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Synthesis, characterization, and thermal property measurement of nano-$Al_{95}Zn_{05}$ dispersed nanofluid prepared by a two-step process

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ABSTRACT

Nanofluids are stable suspension of nanometer sized particles and exhibit extremely attractive thermal properties that make them a potential candidate for application in heat transfer devices ranging from microelectronic gadgets to thermal power plants. In the present study, we have synthesized Al-5wt%Zn nanoparticles by mechanical alloying, characterized these nanoparticles using X-ray diffraction and scanning and transmission electron microscopy. Subsequently, these nanoparticles are dispersed to the tune of 0.01–0.10 vol% in ethylene glycol (base fluid) following a careful mixing protocol. Thermal conductivity of the nanofluids and base fluid has been measured using the transient hot-wire method. It is observed that thermal conductivity of the nanofluids strongly depend on the concentration, particle size, fluid temperature and stability of dispersed nanoparticles in the base fluid. A maximum of 16% enhancement in thermal conductivity has been recorded at a nanoparticle loading of 0.10 vol%. Unlike data reported in some articles, thermal conductivity ratio of Al-5wt%Zn dispersed ethylene glycol based nanofluids is observed to decrease with the increase in crystallite/grain size of the particles.

1. Introduction

Heat transfer (heating/cooling) constitutes an essential and integral part of microelectronic devices, manufacturing machines, power generation, functioning of automobiles, etc. The efficiency of heat transfer devices depends on the performance of the cooling fluid in operation. Improving the heat transfer characteristics of a coolant fluid has always been a major objective in thermal engineering. The conventional heat transfer fluids, namely water, ethylene glycol or engine oil have limited thermal conductivity which in turn restricts the efficiency of the heat transfer devices. In order to enhance the thermal properties of heat transfer fluids, dispersion of solid particles having orders of magnitude higher thermal conductivity to the base fluid is an option explored several times in the past. However, the milli- or micro-sized particles dispersed in the fluids pose problems of sedimentation, clogging of channels, and erosion. The lack of stability of such suspensions induces additional flow resistance. Hence, fluids dispersed with coarse-grained particles have not been successful or commercialized. The advent of nanotechnology provides new opportunities to synthesize ultra-fine particles in nanometric sizes (10–500 nm). About a decade ago it was demonstrated that fluids with suspended nanoparticles, forming a stable colloid and maintaining a quasi-single phase state, called nanofluids can offer extra-ordinary level of heat transport property at very low amount of nanoparticle loading (<1 vol%) [1]. Nanocrystalline solids are mono or polycrystals with crystallite size or coherence length at least in one direction less than 100 nm because of which these particles possess large number of atoms/molecules at the surfaces/interfaces and exhibit unusual and novel properties absent in their coarse grained and equilibrium counterparts of same composition. While properties of nanometric solids are intensely researched and exploited, mechanism of heat transport in nanofluid is not yet established or well understood. However, it is well known that the advantages of dispersing nanoparticles lie in better stability compared to those fluids containing micro- or milli-sized particles and higher thermal conductive capability than the base fluids themselves [2].

A considerable amount of research has been done by several research groups across the globe to investigate the thermal properties of nanofluids. Zhu et al. [3] have studied the effect of pH and stability of nanofluids prepared by dispersing alumina (Al_2O_3) in base fluid water and reported a maximum increase of 10.1% in

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thermal conductivity of the nanofluids for a particle loading of 0.15 wt%. Kim et al. [4] have studied the effect of size on thermal conductivity of TiO_2 and ZnO dispersed in water and ethylene glycol based nanofluids which show a linear decrease in thermal conductivity ratio of nanofluids (with respect to base fluid) with the increase in size of the nanoparticles. In another study, Kim et al. [5] have studied the effects of convective heat transfer coefficient and thermal conductivity of Al_2O_3 and amorphous carbonic nanoparticles dispersed in base fluid water. The convective heat transfer coefficient and thermal conductivity was found to increase by 15% (laminar), 20% (turbulent), and 8% for 3 vol% of Al_2O_3 dispersed nanofluids. For amorphous carbon dispersed nanofluids, no increment in thermal conductivity was observed, whereas the convective heat transfer coefficient was seen to increase by only 8% in the laminar regime. Hwang et al. [6] have prepared nanofluids by dispersing carbon black in water and silver in silicon oil and studied the stability of the nanofluids. It has been observed that the nanofluids prepared by the two-step procedure using a high pressure homogenizer showed good amount of stability for about 60 days. Chen et al. [7] have prepared titanate nanotubes and dispersed them in water to form stable nanofluids which exhibit an increment of ~3% of thermal conductivity at 25 °C and ~5% at 40 °C with 2.5 wt% of nanotube loading. Timofeeva et al. [8] have studied the thermal conductivity and viscosity of Al_2O_3 nanoparticles dispersed in water and ethylene glycol both experimentally and theoretically. Experiments with metal oxide nanoparticles like nano-Al_2O_3/TiO_2/CuO have been carried out by Wu et al. [9], Li and Kleinstreuer [10], Abu-Nada [11], Sharma et al. [12], Hwang et al. [13], Karthikeyan et al. [14], Lee et al. [15], Murshed et al. [16], Mintsa et al. [17], and Choi et al. [18] to investigate the influence of the thermo-physical properties of nanoparticles on the degree of enhancement of thermal conductivity in the concerned nanofluid. Several other groups have synthesized and characterized nanofluids dispersed with pure metals such as Cu, Au, Ag, etc. [19–23]. Chopkar et al. [24] have measured the thermal conductivity of $Al_{70}Cu_{30}$ and $Al_{70}Ag_{30}$ nanoparticle dispersed water/ethylene glycol based nanofluid using the thermal comparator device. All these studies indicate that the type and size of nanoparticles, concentration of dispersion and temperature of fluid strongly affect the thermo-physical properties of the nanofluids.

It appears that most of the earlier studies have been conducted with nanofluids containing metallic oxides and other compounds and a very few with pure nanometric metallic particles. Chopkar et al. [24–26] have explored the scope of thermal property enhancement in water and ethylene glycol based nanofluid by dispersing aluminium alloy nanoparticles in relatively higher (0.5–2.0 vol%) concentration, which adversely affected the stability of particle dispersion. Aluminium and its alloys are light, cheap, good thermal conductor and easily available. However, though synthesizing pure aluminium in nanometric form is extremely difficult, Al-alloy particles can be conveniently synthesized by mechanical alloying, which is a solid state ambient temperature processing technique that allows synthesis of alloys in nanometric particle or crystallite size by subjecting an appropriate elemental powder blend to high energy ball milling [27].

Among the metallic elements with high thermal conductivity (Cu, Ag, Al, Au, Pt), Al is relatively cheap, easily available and significantly lighter (than say, Cu). However, Al is too ductile to undergo particle/grain size reduction to nanometric length only by mechanical milling/attrition. Earlier, mechanical alloying of Cu or Ag with Al was effective to produce Al-rich single phase solution with nanometric particle/grain size [24–26]. In this study, a similar alloy (Al-5wt%Zn) is synthesized to explore if Al-based single phase nanoparticles dispersed in conventional heat transfer fluids like ethylene glycol can reproduce identical level of enhancement of thermal conductivity as in the earlier reported nanofluids of identical nature or constitution. Following mechanical alloying, the Al-5wt%Zn nanoparticles are characterized to indentify the phase, particle/crystallite size, shape/morphology and purity using standard diffraction, microscopic and spectroscopic techniques. After characterization, Al-5wt%Zn nanoparticles are dispersed in ethylene glycol (base fluid) in an appropriate quantity following ultrasonic vibration and magnetic stirring to prepare nanofluids by a two-step process. Two sets of Al-5wt%Zn dispersed ethylene glycol based nanofluids are prepared, one set by varying the concentration of the dispersed nanoparticles (at the smallest particle/crystallite size) and the other set by varying the particle/crystallite size of the nanoparticles (keeping the concentration of the dispersed nanoparticles constant). The thermal conductivity is measured using the transient hot-wire method as a function of concentration and size of the dispersed nanoparticles, fluid temperature and stability time of dispersed nanoparticles in nanofluids. It may be pointed out that Al-5wt%Zn alloy is a new material to be used as a dispersoid for nanofluid preparation. The level of enhancement recorded in the present study at a much lower concentration surpasses earlier studies with comparable systems. Finally, the temperature dependence of Al-alloy dispersed nanofluids surpasses the data reported in earlier studies [28,29] and stability of dispersion have not been studied earlier.

2. Experimental

2.1. Synthesis of nanoparticles

Nanoparticles were synthesized following the mechanical alloying route which allows production of homogeneous powder mass of ultrafine or nanometric particles with mono or poly crystalline microstructure starting from elemental powder blend of desired proportion [30]. The actual process of mechanical alloying begins with mixing the powders in right proportion, loading the same along with grinding balls in closed containers or vials, and placing the vials on the sun disc of the planetary mill. Elemental powders of aluminium and zinc (99.9% purity) were taken and a blend of Al-5wt%Zn was subjected to mechanical alloying at room temperature using a high energy planetary ball mill with WC medium (vials and balls) at 300 rpm and 10:1 ball to powder weight ratio. The milling was carried out in wet medium using toluene to prevent undue oxidation, agglomeration of powders, and coating of the balls and vials with the powder. This powder blend was milled for the desired period of time until a steady state was reached when the composition of every powder particle was the same as the proportion of the elements in the starting powder mix and the average particle or crystallite size reached a saturation limit of reduction. Samples at intermediate regular time intervals were taken out for characterization and thermal conductivity measurement purpose.

2.2. Characterization of nanoparticles and preparation of nanofluids

The synthesized nanoparticles were characterized using X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM) and energy dispersive spectroscopy (EDS) to identify the phase, particle/crystallite size, shape/morphology and purity. Identity and particle/crystallite size of the phases were determined by using a BRUKER XRD with a scan speed of 0.05°per minute and Co–K_α (0.179 nm) radiation. The crystallite/grain size and the lattice strain were calculated from the Scherrer equation using the full peak width at half maximum (FWHM) by separating the X-ray peak broadening contributions due to the Gaussian and Cauchian factors after subtracting the broadening due to strain and instrumental errors [31]. The size,