review the key thermal features and potential applications of these two novel fluids.

2. Nanofluids research

2.1. Conductive and convective heat transfer

Nanofluids are believed to be the next generation heat transfer fluids. This is due to the exciting nanofluids research findings such as unusually high thermal conductivity and significantly enhanced flow and boiling heat transfer performances. However, research efforts to establish nanofluids as advanced coolants are still limited as researchers have mainly focused on their anomalously high thermal conductivity [3, 9]. In order to understand the magnitude of thermal conductivity enhancement, some key results of the effective thermal conductivity of nanofluids as a function of nanoparticle volume fraction obtained from various research groups are shown in figure 2. Although reported data are scattered and inconsistent, it can be seen (figure 2) that nanofluids exhibit much higher thermal conductivities (k_{nf}) compared to their base fluids (k_f) even when the concentrations of suspended nanoparticles are very low. For instance, it was reported in [10] that while thermal conductivity of water increased up to 60% due to dispersion of 5 volume% CuO (36 nm) nanoparticles in it, the thermal conductivity of HE-200 oil increased about 44% by dispersing only

0.052 volume % of Cu (35nm) nanoparticles in it. The enhanced effective thermal conductivity further increases significantly with increasing nanoparticle volume fraction as well as temperature.

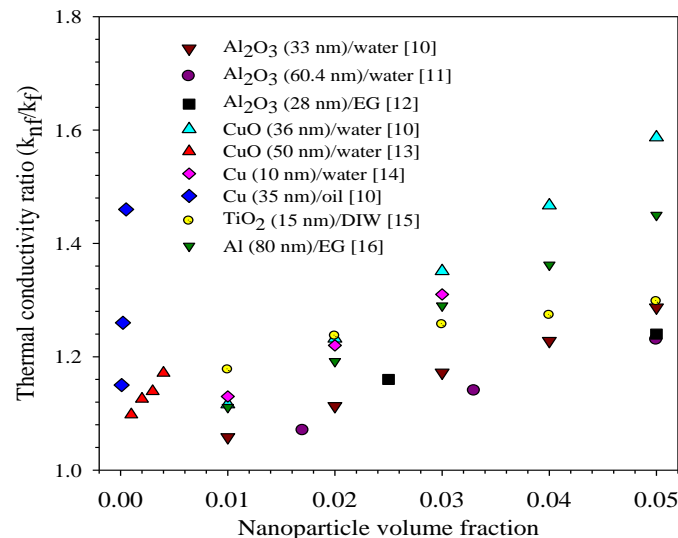


Figure 2. Thermal conductivity data of various nanofluids from literature.

Compared to reported works on static thermal conductivity, studies on convective heat transfer of nanofluids are still scarce. However, the practical applications of nanofluids as advanced fluids are mainly in flowing systems such as mini- or micro-channels and miniaturized heat exchangers. Some key results from the forced convective heat transfer studies of nanofluids are briefly discussed here.

The first study on convective heat transfer of nanofluids (e.g. γ -Al₂O₃/water) under turbulent flow conditions was performed by [17] and results showed that although the Nusselt number (Nu) increased with increasing nanoparticle volume fraction and Reynolds number, the heat transfer coefficient (h) actually decreased by 3-12%. Another study by [18] illustrated that the Nusselt number of Cu/water-based nanofluids increased significantly (about 60% for 2 volume%) with the loading of nanoparticles. The heat transfer behavior of nanofluids at the tube entrance region under laminar flow conditions was investigated by [19] and the local heat transfer coefficient was found to vary with particle volume fraction as well as Reynolds number (Re). Another convective heat transfer study with CuO and Al₂O₃/water-based nanofluids under laminar flow conditions was reported in [20] and heat transfer coefficient was found to increase considerably with particle volume fraction and Peclet number. A slightly higher (6–11%) heat transfer coefficient of TiO₂/water-based nanofluids compared to pure water under turbulent flow conditions was observed by [21] and this coefficient increases with increasing mass flow rate of the hot water as well as nanofluid.

A study on microchannel flow of aqueous CNT-nanofluids at Reynolds numbers between 2 to 17 was reported by [22] and significant increase in heat transfer coefficient of this nanofluid at CNT concentration of 4.4% was observed. Later, an investigation on heat transfer performance of Al₂O₃/water-based nanofluid in a rectangular microchannel under laminar flow condition was performed by [23] and the heat transfer coefficient was increased by more than 32% for 1.8 volume% of nanoparticles. The Nusselt number was found to increase with increasing Reynolds number in the flow regime of $5 > \text{Re} < 300$. A comparison of results of Nusselt number versus Reynolds number for both laminar and turbulent flow conditions from various research groups is presented in figure 3 which shows that the results from various groups vary widely.

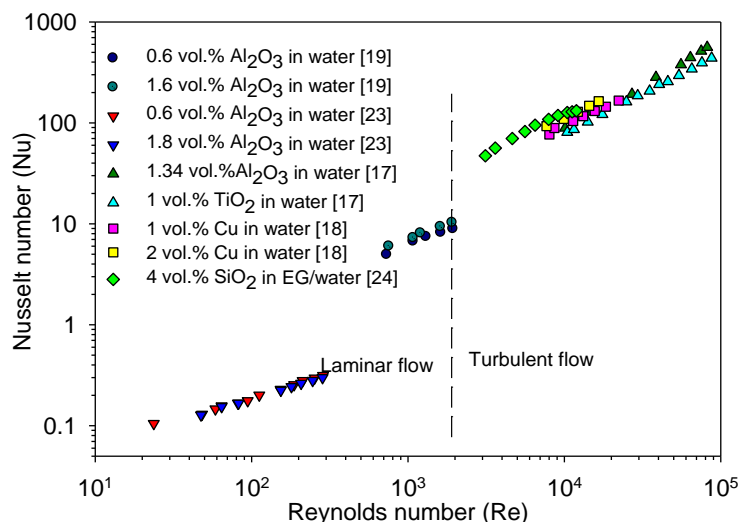


Figure 3. Comparisons of convective heat transfer results of nanofluids from literature.

2.2. Boiling heat transfer

Studies showed that the heat flux (critical) enhancement of nanofluids depend on various factors such as nanoparticle concentration, pH of the solution and the deposition of the nanoparticles on heater surface. It is long back proven that addition of solid particle in base fluid can alter its boiling heat transfer performance. For example, significant increase in pool boiling performance for very small volumetric concentrations (0.1-0.5%) of Al_2O_3 (50 nm) nanoparticles in water was reported in 1984 [25]. Recently, growing number of researchers have come forward to study the boiling heat transfer of nanofluids and some key findings are briefly reviewed here.

A study on pool boiling of for Al_2O_3 -water nanofluid heater performed by [26] showed a three-fold increase in critical heat flux (CHF) compared to water. Whereas another study by [27] reported deterioration of boiling heat transfer of same type of nanofluid and this outcome was partially attributed to the properties of the nanofluid, boiling surface and the interaction between the two. Like [26], results reported in [28] showed about 40% enhancement in boiling heat transfer of the same Al_2O_3 /water nanofluid at 1.25 weight % of nanoparticle.

An experimental investigation was reported [29] to quantify the effect of heater surface roughness on pool boiling heat transfer of Al_2O_3 /water-based nanofluids. While the rough heater surface increases heat transfer significantly (about 70% at 0.5 wt. % of Al_2O_3 nanoparticles), smooth surface actually deteriorates the heat transfer (45% at 2 wt.%) [29]. The pool boiling heat transfer performance of $\gamma\text{-Al}_2\text{O}_3$ (20-30 nm)/water and SnO_2 (55 nm)/water-based nanofluids under various heat flux densities was studied by [30] and except for >0.5 wt.% of SnO_2 nanoparticles, the boiling heat transfer coefficients of these nanofluids found to increase with the particle concentration. These paradoxical results were attributed to the differences in thermal conductivity and size of nanoparticles. Recently, another study on pool boiling experiments of several aqueous nanofluids with modification of sandblasted as well as bare plate heaters was reported by [31] and they showed up to 35% increase in CHF for pre-coated heaters compared to those of bare and sandblasted heaters.

A comparison of heat flux versus superheat results from various groups is shown in figure 4. It can clearly be seen from figure 4 that heat flux (also critical heat flux) data relative to superheat reported by various research groups vary widely. This is probably due to the differences in characterization of nanofluids, different size and concentration of nanoparticles used, different types of heaters used in various groups. Although some researchers observed deterioration of boiling heat transfer of nanofluids, the significant increase in the critical heat flux in boiling of nanofluid is still undisputed.

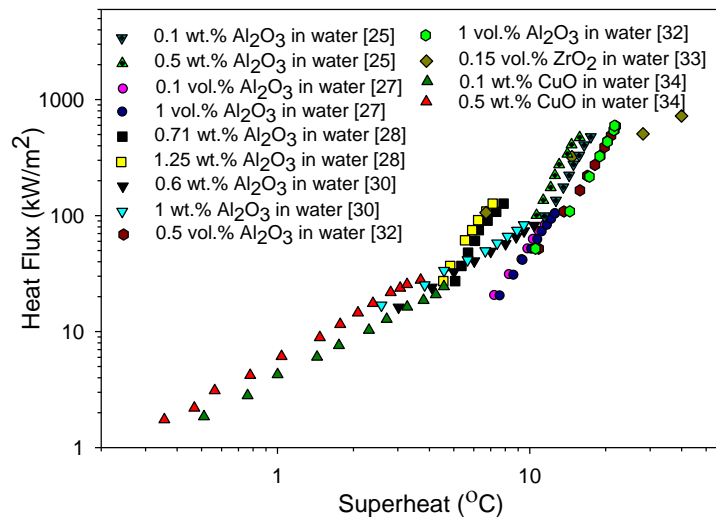


Figure 4. Comparison of heat flux data of pool boiling studies from literature.

3. Research on ionanofluids

Since the concept of ionanofluids is very new, except research works by this group, to our knowledge, only other group, also in Portugal, started to work on ionanofluids. Results from our primary studies [7-8] indicate that this novel fluid exhibits superior thermophysical properties compared to their base ionic liquids. For example, figure 5 demonstrates that at room temperature the effective thermal conductivity of two MWCNT-ionanofluids (k_{INF}) increase considerably and almost linearly (over base ionic liquids i.e., k_{BF} of $[\text{C}_4\text{mim}][\text{NTf}_2]$ and $[\text{C}_2\text{mim}][\text{EtSO}_4]$) with the concentration of MWCNT. Very recently, it has also been demonstrated [36] that at high temperatures MWCNT- $[\text{C}_2\text{mim}][\text{EtSO}_4]$ ionanofluids exhibits slightly higher enhancement in the effective thermal conductivity compared to MWCNT- $[\text{C}_4\text{mim}][\text{NTf}_2]$ for the same weight concentration of MWCNT. However, the effect of temperature on the enhancement of thermal conductivity of ionanofluids was not very significant.

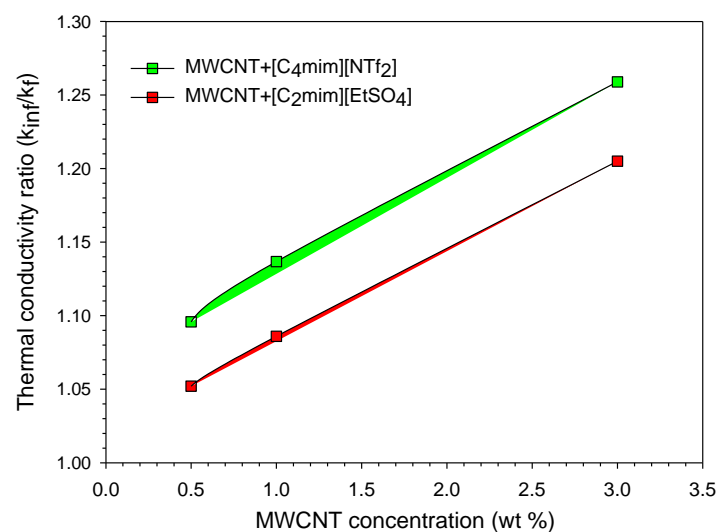


Figure 5. Thermal conductivity enhancement of ionanofluids as a function of MWCNT concentration [35].

Specific heat capacity of MWCNT-ionanofluids (c_{p-INF}) was also reported in our previous study [35] and the specific heat capacity of $[C_4mim][PF_6]$ -based ionanofluids was found to increase significantly (over base fluid, c_{p-BF}) with increasing temperature in the range of 50-90 °C (figure 6). Three distinct temperature ranges were observed where c_{p-INF} behaved very differently and the reason for such behaviour is not fully understood. There was also little increase in specific heat capacity of ionanofluids with loading of MWCNT. Nevertheless, any increase in heat capacity of such fluids is of great importance for their heat transfer-based applications.

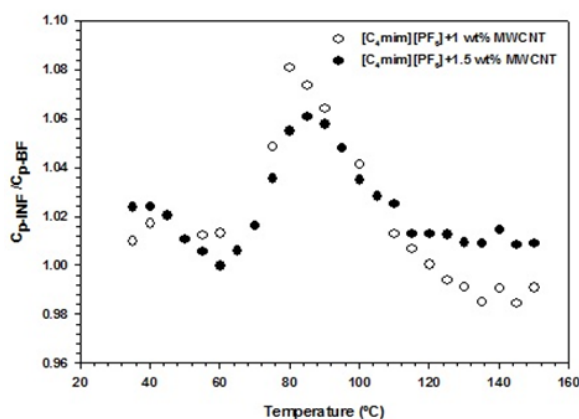


Figure 6. Effect of temperature and concentration on heat capacity of ionanofluids [35].

In order to estimate the reference heat transfer area using $[C_4mim][NTf_2]$ and $[C_2mim][EtSO_4]$ ionic liquids and their ionanofluids containing 1 wt% of MWCNT in a shell and tube heat exchanger a numerical study was conducted by [37]. Results showed that maximum 2.5% decrease in reference heat transfer area due to addition of 1 wt% of MWCNT in the base ILs. This indicates that ionanofluids perform better than ionic liquids in heat transfer devices like heat exchangers.

4. Potential benefits and applications

4.1. Nanofluids

Plenty of studies on increasing thermal conductivity of liquid by suspending small particles have been conducted more than a century back. However, all the studies were confined to suspensions of millimetre or micrometer-sized particles. The major problems of such suspensions are the rapid settling of these particles, clogging the flow channel, and increased pressure drop in the fluid. If the fluid is kept circulating rapidly enough to prevent much settling, these particles would damage the walls of the heat transfer devices and channels. Furthermore, milli- or micro-particles are too large for microsystems to be used. In contrast, nanoparticles remain in suspension reducing erosion and clogging. Thus, with dispersion of nanoparticle nanofluids can flow smoothly through mini- or micro-channels. Another advantage is that the nanoparticles weigh less and chances of sedimentation are also less making nanofluids more stable.

The impact of nanofluid technology is expected to be great, considering that the heat transfer performance of heat exchangers or cooling devices is vital in numerous industries. As mentioned before, when the nanoparticles are properly dispersed, besides anomalously high thermal conductivity, nanofluids offer numerous benefits, which include improved heat transfer and stability, microchannel cooling, miniaturized systems, and reduction in pumping power [3]. The better stability of nanofluids will prevent rapid settling and reduce clogging in the walls of heat transfer devices. The high thermal conductivity of nanofluids translates into higher energy efficiency, better performance, and lower

operating costs. They can reduce energy consumption for pumping heat transfer fluids. Nanofluids can make the thermal systems smaller and lighter.

With the aforementioned highly desirable thermal properties and potential benefits, it is believed that nanofluids have a wide range of applications. They can improve thermal management systems in many engineering applications including transportation, micro-electromechanical systems (MEMS), electronics and instrumentations, heating-ventilating and air-conditioning and in medical science. Furthermore, nanofluids can be used in various advanced cooling technologies such as spray cooling, mini- and micro-channels, and microfluidics [38-41]. Details of the potential applications of nanofluids have been discussed elsewhere [3-5] and is not elaborated further.

4.2. Ionanofluids

Results from our studies [7-8, 36] showed that ionanofluids containing MWCNT exhibit enhanced thermal conductivity and specific heat capacity compared to their base ionic liquids, a fact confirmed by [42]. These properties further increase with concentration of nanoparticles and fluid temperature in some extent. Other attractive features of ionanofluids are that they are designable and fine-tuneable through their base ionic liquids for desired properties and tasks. With these fascinating features including high thermal conductivity, high heat capacity, non-volatile, designable and green solvent, ionanofluids can be used as advanced heat transfer fluids in numerous cooling technologies, chemical engineering and green energy based applications. One fascinating area of application for ionanofluids is that they could be used for the development of new pigments for solar energy-based applications.

5. Conclusions

In this study, an overview of several important thermal features of nanofluids and ionanofluids, their background, as well as key experimental findings on their thermophysical properties is reported. Some representative results of various important features and properties such as thermal conductivity, specific heat capacity, convective heat transfer coefficient (only nanofluids) and boiling heat flux (only nanofluids) of these fluids are also presented and discussed. Review showed that nanofluids possess significantly higher thermal conductivity, convective heat transfer coefficient and boiling critical heat flux compared to their base fluids and these properties further increase with increase concentration of nanoparticles. Thus, nanofluids are already considered to be the next generation heat transfer fluids. However, there remain inconsistencies in experimental data from various groups as well as controversy in heat transfer mechanisms of nanofluids. Based on findings from limited studies, ionanofluids are found to exhibit superior thermophysical properties compared to base ionic liquids. Simulated results on heat transfer areas from a model study also indicate that ionanofluids are better heat transfer fluids for heat exchangers or other heat transfer devices than ionic liquids.

In summary, both nanofluids and ionanofluids show great promises to be used as advanced heat transfer fluids and novel media for many thermal management systems as well as green energy-based applications. These are newly emerging fluids and more extensive investigations are to be performed in order to explore many more uncovered potential applications and benefits of these fluids.

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