International Journal of Thermal Sciences 82 (2014) 84–99

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Mass transfer in nanofluids: A review

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ARTICLE INFO

Article history:
Received 7 September 2013
Received in revised form
20 March 2014
Accepted 26 March 2014
Available online 7 May 2014

Keywords:
Nanofluid
Transfer processes
Mass transfer
Mass diffusivity

ABSTRACT

Growing attention has been recently paid to nanofluids because of their potential for augmenting transfer processes – i.e., heat and mass transfer. Conflicting results have been reported in the literature on mass transfer in nanofluids. The aim of this paper is to summarize the literature on mass transfer in nanofluids stating the conflicts and possible reasons. Literature on mass transfer in nanofluids has been reviewed in two sections. The first section concentrates on surveying mass diffusivity in nanofluids while the second section focuses on convective mass transfer in nanofluids. In each section, published articles, type of nanofluids used, size and concentration range of nanoparticles, measurement methods, maximum observed enhancement, and suggested mass transport mechanisms are summarized.

1. Introduction

Nanoparticle colloids have particular physical properties that make them useful for a wide range of applications including paints and coatings, ceramics, drug delivery and food industries [1–5]. Colloids composed of ultrafine nanoparticles (~100 nm or smaller) are called nanofluids [5]. Growing attention has been recently paid to nanofluids because of their enhancement in heat transfer [5–11]. This desirable characteristic opens numerous applications of nanofluids as super-coolant in nuclear reactors, car engines, radiators, computers, X-rays and many other industrial products. Nanofluids are called super-coolant because they can absorb heat more than any traditional fluids, so they can reduce the size of system and increase its performance [5,12].

Oxide ceramics (Al_2O_3, CuO); nitride ceramics (AlN, SiN); carbide ceramics (SiC, TiC); metals (Ag, Al, Au, Cu, Fe); semiconductors (SiO_2, TiO_2); single, double, or multi wall carbon nanotubes (SWCNT, DWCNT, MWCNT); and composite materials such as nanoparticle core–polymer shell composites are certain materials which are used to produce nanoparticles and are dispersed in a host liquid to make the nanofluid. Water is used as a traditional host liquid due to its high thermal conductivity, abundance, low cost, and friendliness to the environment [12].

Although by adding nanoparticles to the base fluid, the reduction in heat transfer coefficient has also been observed, most studies show enhancement in heat transfer. To interpret enhancement, different mechanisms such as Brownian motion of nanoparticles and induced microconvection, thermal diffusion, increased conduction through aggregates, or particle-to-particle coupling through the interparticle potentials, liquid layering on the nanoparticle–liquid interface and reduction in thermal boundary layer thickness have been reported [11–13].

Since some researchers considered Brownian movement of nanoparticles as one of the major responsible factors in the enhancement of heat transfer, investigation of mass transfer enhancement in nanofluids with similar mechanism has been initiated [13–15]. Investigations on mass transfer in nanofluids can be divided into two main groups. The first group of studies deals with studying diffusion coefficients in nanofluids and the second group of studies focuses on studying convective mass transfer coefficients in nanofluids [16].

Mass diffusion is a molecular phenomenon refers to the diffusive transport of a species due to concentration gradients in a mixture. But, convective mass transfer occurs whenever fluid flows; that is, some mass is transferred from one place to another by the bulk fluid motion [17]. Most investigations on mass transfer in nanofluids have attempted to the second group and there are limited researches focusing on mass diffusivities in nanofluid systems. The greatest diffusivity enhancement has been reported by Fang et al. [18]. They found that the diffusion coefficient of Rhodamine B in Cu–water nanofluid with 0.5% Cu nanoparticle volume fraction is 26 times greater than that in the base fluid at 25 °C [18]. Another group described observations of a 14-fold increase in diffusion coefficient of fluorescein dye in an aqueous

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http://dx.doi.org/10.1016/j.ijthermalsci.2014.03.017
1290-0729/

suspension of Al_2O_3 nanoparticles with nanoparticle concentration of 0.5 vol% (volume fraction). If such mass diffusion enhancements are proved, it opens up numerous additional applications for nanofluids where mass diffusion is important. For example, many microfluidic devices, such as "lab-on-a-chip" type of systems, have limited mass transfer at low Reynolds numbers. If the mass transfer can be improved by passive, nonreacting nanoparticles, a convenient and inexpensive technique to improve the performance of microfluidic devices will be achieved [13]. Also, such results increase the possibility of manipulating the mass diffusion to accelerate micromixing processes [5,18–20].

The results of mass diffusion coefficients obtained by various researches are inconsistent. Some groups have reported enhancement in mass diffusion by addition of nanoparticles to the base fluid [13,18,21] while some observed reduction in diffusion coefficient [22,23] or no enhancement [5,24,25]. These conflicting results show that more researches are required to obtain reliable experimental data and understand the mechanism of mass transport in nanofluids [24].

For the second group studies of mass transfer in nanofluids (convective mass transfer), enhancements in nanofluids have been reported for a variety of nanoparticle types and nanoparticle concentrations. In this group of studies, by increasing nanoparticle concentration, mass transfer enhancement in the presence of different kinds of nanoparticles have been mostly reported, with the highest enhancement observed for carbon dioxide mass transfer, 48 times larger into water in the presence of 1% volume fraction of iron oxide nanoparticles [25,26].

The values of observed enhancements in mass diffusion coefficient and convective mass transfer coefficient in nanofluids are much greater than the reported values of enhancement in heat transfer studies. This shows the importance of dealing with studying the influence of nanoparticles on mass transfer and presenting mechanisms which are able to predict such enhancements.

Although some review papers have been published on heat transfer in nanofluids [12,27–30], but mass transfer in nanofluids have not been reviewed yet. It is clear that such review paper provides the possibility of better comparison between the results of various researches in the field of mass transfer in nanofluids and can be very useful for future studies to achieve the reliable experimental data and to elucidate the reasons and mechanisms behind mass transport in nanofluids. So, this paper reviewed researches which have studied mass transport in nanofluids. In this work, researches on diffusion coefficient and convective mass transfer coefficient in nanofluids are reported in separate sections. In each section, performed studies, type of nanofluids, size and concentration range of nanoparticles, mass transfer measurement method, maximum observed enhancement and suggested mass transport mechanisms are pointed out.

2. Mass diffusion coefficient in nanofluids

This section focuses on studying mass diffusion coefficient in nanofluids. In 2006, research in this field was initiated by Krishnamurthy et al. [13], who studied mass diffusion of fluorescein dye in nanofluids by taking time-dependent images [14]. They visualized dye diffusion in water-based nanofluids with 20-nm Al_2O_3. In their work, nanofluids were prepared by dispersing Al_2O_3 nanoparticles in deionized water for volume fractions from 0.1% to 1%. By postprocessing the images obtained from their experiments, they determined the diffusion coefficient of dye in nanofluids based on the mean displacement of the dye. They observed that the diffusion coefficient of fluorescein dye in the nanofluid was greater than that in deionized water, with a maximum 14 times enhancement in the diffusion coefficient of dye at a nanoparticle volume fraction of 0.5% relative to in deionized water [13].

Based on an order-of-magnitude analysis, they suggested that the velocity disturbance field in the fluid, created by the Brownian motion of nanoparticles can be responsible for such enhancement. They assumed that with increasing nanoparticle volume fraction there is a greater possibility for particle aggregation, producing in effect larger, more massive particles with reduced capacity to increase localized convection and mass diffusion [13].

Similar to Krishnamurthy et al.'s observation [13], Fang et al. [18] also reported extraordinary enhancement in diffusion coefficient because of the presence of nanoparticles. They performed experiments on mass diffusion of fluorescent Rhodamine B in Cu–water nanofluids with different nanoparticle volume fractions (0.1–0.5%) and different temperatures (15, 20, and 25 °C). They designed an optical experimental system to measure the diffusion coefficient of Rhodamine B in the nanofluid using Taylor dispersion method. By processing the fluorescence images of Rhodamine B diffusing over time and based on the mean square displacement of the dye, they obtained the diffusion coefficient of Rhodamine B in nanofluid [18]. Their results showed that Rhodamine B diffused faster in nanofluids compared to that in water and enhancement in diffusion coefficient increased with increasing nanoparticle volume fraction. They observed the maximum 26 times enhancement in the diffusion coefficient of Rhodamine B in Cu–water nanofluid with nanoparticle concentration of 0.5 vol% compared to that in the base fluid at 25 °C. They interpreted that the presence of nanoparticles promotes mass transport inside the nanofluid similar to energy transport enhancement phenomenon as the result of created microconvection by Brownian motion of suspended nanoparticles. Based on their conclusion, increase in the nanoparticle volume fraction further enhances the intensity and frequency of the microdisturbance inside the suspension and leads to increasing the diffusion coefficient or thermal conductivity of nanofluids [18]. Moreover, Fang et al. [18] argued that higher suspension temperature leads to stronger Brownian motion of nanoparticles and more intense microconvection inside the nanofluid, which further enhances energy and mass transfer processes inside the suspension [18].

In 2009, contrarily to the mentioned observations, Turanov and Tolmachev [22] found reduction in mass diffusion coefficient by adding nanoparticles to the base fluid. Using the pulsed field gradient nuclear magnetic resonance (PFG NMR) method, they determined the solvent self-diffusion coefficient in aqueous suspensions of quasi-monodisperse spherical silica nanoparticles [22].

They measured the self-diffusion coefficient by means of Stejskal–Tanner sequence (90°–s–180°–s echo) with PFGs [31] for nanofluids with 3.8–23% nanoparticle volume fraction and at temperature of 20 °C [22]. Turanov and Tolmachev [22] observed that self-diffusion coefficient in aqueous suspensions of spherical silica nanoparticles decreased with increasing nanoparticles volume concentration. They found that this decrease was faster than prediction by the effective medium theory and discussed that this deviation can be explained by interaction of water with the silica particles and water retention by the nanoparticles [22].

In agreement with Turanov and Tolmachev's results [22], Gerardi et al. [23] also observed decrease in mass diffusion in the presence of nanoparticles. They measured the self-diffusion coefficient of water in the aqueous suspension of Al_2O_3 nanoparticles for concentrations up to 6% nanoparticle volume fraction at 25 °C. In their work, the diffusion coefficient was measured using a pulsed gradient stimulated echo sequence with bipolar gradients, also known as the Cotts 13-interval pulse sequence [23,32].

Gerardi et al. [23] observed that the diffusion coefficient decreased with increasing nanoparticle concentration. They concluded that the reduction was due to two effects: first, the