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A comprehensive review of preparation, characterization, properties and stability of hybrid nanofluids

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ABSTRACT

Nanofluids are emerging as promising thermo fluids for heat transfer application. Nano fluids are two phase fluids of solid liquid mixture. The presence of solid nanoparticles in the base fluid increases significantly the effective thermal conductivity of the fluid and consequently enhances the heat transfer characteristics. Addition of single nanoparticle in base fluid, to improve the flow and heat transfer characteristics of the base fluid is a proven technology. In recent years, attention is focused on research studies involving impregnation of two or more nanoparticles in base fluids, called hybrid or composite nanofluids. Research studies on nanofluid containing composite nanoparticle showed better enhancement in thermal and rheological characteristics of base heat transfer fluid compared to mono nanoparticle based nanofluids. The research studies carried out on preparation, characterization, properties and stability of hybrid nanofluids are comprehensively reviewed in this paper. The models for properties such as thermal conductivity, viscosity, density, specific heat, friction factor and heat transfer coefficient of hybrid nanofluids are presented. The potential application and the challenges including stability methods and measures for hybrid nanofluids are discussed.

1. Introduction

Nanofluid, a term coined by Stephen U.S. Choi, is an engineered colloidal suspensions of nanometer-sized particles (called nanoparticles) in a base fluid. Nanoparticles have thermal conductivities, typically an order-of-magnitude higher than those of the base fluids and with sizes significantly smaller than 100 nm [1]. Addition of these nanoparticles in base fluids increases thermal conductivities considerably as compared to those of conventional heat transfer fluids, and hence nanofluids promise to be a potential heat transfer fluid with enhanced heat transfer. The advantages of properly engineered nanofluids are (i) higher thermal conductivities than that predicted by currently available macroscopic models (ii) excellent stability and (iii) negligible penalty in pumping power due to pressure drop and pipe wall abrasion [2]. Researchers have used different types of nanoparticles such as metallic particles (Cu, Al, Fe, Au, and Ag) [3–7], non-metallic particles (Al_2O_3, CuO, Fe_3O_4, TiO_2, and SiC) [8–12] and carbon nanoparticle [13]. Enhancement in heat transfer and flow characteristics of different nanofluids are reported by many researchers in the recent past [14–22]. The authors have reviewed the reported research studies on single nanofluids, i.e. base fluid with single nanoparticle, covering the preparation, characterization, properties, applications and challenges [23]. Very recently, in order to improve further the heat transfer characteristics, impregnation of two or more nanoparticles in base heat transfer fluids is the subject of many heat transfer research studies. A new kind of nanofluid, which is prepared by suspending two different types of nanoparticles named hybrid or nanocomposite particles in basefluid is called hybrid or nanocomposite fluid. A hybrid nanoparticle is a substance which combines physical and chemical properties of different nanoparticles simultaneously and provides the properties in a homogeneous phase. Synthetic hybrid nanoparticles exhibit a remarkable physicochemical property that does not exist in the individual particles [24]. Hence, hybrid nanofluids are observed to have higher thermal conductivity compared with the single nanofluids containing the individual nanoparticles separately. Hence, this paper focuses on reviewing the hybrid nanofluid research works in order to understand the new technology and to identify the issues so as to address them in future through advanced research works to make this technology commercially viable. Reported theoretical, numerical and experimental works on single nanofluid show that there are many potential applications of nanofluids such as cooling in electronics, cameras, microdevices, displays, heat exchangers, spacecraft, military equipments, ships, medicine, nuclear reactors, sensors, and fuel cells [25]. Since, a hybrid nanofluid shows better heat transfer enhancement than single nanofluids, importantly where heat transfer rate is of very much importance such as electronic cooling, heat exchanger, pool

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boiling, etc. So far a few research works have been done with regard to the application of hybrid nanofluid. Also, being a new technology, there are only a few thermo-physical properties and heat transfer parameters models developed for hybrid nanofluids also discussed in this paper. The objective of the present study is to comprehensively review the reported research works on preparation, characterization techniques, properties and their models of hybrid nanofluids to help the researchers to understand and apply the new technology in heat transfer systems. A section on stability of hybrid nanofluid, a key challenge which hinder the wide spread applications of nanofluid in general, is presented covering the methods of enhancing and estimating the stable dispersion of nanoparticles in the base fluid.

2. Preparation of hybrid nanofluids

Nanofluids are prepared either by one-step or two-step method. In one-step method, nanoparticles are suspended in a base fluid directly and mainly by means of chemical methods [17]. In the case of two-step method, nanoparticles are prepared first in the form of powders by physical or chemical methods, and then suspended in a base fluid [26]. The main objective of hybrid nanofluids is to obtain the properties of its constituent materials. A single material does not possess all the favorable characteristics required for a particular application; it may either have good thermal properties or rheological properties. But in many practical applications, it is required to trade-off between several properties. Hybrid nanofluid can come in handy in such situations, the hybrid nanofluid is expected to yield better thermal conductivity compared to individual nanofluids due to synergistic effect. Niihara [27] and Oh et al. [28,29] demonstrated the fabrication of Al_2O_3–Cu nanocomposite prepared from fine Al_2O_3 and CuO nano sized powder mixtures. Nanocomposites proposed by them had a new material design concept and significantly improved mechanical and thermal properties. Jena et al. [30] have explained the synthesis of Cu– Al_2O_3 nanocomposites from chemically prepared CuO– Al_2O_3 mixtures using hydrogen reduction technique. Thermochemical method has been used by Korac [31] and Andic et al. [32,33] to synthesize nanocomposite (Cu-Al_2O_3) powder, as a transient component, soluble nitrates of copper and aluminium, Cu $(NO_3)_2{\cdot}3H_2O$ and Al $(NO_3)_3{\cdot}9H_2O$. The synthesis process to form nanocomposite, according to Andic et al. [33], consist of four important stages: spray drying, heat treatment, reduction and homogenization. Jana et al. [34] added CNTs with different volume fractions in water to produce CNT suspensions. AuNP (gold nanoparticle) colloid was added to deionized water to produce AuNP suspension. AuNP was added to CNT suspensions with different volume fraction of CNTs to achieve CNT–AuNP suspensions. In CuNP (copper nanoparticle) suspensions, the ingredients were laurate salt and deionized water. Laurate salt was added for stability of CuNPs in suspension. A Bransonic Ultrasonic Cleaner was used as a low-power sonication to disperse the nanoparticles into water. Addition of CNTs into CuNP nanofluid reduced the sedimentation of CuNPs. The suspensions of hybrid nanoparticles were sonicated for 1 h. Ho et al. [35,36] used interfacial poly condensation together with emulsion technique in preparation of PCM (Phase change material) suspension. The core PCM in the micro encapsulated PCM particles is *n*-eicosane which was emulsified in water-soluble urea–formaldehyde per-polymer solution without deliberately added emulsifier. The PCM suspension was formulated by mixing appropriate quantities of micro encapsulated PCM particles with ultra-pure Milli-Q water in a flask and then dispersing in an ultrasonic vibration bath for at least two hours. Next water-based nanofluid was prepared by dispersing Al_2O_3 nanoparticles of various mass fractions in ultra-pure Milli-Q water using a magnetic stirrer. Then, the hybrid water-based suspensions were formulated by mixing the nanofluid with PCM suspension in an ultrasonic vibration bath for at least two hours. Paul et al. [17] synthesized Al–Zn nanoparticles by mechanical alloying. They have taken elemental powders of aluminium (95%) and zinc (5%) and blended by mechanical alloying at room temperature using a high energy planetary ball mill. They have milled the powder blend for the desired period of time to reach to steady state (when the composition of powder blends to become uniform). Then finally prepared the hybrid nanofluids by two-step process by adding ultra-fine Al–Zn nanoparticles in appropriate quantity in ethylene glycol (base fluid) and subjecting the resultant mixture to ultrasonic vibration followed by magnetic stirring.

Suresh et al. [37] synthesized nanocrystalline alumina–copper hybrid (Al_2O_3–Cu) powder by a thermochemical synthesis method which consists of the following stages: spray-drying, oxidation of precursor powder, reduction by hydrogen and homogenization. Soluble nitrates of copper and aluminium, Cu $(NO_3)_2{\cdot}3H_2O$ and Al $(NO_3)_3{\cdot}9H_2O$ were the starting materials. The water solution of the above mentioned salts was first prepared. The proportions of the precursor salts were decided so that the relative proportion of alumina and copper oxide in the powder mixture was to be 90:10. They prepared solution then spray dried at 180 °C to obtain the precursor powder. The precursor powder was then heated at 900 °C in air atmosphere for 60 min to form a powder mixture of copper oxide and stable Al_2O_3. The alumina–copper oxide powder mixture thus formed was heated at 400 °C for one hour in hydrogen atmosphere using a tubular furnace. The powder sample was placed in an alumina boat and then kept in a horizontally placed alumina tube of the furnace which was heated by silicon carbide heating elements. The CuO was preferentially reduced in hydrogen to metallic copper whereas Al_2O_3 remains in the unchanged form. The powder mixture was finally ball milled at 400 rpm for 1 h for obtaining a homogeneous Al_2O_3–Cu nanocomposite powder. Al_2O_3–Cu/water hybrid nanofluids with volume fractions from 0.1% to 2% were prepared by dispersing a specified amount of Al_2O_3–Cu nanoparticles in deionized water with sodium lauryl sulfate (SLS) as a dispersant by using an ultrasonic vibrator generating ultrasonic pulses of 180 W at 40 kHz. To get a uniform dispersion and stable suspension, which determine the final properties of nanofluids, the nanofluids were kept under ultrasonic vibration continuously for 6 h. They prepared nanofluid with different volume concentrations of nanoparticles (0.1%, 0.33%, 0.75%, 1% and 2%).

Baby et al. [38] synthesized CuO decorated graphene (CuO/HEG) by hydrogen induced exfoliation of graphite oxide (GO) followed by chemical reduction. The synthesized HEG was functionalized with acid treatment and further used for coating CuO nanoparticles. A calculated amount of CuO/HEG was dispersed in the base fluid (Deionized (DI) water or ethylene glycol) by ultrasonication for duration from 45 min to 1 h. The hybrid nanofluids containing silver and silica nanoparticles were prepared by Botha et al. [39] following one-step method and synthesized with particle size distribution of 5.5 ± 2.4 nm supported on silica, and the nano oil, a mixture of transformer oil and silver-silica nanoparticles. They reported that CuO decorated graphene have high thermal conductivity and excellent electrical insulating properties for ideal nano oil. Silica was mixed together with the base fluid by means of magnetic stirring and allowed to stir at 130 °C. Since high temperature could lead to oxidation of the oil and hence the reductions of Ag+ ions to Ag by electron transfer reaction.

Sundara Ramaprabhu [40] employed a novel synthesis method for silver decorated functionalized hydrogen induced exfoliated graphene (Ag/HEG) and preparation of nanofluids by dispersing the material. Ag/HEG in deionized water and ethylene glycol using ultrasonic agitation and proper dispersion is achieved without any surfactant and the synthesized nanofluid is stable for more than three months. The as-synthesized HEG was impossible to disperse in polar solvents. The presence of carboxyl and hydroxyl functional groups helps for proper dispersion. Therefore as-synthesized HEG was functionalized for proper Ag coating and dispersion. The synthesized HEG was functionalized in 3:1 H_2SO_4:HNO_3 acid medium. HEG was ultrasonicated in the acid medium for 3 h and later the sample was washed,