Renewable and Sustainable Energy Reviews 91 (2018) 584–599

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review on development of ionic liquid based nanofluids and their heat transfer behavior

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ARTICLE INFO

Keywords:
Ionic liquid
Nanoparticles
Ionic liquid based nanofluids
Laminar flow
Heat transfer
Thermophysical properties

ABSTRACT

Ionic liquids are an innovative class of fluids having a wide range of potential applications from chemical industries and processes to energy harvesting particularly in solar power plants. Also, these liquids are non-flammable and non-volatile at ambient conditions and recyclable, and are also considered as green fluids. All these important features make them as new alternatives in many applications. Adding nanoparticles to these ionic liquids gets to a new challenging area, which is a special type of nanofluids, termed "ionanofluids". This review summarizes recent research and development in this innovative area and tries to assess all results by comparing them on the same numerical basis. Although literature results are scattered, they demonstrate that ionanofluids possess great potential in many new and advanced applications particularly related to thermal management and energy harvesting. Literature findings of these new fluids were also implemented in computational fluid dynamics in order to analyze their behavior at thermal systems. Results are very interesting in demonstrating their possible usage for heating and it also underlies the large uncertainty that exists in characterizing thermophysical properties of these new fluids. Nonetheless research on ionanofluids is very important and tremendous efforts are needed in order to fully describe these new heat transfer fluids and to explore their potential in wide range of applications.

1. Introduction

Ionanofluids, which are an innovative class of new fluids, are suspensions of nanoparticles in ionic liquids (ILs). Thus, ionanofluids (INFs) are a special type of nanofluids. Since ILs are the only base fluids for ionanofluids, it is important to briefly highlight the main characteristics, advantages as well as potential applications of ILs first. Ionic liquids are also an innovative class of fluids, which consist entirely of ions and have the melting point lower than 100 °C [1]. Recently the development of room temperature ionic liquids (RTILs) have attracted tremendous interest from researchers and industrial people due to their low melting temperatures (< 30 °C) which allows these host fluids for INFs to be used in wide range of applications [2].

Ionic liquids exhibit several unique features that allow to develop and synthesize new heat transfer fluids by tailoring the cation-anion structure for desired physiochemical properties and thus for the target applications. As these liquids are not combustible or volatile at ambient conditions and are also recyclable they are considered as environmental-friendly fluids [3,4]. ILs also have extremely low vapor pressure, high thermal stability as well as high heat capacity, and the combination of these features makes these fluids better heat transfer media at low or very low pressures or even under vacuum conditions. In fact, due to these features, ILs have been investigated as heat transfer media even from the beginning of the 21-st century. Some studies [e.g., 5] also suggested that, due to their very low vapor pressure preventing them to be cooled by evaporations, ILs can be used for thermal energy storage in an open system. Thus, ionic liquids are a good medium for thermal storage systems as well as heat transfer fluids in solar power generation applications.

ILs can also be used as heat transfer fluids in heat exchange systems such as conventional heat exchangers. For instance, due to their high heat capacity and thermal conductivity França et al. [6] studied ILs as possible heat transfer fluids in a shell and tube heat exchanger. The heat transfer areas were estimated to be comparable or even bigger for ILs as compared to some usual heat transfer fluids. It was later demonstrated that the combination of nanomaterials and ILs show great potential as heat transfer fluids through the enhancement of the thermal properties [7]. Abumandour et al. [8] demonstrated that water mixed ILs can be used in absorption heat transformers as well.

Apart from the heat transfer and various thermal management

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https://doi.org/10.1016/j.rser.2018.04.021
Received 28 June 2017; Received in revised form 1 November 2017; Accepted 9 April 2018
1364-0321/

Nomenclature

C	heat capacity
c_p	specific heat
D	hydraulic diameter
h	heat transfer coefficient
k	thermal conductivity
L	channel length
P	dimensionless pressure
p	pressure
Pr	Prandtl number
r	radius
R	non-dimensional tube radius
Re	Reynolds number
T	temperature
q	wall heat flux
u, v, w	velocity components, m/s
u_∞	average velocity for inlet flow
U	dimensionless tangential velocity
V	dimensionless radial velocity
W	dimensionless axial velocity,
x, y, z	cartesian coordinates
X, Y, Z	non-dimensional coordinates

Greek symbols

θ	cylindrical coordinate
φ	volume fraction of particles
ρ	density
μ	fluid dynamic viscosity
Θ	dimensionless temperature

Subscripts

b	bulk
bf	refers to base-fluid (i.e. ionic liquid)
eff	effective
nf	refers to ionanofluid property
p	particle
r	refers to “nanofluid/base-fluid” ratio
w	wall

Abbreviations

CFD	computational fluid dynamics
HTC	heat transfer coefficient
IL	ionic liquid
INF	ionanofluid (ionic liquid based nanofluids)

systems, ILs can be implemented in an extensive range of techniques and systems such as catalysis [9], synthesis [10], solar absorbing panels [11], lubricants [12,13], absorption refrigeration systems [14], solid liquid separation process [15], and supercritical fluids [16]. ILs can be also used as the solvent system and as the reactant/catalyst in a reaction process [17]. There are numerous other potential applications of ILs [1,3,4].

Some of the key advantages of ionic liquids are listed as follows:

- good solvents for a large variety of materials
- high solubility
- large working temperature range (−40 to +200 °C)
- non-volatility
- no vapor pressure
- designability
- potential to catalyze certain reactions

In 2007, Fukushima and Aida [18] were the first to mix high concentration of carbon nanotubes (CNT) in ionic liquids at room temperature to form gels named as “bucky gels” that can have potential applications in many engineering or chemical processes. These “Bucky gels” are actually emulsions of ionic liquids with nanomaterials and they are basically the CNT ionanofluids of high concentration. Since then numbers of research works [19–52] were performed in this new area of ionanofluids and the most tremendous research works in this area [e.g., 19–21,28,31–33,37,38] have been accomplished by a group (Nieto de Castro and co-workers) from Universidade de Lisboa, Portugal, who in fact coined the term “ionanofluids”.

Only research related to thermophysical properties of ionanofluids will be deeply discussed in this review because it mainly focuses on heat transfer aspects of these new fluids. It is also noted that research on other areas of these new fluids has yet to receive noticeable attention from researchers.

Sheveylyova et al. [22] studied $[C_4mim][BF_4]$ and $[C_4mim][PF_6]$ ionanofluids with multi-walled carbon nanotubes (MWCNT) of around 12 wt% concentration, and demonstrated a maximum enhancement of heat capacity of 8% and their results were similar with the results obtained by Nieto de Castro et al. [19,21], but with a lower concentration of nanoparticles. In regard to viscosity of INFs, the results are not consistent and sometimes are contradictory as detailed in the next sections. For instance, Visser et al. [24] found that $[C_4mim][N(SO_2C_2F_5)_2]$ with MWCNT had the highest increase in viscosity and affirmed that this occurrence appear because of the nanoparticles interaction with the ionic liquid cations and anions. Other research was found to be contradictory in terms of rheological behavior of ionanofluids. Compared to efforts on viscosity more studies were done on thermal conductivity and the results were encouraging in terms of the increase in thermal conductivity due to loading nanoparticles in to the base ionic liquid [29,30].

Chaban and Fileti [40] used all-atom molecular dynamics simulation to illustrate the transfer mechanisms within nanodiamonds, carbon nanotubes, and *N*-butylpyridinium tetrafluoroborate ionic liquid and demonstrated that the heat transfer in the enhanced liquid is much pronounced compared to that in the pure base ionic liquid.

In a different study, Deb and Bhattacharaya [41] investigated the influence of ionic-liquid-tethered Al_2O_3 nanoparticle on the non-isothermal cold crystallization in ionic-liquid-based nanofluids and concluded that the chained nanoparticles within the ionanofluids act as heterogeneous nucleation agent, thus diminishing the free energy obstruction to nucleation.

Moganty et al. [42] discussed a very new class of silica ionogels prepared by dispersing silica nanoparticles in SpmImTSFI which was further dispersed in host BmpyrTFSI ionic liquids. Their research was focused on a large temperature range and crystallization of the host IL was suppressed by addition of SiO_2-SpmImTSFI in it. They also suggested a new approach of having hybrid ionic fluids with improved thermal and mechanical properties.

On another hand, Wang et al. [43] prepared ionanofluids with gold nanoparticles and studied both experimentally and theoretically their thermal conductivity. They concluded that the viscosity of the base ionic liquid is of major importance on the thermal behavior of the ionanofluid.

Copper oxide based ionanofluids were studied by Swadzba-Kwasny et al. [44]. They performed an experimental analysis of physical properties using classical methods (i.e. spectroscopy, TGA, DSC, densitometry) but did not provide information on viscosity and thermal conductivity.

Other recent articles [48,49] reported the so called “bucky gels” at a