Review of Stability & Effective Utility of Nanofluids in Advance Heat Transfer Applications

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ABSTRACT

Recent advancements in the field of nanotechnology have originated the new emerging heat transfer fluids called nanofluids . Nanofluids contain both the properties of better heat conductivity and greater convective heat transfer capability with respect of its base fluids. Because of enhanced properties, better heat transfer performance is obtained in a variety of energy and heat transfer devices as compared to traditional fluids. Here we tried to put our efforts on the study of recent progress of nano-fluid regarding its stability and the ways to enhance it, effective utilization of nanofluids in advance heat transfer tools as heat transfer fluid. Nanofluids are potential heat transfer fluids with enhanced thermo-physical properties and heat transfer performance can be applied in many devices for better performances (i.e. energy, heat transfer performances etc).

Keywords: *Nanofluids, two-phase system, thermal diffusivity.*

1. INTRODUCTION

Nanofluids are a comparatively new class of fluids which consist of a base fluid with nano-sized particles (1–100 nm) suspended within them. “A lot of recent advances in nanotechnology were taken place in the last couple of decades that have lead to emerging of new generation of coolants called “nanofluids”. Nanofluids can be expressed as suspension of nanoparticles in a basefluid. Some examples of nanofluids are ethylene glycol based copper nanofluids and water based copper oxide nanofluids, Nanofluids are dilute suspensions of functionalized nanoparticles composite materials that gets developed few years back with the specific aim of increasing the thermal conductivity of heat transfer fluids, which ultimately leads into a promising nanotechnological area. Such thermal nanofluids for heat transfer applications represent a class of its own difference from conventional colloids for other applications. As compared to conventional solid–liquid suspensions for heat transfer intensifications, nanofluids possess the following advantages:

- High specific surface area and therefore more heat transfer surface between particles and fluids.
- High dispersion stability with predominant Brownian motion of particles.
- Reduced pumping power as compared to pure liquid to achieve equivalent heat transfer intensification.
- Reduced particle clogging as compared to conventional slurries, thus promoting system miniaturization.
- Adjustable properties including thermal conductivity and surface wettability by varying particle concentrations to suit different applications [1].

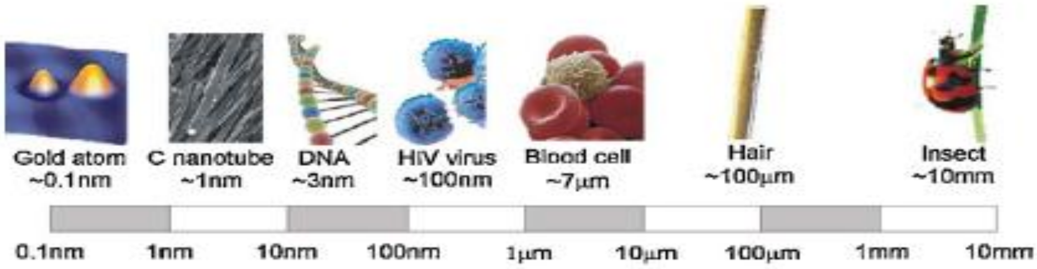

Figure 01: Length scale and some examples of Nanoparticles

2. STABILITY OF NANOFLUID & WAYS OF ITS ENHANCEMENT

The agglomeration of nanoparticles results in not only the settlement and clogging of microchannels but also the decreasing of thermal conductivity of nanofluids. So, the investigation on stability is also a key issue that influences the properties of nanofluids for application, and it is necessary to study and analyze influencing factors to the dispersion stability of nanofluids.

2.1 SURFACTANTS USED IN NANOFLUIDS

Surfactants used in nanofluids are also called dispersants. Addition of dispersants in the two-phase systems is an easy and economic method to enhance the stability of nanofluids [2]. Dispersants can effectively affect the surface characteristics of a system in small quantity. It consists of a hydrophobic tail portion, usually a long-chain hydrocarbon, and a hydrophilic polar head group. Dispersants were used to increase the contact of two materials, sometimes known as wettability. In a case of two-phase system, a dispersant approaches to locate at the interface of the two phases, where it introduces a degree of continuity between the nanoparticles and fluids. According to the composition of the head, surfactants are divided into four classes: (i) nonionic surfactants without charge groups in its head (include polyethylene oxide, alcohols, and other polar groups), (ii) anionic surfactants with negatively charged head groups (anionic head groups include long-chain fatty acids, sulfosuccinates, alkyl sulfates, phosphates, and sulfonates), (iii) cationic surfactants with positively charged head groups (cationic surfactants may be protonated long-chain amines and long-chain quaternary ammonium compounds), and (iv) amphoteric surfactants with zwitterionic head groups (charge depends on pH. The class of amphoteric surfactants is represented by betaines and certain lecithins). As far as the selection of suitable dispersants is considered, when the base fluid of nanofluids is polar solvent, we should select water-soluble surfactants; otherwise, we will select oil soluble ones.

2.2 SURFACE MODIFICATION TECHNIQUES: SURFACTANT-FREE METHOD

Utilization of functionalized nanoparticles is good approach to achieve long-term stability of nanofluid. It reflects the surfactant-free technique. Yang and Liu [3] presented a work on the synthesis of functionalized silica (SiO_2) nanoparticles by grafting silanes directly to the surface of silica nanoparticles in original nanoparticle solutions. The unique feature of the nanofluids was that no deposition layer formed on the heated surface after a pool boiling process. Hwang et al. [4] introduced hydrophilic functional groups on the surface of the nanotubes by mechanochemical reaction. The prepared nanofluids, with no contamination to medium, good fluidity, low viscosity, high stability, and high thermal conductivity, would have potential applications as coolants in advanced thermal systems. A wet mechanochemical reaction was applied to prepare surfactant-free nanofluids containing double- and single-walled CNTs. Outputs from the infrared spectrum and zeta potential measurements showed that the hydroxyl groups had been introduced onto the treated CNT surfaces [5].

2.3 STABILITY MECHANISMS OF NANOFLUIDS

Particles in dispersion may adhere together and form aggregates of increasing size which may settle out due to gravity. Meaning of stability emphasis the particles do not aggregate at a significant rate. The rate of aggregation is in general determined by the frequency of collisions and the probability of cohesion during collision. Derjaguin, Verway, Landau, and Overbeek (DVLO) developed a theory which dealt with colloidal stability [6, 7]. DLVO theory suggests that the stability of a particle in solution is determined by the sum of van der Waals attractive and electrical double layer repulsive forces that exist between particles as they approach each other due to the Brownian motion they are undergoing. If the attractive force is larger than the repulsive force, the two particles will collide, and the suspension is not stable. If the particles have a sufficient high repulsion, the suspensions will exist in stable state. For stable nanofluids or colloids, the repulsive forces between particles must be dominant. With respect to the types of repulsion, the fundamental mechanisms that affect colloidal stability are divided into two kinds, one is steric repulsion, and another is electrostatic (charge) repulsion, shown in Figure 2.

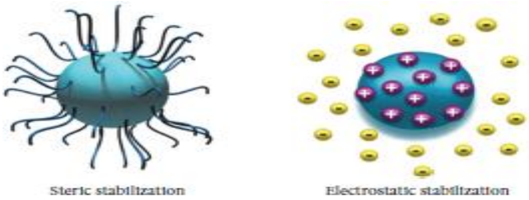

Figure 02: Types of colloidal stabilization

For steric stabilization, polymers are always involved into the suspension system, and they will adsorb onto the particles surface, producing an additional steric repulsive force. For example, Zinc oxide nanoparticles modified by PMAA have good compatibility with polar solvents [08]. Silver nanofluids are very stable due to the protective role of PVP, as it retards the growth and agglomeration of nanoparticles by steric effect. PVP is an efficient agent to improve the stability of graphite suspension [09]. The steric effect of polymer dispersant is determined by the concentration of the dispersant. If the PVP concentration is low, the surface of the graphite particles is gradually coated by PVP molecules with the increase of PVP. Kamiya et al.[10] studied the effect of polymer dispersant structure on electrosteric interaction and dense alumina suspension behaviour. An optimum hydrophilic to hydrophobic group ratio was obtained from the maximum repulsive force and minimum viscosity. For electrostatic stabilization, surface charge will be developed through one or more of the following mechanisms: (1) preferential adsorption of ions, (2) dissociation of surface charged species, (3) isomorphic substitution of ions, (4) accumulation or depletion of electrons at the surface, and (5) physical adsorption of charged species onto the surface.

3.0 NANOFLUID UTILITY IN HEAT TRANSFER APPLICATIONS

3.1 INDUSTRIAL COOLING APPLICATIONS

The application of nanofluids in industrial cooling will leads to significant energy savings and emission reductions. For US industry, the replacement of cooling and heating water with nanofluids has the potential to conserve 1 trillion Btu of energy [11, 12]. For the US electric power industry, using nanofluids in closed loop cooling cycles could save about 10–30 trillion Btu per year (equivalent to the annual energy consumption of about 50,000–150,000 households). The associated emissions reductions would be approximately 5.6 million metric tons of carbon dioxide, 8,600 metric tons of nitrogen oxides, and 21,000 metric tons of sulfur dioxide [13]. A lot of experiments were performed using a flow-loop apparatus to explore the performance of polyalphaolefin nanofluids containing exfoliated graphite nanoparticle fibers in cooling [14] and the observations were listed as: (i) the specific heat of nanofluids was found to be 50% higher for nanofluids compared with polyalphaolefin, and it increased with temperature.(ii) The thermal diffusivity was found to be 4 times higher for nanofluids.(iii) The convective heat transfer was enhanced by 10% using nanofluids compared with using polyalphaolefin. Ma et al. [15] proposed the concept of nanoliquid-metal fluid, with an eye to establish an engineering path to make the highest conductive coolant with about several dozen times larger thermal conductivity than that of water. The liquid metal with low melting point is expected to be an idealistic base fluid for making superconductive solution, which may lead to the ultimate coolant in a wide variety of heat transfer enhancement area. The thermal conductivity of the liquid metal fluid can be enhanced through the addition of more conductive nanoparticles.

Some researchers employed nanofluids for industrial cooling and showed great energy savings that leads emission reductions [16]. They showed that replacement of cooling and heating water with nanofluids has the potential to conserve about 300 million kWh of energy for industries. For the electric power industry using nanofluids could save about 3000-9000 million kWh of energy per year which is equivalent to the annual energy consumption of about 50,000-150,000 households. The associated emission reductions would be approximately 5600 million kg of carbon dioxide, 8.6 million kg of nitrogen oxides and 21 million kg of sulfur dioxide. In the Defence Advanced Projects demonstrated cooling enhancement by ~ 8-30% using nanofluids in compact heat exchangers. The nanofluids were found to precipitate nanofins on the heater surface and there augment the heat flux. The nanoparticles used in this study were ex-foliated graphite and multi-walled carbon nanotubes (MWCNT). It was observed that the nanofluids specific heat capacity was enhanced by 50%. Hence, it may be concluded that, nanofluids have better efficacy in thermal energy storage applications compared to cooling applications.

3.2 ADVANCE HEAT TRANSFER APPLICATIONS

The cooling applications of nanofluids include Crystal Silicon Mirror Cooling, Electronics cooling, Vehicle cooling, Transformer cooling, Space and Nuclear systems cooling, Defense applications and so on[17]. One of the first applications of research in the field of nanofluids is for developing an advanced cooling technology to cool crystal silicon mirrors used in high-intensity X-ray sources as discussed by Lee and Choi[18]. As nanofluids remarkably reduce the thermal resistances and increase the power densities, the superiority of nanofluid cooled silicon micro channel heat exchanger compared with water and liquid nitrogen is obvious. The benefits of using nanofluids as a room-temperature coolant are clear, including dramatic enhancement of cooling rates while operating the advanced cooling system at room temperature. Moreover, the possibility of thermal distortion and flow induced vibration will be eliminated by passing the nanofluids through micro channels within the silicon mirror itself. The advanced cooling technology developed by Lee and Choi [18] employs micro channel filled with nanofluids. The advanced cooling technology could provide more efficient cooling than that of other cooling technologies because the micro channels increase the effective heat transfer area, and the metallic nanoparticles increase the effective thermal conductivity of coolants. The advanced cooling technology may be used in cooling engines, superconducting magnets, and densely packed computer chips. Lee and Choi [18] estimated that for high-aspect-ratio micro channels, power densities of approximately 3000 W/cm^2 is achievable using nanofluids. Therefore, future experimental work on nanofluid-cooled micro channel heat exchangers will advance the art of cooling high-heat-load devices.

Some researchers found out that the use of a temperature-dependent property model predicts much better thermal and hydraulic performance than that in previous predictions using constant properties and investigated the heat transfer characteristics of copper nanofluids with acoustic cavitation bubbles and this significant work is capable of enhancing the practical applications of nanofluids. The results from the work of Palm *et al.[19]* which dealt with heat transfer enhancement capabilities of nanofluids inside typical radial flow impingement jet cooling systems reflects that nanofluids can increase the average wall heat transfer coefficient significantly and decrease the wall shear stress. This is an encouraging milestone for the use of nanofluids in impinging *jet cooling systems*. It is quite interesting to note that nanoparticles can be dispersed not only in coolants and engine oils, but also in transmission fluids, gear oils, and other fluids and lubricants. Actually nanofluids provide better overall thermal management and better lubrication. The outputs from the first application of nanofluid research in cooling a real- world automatic power transmission system by Tzeng *et al.* [20] on the experimental platform of the real rotary blade coupling (RBC) of a power transmission system of a real-time four-wheel-drive vehicle reflects that CuO nanofluids have the lowest temperature distribution at both high and low rotating speed and accordingly the best heat transfer effect. Really, it shows a real-world application of nanofluids and as a consequence represents a big step forward for industrial applications of nanofluids. The power generation industry is interested in transformer cooling application of nanofluids for reducing transformer size and weight. The enhanced demand for greater electricity production will require upgrades of most transformers at some point in the near future at a potential crest of millions of dollars. If the heat transfer capability of existing transformers can be increased, many of the upgrades may not be necessary. The important key element in nanofluid technology which is the uniform dispersion of non agglomerated nanoparticles and is still challenging for new combination of nanoparticle-based fluid and more focus is needed on the study of dynamic interactions between nanoparticles and liquid molecules and interface structure and chemistry for better heat transfer reflections.

3.2.1ADVANCED HEAT TRANSFER APPLICATIONS- DOUBLE PIPE HEAT EXCHANGER

P. Sivashanmugam [21] and Chun et al. [22] experimentally reported the convective heat transfer of nanofluids made of transformer oil and three kinds of alumina nanoparticles in laminar flow through a double pipe heat exchanger system. The experimental system includes two double-pipe heat exchangers for heating and cooling of nanofluid and was made of a non-corrosive stainless steel. Their experimental data showed that the addition of nanoparticles in the fluid enhances the average heat transfer coefficient of the system in laminar flow. By non-linear regression of experimental data, the correlation (Eq.01) for heat transfer coefficient was decided as follows

$h_i = (k/D)^* \, 1.7Re^{0.4}$ …………………………………………………………………………..(01)

The surface properties of nanoparticles, particle loading, and particle shape were key factors for enhancing the heat transfer properties of nanofluids. The authers stated that these increases of heat transfer coefficients may be caused by the high concentration of nanoparticles in the wall side by the particle migration. Duangthongsuk and Wongwises [23] experimentally studied the heat transfer coefficient and friction factor of a nanofluid consisting of water and 0.2 vol. % TiO_2 flowing in a horizontal double-tube counter flow heat exchanger under turbulent flow conditions. Their test section was a 1.5 m long counter flow horizontal double-tube heat exchanger with nanofluid flowing inside the tube while hot water flows in the annular. The inner tube is made from smooth copper tubing with a 9.53 mm outer diameter and an 8.13 mm inner diameter, while the outer tube is made from PVC tubing and has a 33.9 mm outer diameter and a 27.8 mm inner diameter. The test section was thermally isolated from its upstream and downstream section by plastic tubes in order to reduce the heat loss along the axial direction.

Duangthongsuk and Wongwises [24] experimentally studied the heat transfer coefficient and friction factor of the TiO_2-water nanofluids flowing in a horizontal double tube counterflow heat exchanger under turbulent flow conditions. Their test fluid was TiO_2 nanoparticles with diameters of 21 nm dispersed in water with volume concentrations of 0.2 - 2 vol. %. The heat transfer coefficient of nanofluids was approximately 26% greater than that of pure water and the results also showed that the heat transfer coefficient of the nanofluids at a volume concentration of 2.0 vol.% was approximately 14% lower than that of base fluids for given conditions. Their results showed that the Pak and Cho correlation (Eq. (2)) can predict the heat transfer coefficient of nanofluids and gives results that corresponded well only with the experimental results for the volume concentration of 0.2%, i.e. from equation

$$Nu = 0.021\, Re^{0.8}\, Pr^{0.5} \quad \ldots(02)$$

However, for the volume concentrations of 0.6% and 1.0%, the Pak and Cho equation fails to predict the heat transfer performance of the nanofluids. For the pressure drop, their results showed that the pressure drop of nanofluids was slightly higher than the base fluid and increases with increasing the volume concentrations. New heat transfer and friction factor correlations (Eqs 03 and 04) for predicting the Nusselt number and friction factor of TiO_2-water nanofluids were proposed in the form of

$$Nu = 0.074 Re^{0.707}\, Pr^{0.385}\, \phi^{0.074} \quad \ldots(03)$$

$$f = 0.961\, \phi^{0.052} * Re^{-0.375} \quad \ldots(04)$$

The majority of the data falls within ±10% of the proposed equation. These equations are valid in the range of Reynolds number between 3000 and 18,000 and particle volume concentrations in the range of 0 and 1.0 vol. % for Nusselt number and 0 and 2.0 vol. % for friction factor. Asirvatham et al., [25] investigated the convective heat transfer of nanofluids using silver – water nanofluids under laminar, transition and turbulent flow regimes in a horizontal 4.3 mm inner-diameter tube-in-tube counter-current heat transfer test section. The volume concentration of the nanoparticles were varied from 0.3% to 0.9% in steps of 0.3% and the effects of thermo-physical properties, inlet temperature, volume concentration, and mass flow rate on heat transfer coefficient were investigated. Outcomes of experiments reflects that the suspended nanoparticles remarkably increased the convective heat transfer coefficient, by as much as 28.7% and 69.3% for 0.3% and 0.9% of silver content, respectively. Based on the experimental results a correlation (Eq.05) was developed to predict the Nusselt number of the silver–water nanofluid, with ±10% agreement between experiments and prediction.

$$Nu_{nf} = 0.023 Re^{0.8}\, Pr^{0.3} + (0.617\phi - 0.135)\, Re^{(0.445}\phi^{-0.37)}\, Pr(^{1.081}\phi^{\,-1.305)} \quad \ldots(05)$$

Where, ϕ represents the volume fraction of suspended particles.

2. CONCLUSION & FUTURE TRENDS OF NANOFLUIDS

The current paper highlights an overview of the recent developments in the study of nanofluids that includes the evaluation methods for their stability, the ways to enhance their stability, the stability mechanisms, and their applications in heat transfer. An outcome of certain past experimental results reflects an enhancement of convective heat transfer coefficient on certain volume concentration of the nanoparticles. ***The following key***

issues should receive greater attention in the future. Firstly, further experimental and theoretical research is required to find the major factors influencing the performance of nanofluids. Higher viscosity & lower specific heat are some of the major challenge that may come in coming future as the viscosity of nanoparticle–water suspensions increases in accordance with increasing particle concentration in the suspension. So, the particle mass fraction cannot be increased unlimitedly and an ideal coolant should possess higher value of specific heat that enables the coolant to remove more heat. In coming future, selective nanofluids should be studied not only under real- world conditions of use, but also over a longer period of time. We can said that positively in coming future the utility of nanofluids will be widely dispersed across the globe for numerous demand and applications in the industry. Our current understanding on nanofluids is limited in specific areas. Besides thermal conductivity effect, future research should consider other properties, especially viscosity and wettability, and should examine step by step their influence on flow and heat transfer. A thorough research is required to investigate interactions between particles, stabilizers, the suspending liquid and the heating surface for a wide direction of applications.

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