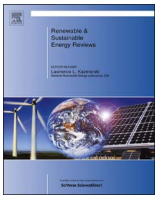
Renewable and Sustainable Energy Reviews 68 (2017) 185–198

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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



Hybrid nanofluids preparation, thermal properties, heat transfer and friction factor – A review

L. Syam Sundar[a,*], K.V. Sharma[b], Manoj K. Singh[a,**], A.C.M. Sousa[a]

[a] TEMA-Department of Mechanical Engineering, University of Aveiro, 3810-193 Aveiro, Portugal
[b] Department of Mechanical Engineering, J.N.T. University, Hyderabad, India

ARTICLE INFO

Keywords:
Hybrid nanofluids
Thermal properties
Heat transfer
Friction factor
Enhancement

ABSTRACT

In the past decade, research on nanofluids has been increased rapidly and reports reveal that nanofluids are beneficial heat transfer fluids for engineering applications. The heat transfer enhancement of nanofluids is primarily dependent on thermal conductivity of nanoparticles, particle volume concentrations and mass flow rates. Under constant particle volume concentrations and flow rates, the heat transfer enhancement only depends on the thermal conductivity of the nanoparticles. The thermal conductivity of nanoparticles may be altered or changed by preparing hybrid (composite) nanoparticles. Hybrid nanoparticles are defined as nanoparticles composed by two or more different materials of nanometer size. The fluids prepared with hybrid nanoparticles are known as hybrid nanofluids. The motivation for the preparation of hybrid nanofluids is to obtain further heat transfer enhancement with augmented thermal conductivity of these nanofluids. This review covers the synthesis of hybrid nanoparticles, preparation of hybrid nanofluids, thermal properties, heat transfer, friction factor and the available Nusselt number and friction factor correlations. The review also demonstrates that hybrid nanofluids are more effective heat transfer fluids than single nanoparticles based nanofluids or conventional fluids. Notwithstanding, full understanding of the mechanisms associated with heat transfer enhancement of hybrid nanofluids is still lacking and, consequently it is required a considerable research effort in this area.

1. Introduction

The single phase heat transfer fluids such as water, engine oil, ethylene glycol, propylene glycol and transformer oil are mainly used in process industries, chemical and thermal power plants. The heat transfer performance of single phase heat transfer fluids, in general, is very poor due to the low values of their thermal conductivity. The heat transfer intensification is very important to achieve significant energy and cost savings. Therefore, one possible route is increase the thermal conductivity of the working fluids. As it is well-known, solid materials possess higher thermal conductivity when compared to single phase fluids. The addition of solid particles to the single phase fluids technique was first proposed by Maxwell [1], who observed enhanced thermal conductivity values. However, the simple dispersion of solid particles in single phase fluids leads to their sedimentation and consequent clogging of the flow passages; moreover, the particles cause erosion on the flow passage walls, while increasing the pressure drop across the installations. Later on, Masuda et al. [2] dispersed micrometer size solid particles in single phase fluids and observed thermal conductivity enhancement, but also faced particle sedimentation in the base fluid, which reduces the enhancement in thermal conductivity. In 1995, Choi [3] prepared nanofluids (fluids containing nanometer size solid particles) and observed marked enhancement of thermal conductivity. The dispersion of nanometer size particles in single phase fluids presents higher specific surface area than conventional colloidal suspensions and is more stable than conventional slurries.

The commonly used nanoparticles are metals – e.g., Cu, Au, Ag, and Ni; metal oxides – e.g., Al_2O_3, CuO, Fe_2O_3, Fe_3O_4, SiO_2, TiO_2, and ZrO_2; metal carbides (SiC), metal nitrides – e.g., AlN, and SiN; carbon materials – e.g., carbon nanotubes, graphite, and diamond. The preparation of nanofluids using different kind of nanoparticles along with their convective heat transfer performance has been reported by many researchers. Pak and Cho [4] conducted heat transfer and friction factor experiments for Al_2O_3/water and TiO_2/water nanofluids in the Reynolds number range from 10^4 to 10^5 and the particle concentration ranging from 0% to 3% and observed heat transfer enhancement compared to the base fluid (water); they also propose newly-developed Nusselt number correlation. Later on, Xuan and Li [5] used Cu/water

---

* Corresponding author.
** Corresponding author.
E-mail addresses: sslingala@gmail.com (L.S. Sundar), mksingh@ua.pt (M.K. Singh).

http://dx.doi.org/10.1016/j.rser.2016.09.108
Received 9 March 2016; Received in revised form 28 August 2016; Accepted 25 September 2016
1364-0321/

and Cu/transformer oil nanofluids and observed heat transfer enhancements as compared to the base fluids. In another study, Xuan and Li [6] observed heat transfer enhancement of 60% for 2.0% volume concentration of Cu/water nanofluid flowing in a tube at a Reynolds number of 25000 and they report separated Nusselt number correlations for laminar and turbulent flow, respectively. Wen and Ding [7] conducted heat transfer experiments for Al_2O_3/water nanofluid in a tube under laminar flow and they observed heat transfer enhancement of 47% at 1.6% volume fraction as compared to the base fluid (water). Heris et al. [8] also used Al_2O_3/water nanofluids in a tube under laminar flow and observed heat transfer enhancement using constant wall temperature boundary conditions. Williams et al. [9] reported convective heat transfer enhancement with alumina/water and zirconia/water nanofluids flow in a horizontal tube under turbulent flow. Duangthongsuk and Wongwises [10] found heat transfer enhancement of 20% and 32% for 1.0% vol of TiO_2/water nanofluid flowing in a tube at Reynolds numbers of 3000-18000, respectively. Ghozatloo et al. [11] obtained heat transfer enhancement of 35.6% at a temperature of 38 °C for 0.1 wt% of graphene/water nanofluids flow in a tube under laminar flow. Sundar et al. [12] found heat transfer enhancement of 30.96% with a pumping penalty of 10.01% for 0.6% vol of Fe_3O_4/water nanofluid flow in a tube at a Reynolds number of 22000. Sundar et al. [13] observed heat transfer enhancement of 39.18% with a pumping penalty of 19.12% for 0.6% vol of Ni/water nanofluid flow in a tube at a Reynolds number of 22000. Other researchers have also observed heat transfer enhancement using different kinds of nanofluids. The examples are – Amrollahi et al. [14], Wang et al. [15], Ding et al. [16] used CNT nanofluids, Sajadi and Kazemi [17] used TiO_2 nanofluids, Ghazvini et al. [18] used diamond/engine oil nanofluids, Xuan and Li [19] used Cu/water nanofluids, Ferrouillat et al. [20] used SiO_2/water nanofluids, Guo et al. [21] obtained significant heat transfer rates by using Fe_2O_3/water nanofluids. There is a considerable body of experimental data about heat transfer enhancement with different nanofluids, which is well summarized in review articles published during the past decade [22–28].

The researchers have consistently observed higher heat transfer rates with different kinds of nanofluids (among others, Al_2O_3, Cu, CuO, Fe_3O_4, Fe_2O_3, CNT, nickel, nanodiamond, TiO_2, and SiO_2) flow in a tube under laminar or turbulent flow conditions. The heat transfer enhancement of nanofluids depends on particle concentrations, thermal conductivity of nanoparticles and mass flow rates. The thermal conductivity of nanoparticles may be altered or changed by synthesizing the hybrid (nanocomposite) nanoparticles and it is expected that fluids prepared with hybrid nanoparticles may cause further heat transfer enhancements. The hybrid nanoparticles may be defined as two or more different materials in the nanometer size; hybrid nanoparticles represent an area of nanotechnology, which is experiencing a marked growth due to its potential impact in material science and engineering. For the preparation of hybrid nanofluids there are different available methods, which enable the synthesis of hybrid nanoparticles; the use of the most common methods is succinctly reviewed in what follows. Jia et al. [29] used the hydrothermal method, Zhang et al. [30] used the solvothermal method and Shi et al. [31] used the polyols method for the synthesis of CNT/Fe_3O_4 hybrid nanoparticles. Guo et al. [32] used sonication and sol-gel chemistry technique for the synthesis of silica (Si) coated carbon nanotube (CNTs) coaxial nanocables. Li et al. [33] prepared CNT/SiO_2 and CNT//SiO_2/Ag hybrid nanoparticles using plasma treatment. Baby and Ramaprabhu [34] used the simple chemical reduction technique for the preparation of silicon dioxide (SiO_2) coated on magnetite (Fe_3O_4) particle doped multi-walled carbon nanotubes (MWCNTs) (Fe_3O_4@SiO_2/MWCNTs) hybrid nanoparticles.

The available literature is relatively scarce in what concerns the preparation of hybrid nanofluids and the determination of their thermal properties, heat transfer and friction factor. Suresh et al. [35] prepared Al_2O_3-Cu hybrid nanofluids and obtained heat transfer enhancement of 13.56% for 0.1% vol at a Reynolds number of 1730, while Madhesh et al. [36], with Cu-TiO_2 hybrid nanofluids, obtained heat transfer enhancement of 52% for 2.0% vol Sundar et al. [37] prepared nanodiamond-nickel (ND-Ni) nanocomposite (hybrid) nanofluids and determined experimentally the thermal conductivity and viscosity. Sundar et al. [38] also prepared MWCNT-Fe_3O_4 hybrid nanofluids and found heat transfer enhancement of 31.10% with a pumping penalty of 18% for 0.3% vol at a Reynolds number of 22000. These studies clearly indicate that hybrid nanofluids yield higher heat transfer enhancement than single nanoparticles-based nanofluids. However, to fully understand the hybrid nanofluids mechanisms enhancing heat transfer, further experiments and analyses will be required.

The present review deals with hybrid nanofluids, which have the potential of making an important contribution to heat exchange equipment cost reduction by increasing its effectiveness and consequently making it smaller and lighter. In addition, an increased effectiveness may lead to substantial worldwide energy savings. Therefore, it will be presented an overview of synthesis and characterization of different hybrid nanoparticles, preparation of hybrid nanofluids and also the state of ongoing research work enabling the use of hybrid nanofluids and current challenges. It will be also reviewed and discussed their thermo-physical properties, heat transfer, friction factor and the available Nusselt number and friction factor correlations.

2. Types of hybrid (nanocomposite) materials

Depending on the metal matrix, the hybrid (composite) materials can be divided into three types. (a) Metal matrix nanocomposites – the examples are, among others, Al_2O_3/Cu, Al_2O_3/Ni, MgO/Fe, Al/CNT, Mg/CNT, Al_2O_3/Fe-Cr, and ND/Ni, (b) Ceramic matrix nanocomposites – the examples are, among others, Al_2O_3/SiO_2, Al_2O_3/TiO_2, SiO_2/Ni, CNT/Fe_3O_4, Al_2O_3/SiC, and Al_2O_3/CNT, (c) Polymer matrix nanocomposites – the examples are, among others, polymer/layered double hydroxides, polymer/CNT, thermoplastic/thermoset polymer/layered silicates, and polyester/TiO_2.

The materials used for metal matrix nanocomposites (MMNC) are, for example, Ag (silver), Al (alumina), Au (gold), Cu (copper), Fe (iron), nanodiamond (ND), Ni (nickel), Mg (magnesium), and Sn (tin).

The materials used for ceramic matrix nanocomposites (CMNC) are, among others, Al_2O_3 (aluminum oxide), CuO (copper oxide), Fe_2O_3 (hematite), Fe_3O_4 (magnetite), NiO (nickel oxide), SiC (silicon carbide), SiO_2 (silicon oxide), TiO_2 (titanium oxide), and ZnO (zinc oxide).

The materials used for polymer matrix nanocomposites (PMNC) are, in general, vinyl-polymer, ethylene vinyl-alcohol, poly-vinyl chloride, polyethylene, and poly-propylene.

The materials used for carbon-based nanocomposites are typically: single walled carbon nanotubes (SWCNTs), multi walled carbon nanotubes (MWCNT), graphite (G), and graphene oxide (GO). The commonly used synthesis techniques for nanocomposites are chemical, mechanical (ball-milling), and vapor deposition (physical, chemical). For all the cases, the hybrid (nanocomposites) particles size should be less than 100 nm.

3. Synthesis of hybrid (nanocomposite) nanoparticles

There are several techniques available for the synthesis of hybrid nanoparticles. Suresh et al. [35,39] used the thermo-chemical synthesis technique for the preparation of Al_2O_3-Cu hybrid nanoparticles using $Cu(NO_3)_2{\cdot}3H_2O$ (copper nitrate) and $Al(NO_3)_3{\cdot}9H_2O$ (aluminum nitrate) reagent grade chemicals. Sundar et al. [38] prepared MWCNT/Fe_3O_4 hybrid nanoparticles using the in-situ and chemical co-precipitation method. Batmunkh et al. [40] employed the ball milling technique for the synthesis of Ag-TiO_2 nanoparticles. Baby and Ramaprabhu [41–43] used catalytic chemical vapor deposition