Studies on the Nanofluids Applications: due to their Amazing Properties

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Abstract

The focus of the present work concerns the applications due to the properties, especially thermal properties of suspensions of nanoparticles in fluids. They commonly referred to as nanofluids. In another explanation, nanofluids are nanoscale colloidal suspensions containing consendensed nanomaterials. They are two-phase systems with one phase (solid phase) in another (liquid phase).Nanofluids are suspensions of nanoparticles in fluids. They show substantial augmentation of their properties at modest nanoparticle concentrations. They have also shown many interesting properties, and the distinctive features offer unprecedented potential for many applications. Most of the publications on nanofluids are about understanding their behavior so that they can be utilized where straight enhancement of nanofluids is paramount as in many industrial applications, nuclear reactors, transportation, electronics as well as biomedicine and food. My paper focuses on presenting the wide range of its applications that involve nanofluids, prominence to their improved properties that are controllable and the specific characteristics that these nanofluids possess that make them suitable for such applications. The properties like heat transfer, thermal properties and so on, will be used in many applications of nanofluids, has also been reported.

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Introduction

Nanofluids are a new class of fluids engineered by dispersing nanometer-sized materials (nanoparticles, nanofibers, nanotubes, nanowires, nanorods, nanosheet, or droplets) in base fluids. In other words, nanofluids are nanoscale colloidal suspensions containing consendensed nanomaterials.

They are two-phase systems with one phase (solid phase) in another (liquid phase).

Nanofluids have been found to possess enhanced thermo-physical properties such as thermal conductivity, thermal diffusivity, viscosity and convective heat transfer coefficients

compared to those of base fluids like oil or water. It has demonstrated great potential applications in many fields. In this paper we will review the biological applications of nanofluids due to their important characteristics and advantages of their

properties. In recent years, nanofluids have attracted more and more attention. The main driving force for nanofluids research lies in a wide range of applications. Although some review articles involving the progress of nanofluid investigation were published in the past several years [1-6], most of the reviews are concerned on the experimental and theoretical studies of the thermophysical properties or the convective heat transfer of nanofluids.

The purpose of this paper will focuses on the applications of nanofluids based on their properties, especially the new application trends for nanofluids in addition to the heat transfer properties , i.e., thermal properties of nanofluids. We will try to find some challenging issues that need to be solved for future research based on the review on these aspects of nanofluids. My only aim is to expose the applications due to amazing properties of nanofluids.

Applications of Nanofluids / Ferrofluids

- **Applications in Industry**

More efficient heat transfer systems are increasingly preferred because of the accelerating miniaturization, on the one hand, and the ever-increasing heat flux, on the other. In many industrial processes, including power generation, chemical processes, heating or cooling processes, and microelectronics, heat transfer fluids such as water, mineral oil, and ethylene glycol always play vital roles. The poor heat transfer properties of these common fluids compared to most solids is a primary obstacle to the high compactness and effectiveness of heat exchangers [8].

An innovative way of improving the thermal conductivities of working media is to suspend ultrafine metallic or nonmetallic solid powders in traditional fluids since the thermal conductivities of most solid materials are higher than those of liquids. A novel kind of heat transfer enhancement fluid, the so-called nanofluid, has been proposed to meet the demands [9].

- **Applications due to thermal properties**

Nanofluids have great potential for heat transfer enhancement and are highly suited to application in practical heat transfer processes. This provides promising ways for engineers to develop highly compact and effective heat transfer equipments. More and more researchers have paid their attention to this exciting field. When addressing the thermal conductivity of nanofluids, it is foremost important to guarantee the accuracy in the measurement of the thermal conductivity of nanofluids[7].

Two aspects should be considered.

The first one is to prepare homogeneous and long-term stable nanofluids. The second one is to keep the initial equilibrium before measuring the thermal conductivity. In general, the thermal conductivity enhancement increases monotonously

with the particle loading. The effect of temperature on the thermal conductivity enhancement ratio is somewhat different for different nanofluids. It is very important to note that the temperatures of the base fluid and the nanofluid should be the same while comparing the thermal conductivities between them.

With an increase in the thermal conductivity of the base fluid, the thermal conductivity enhancement ratio decreases. Considering the effect of the size of the inclusion, there exists an optimal value for alumina nanofluids, while for the CNT nanofluid, the thermal conductivity increases with a decrease of the average diameter of the included CNTs[8,9]. The thermal characteristics of nanofluids might be manipulated by means of controlling the morphology of the inclusions, which also provide a promising way to conduct investigation on the mechanism of heat transfer in nanofluids. The additives like acid, base, or surfactant play considerable roles on the thermal conductivity enhancement of nanofluids[12].

The thermal requirements on the personal computer become much stricter with the increase in thermal dissipation of CPU. One of the solutions is the use of heat pipes. Nanofluids, employed as working medium for conventional heat pipe, have shown higher thermal performances, having the potential as a substitute for conventional water in heat pipe. At a same charge volume, there is a significant reduction in thermal resistance of heat pipe with nanofluid containing gold nanoparticles as compared with water [13]. The measured results also show that the thermal resistance of a vertical meshed heat pipe varies with the size of gold nanoparticles. The suspended nanoparticles tend to bombard the vapor bubble during the bubble formation. Therefore, it is expected that the nucleation size of vapor bubble is much smaller for fluid with suspended nanoparticles than that without them. This may be the major reason for reducing the thermal resistance of heat pipe.

Chen *et al*. studied the effect of a nanofluid on flat heat pipe (FHP) thermal performance [14], using silver nanofluid as the working fluid. The temperature difference and the thermal resistance of the FHP with the silver nanoparticle solution were lower than those with pure water. The plausible reasons for enhancement of the thermal performance of the FHP using the nanofluid can be explained by the critical heat flux enhancement by higher wettability and the reduction of the boiling limit. Nanofluid oscillating heat pipe with ultrahigh-performance was developed by Ma *et al.* [15]. They combined nanofluids with thermally excited oscillating motion in an oscillating heat pipe, and heat transport capability significantly increased. For example, at the input power of 80.0 W, diamond nanofluid could reduce the temperature difference between the evaporator and the condenser from 40.9 to 24.3°C. This study would accelerate the development of a highly efficient cooling device for ultrahigh-heat-flux electronic systems.

The thermal performance investigation of heat pipe indicated that nanofluids containing silver or titanium nanoparticles could be used as an efficient cooling fluid for devices with high energy density. For a silver nanofluid, the temperature difference decreased 0.56-0.65 compared to water at an input power of 30-50 W [16]. For the heat pipe with titanium nanoparticles at a volume concentration of 0.10%, the thermal efficiency is 10.60% higher than that with the based working fluid [17]. These positive results are promoting the continued research and development of nanofluids for such applications.

- **Applications on Transportation**

Nanofluids have great potentials to improve automotive and heavy-duty engine cooling rates by increasing the efficiency, lowering the weight and reducing the complexity of thermal management systems. The improved cooling rates for automotive and truck engines can be used to remove more heat from higher horsepower engines with the same size of cooling system. Alternatively, it is beneficial to design more compact cooling system with smaller and lighter radiators. It is in turn benefit the high performance and high fuel economy of car and truck. Ethylene glycol based nanofluids have attracted much attention in the application as engine coolant [18-20], due to the low-pressure operation compared with a 50/50 mixture of ethylene glycol and water, which is the nearly universally used automotive coolant. The nanofluids has a high boiling point, and it can be used to increase the normal coolant operating temperature and then reject more heat through the existing coolant system [21].

Kole et al. prepared car engine coolant (Al_2O_3 nanofluid) using a standard car engine coolant (HP KOOLGARD) as the base fluid [22], and studied the thermal conductivity and viscosity of the coolant. The prepared nanofluid, containing only 3.5% volume fraction of Al_2O_3 nanoparticles, displayed a fairly higher thermal conductivity than the base fluid, and a maximum enhancement of 10.41% was observed at room temperature. Tzeng et al. [23] applied nanofluids to the cooling of automatic transmissions. The experimental platform was the transmission of a four-wheel drive vehicle. The used nanofluids were prepared by dispersing CuO and Al_2O_3 nanoparticles into engine transmission oil. The results showed that CuO nanofluids produced the lower transmission temperatures both at high and low rotating speeds. From the thermal performance viewpoint, the use of nanofluid in the transmission has a clear advantage.

The researchers of Argonne National Laboratory have assessed the applications of nanofluids for transportation [24]. The use of high-thermal conductive nanofluids in radiators can lead to a reduction in the frontal area of the radiator up to 10%. The fuel saving is up to 5% due to the reduction in aerodynamic drag. It opens the door for new aerodynamic automotive designs that reduce emissions by lowering drag. The application of nanofluids also contributed to a reduction of friction and wear, reducing parasitic losses, operation of components such as pumps and compressors, and subsequently leading to more than 6% fuel savings. In fact, nanofluids not only enhance the efficiency and economic performance of car engine, but also will greatly influence the structure design of automotives.

For example, the engine radiator cooled by a nanofluid will be smaller and lighter.

- **Energy applications**

For energy applications of nanofluids, two remarkable properties of nanofluids are utilized, one is the higher thermal conductivities of nanofluids, enhancing the heat transfer, another is the absorption properties of nanofluids.

1) Energy storage

The temporal difference of energy source and energy needs made necessary the development of storage system. The storage of thermal energy in the form of sensible and latent heat has become an important aspect of energy management with the emphasis on efficient use and conservation of the waste heat and solar energy in industry and buildings [25].

Latent heat storage is one of the most efficient ways of storing thermal energy. Wu *et al*. evaluated the potential of Al_2O_3-H_2O nanofluids as a new phase change material (PCM) for the thermal energy storage of cooling systems. The thermal response test showed the addition of Al_2O_3 nanoparticles remarkably decreased the supercooling degree of water, advanced the beginning freezing time and reduced the total freezing time. Only adding 0.2 wt% Al_2O_3 nanoparticles, the total freezing time of Al_2O_3-H2O nanofluids could be reduced by 20.5%.

Liu *et al*. prepared a new sort of nanofluid phase change materials (PCMs) by suspending small amount of TiO_2 nanoparticles in saturated $BaCl_2$ aqueous solution [26]. The nanofluids PCMs possessed remarkably high thermal conductivities compared to the base material. The cool storage/supply rate and the cool storage/supply capacity all increased greatly than those of $BaCl_2$ aqueous solution without added nanoparticles. The higher thermal performances of nanofluids PCMs indicate that they have a potential for substituting conventional PCMs in cool storage applications. Copper nanoparticles are efficient additives to improve the heating and cooling rates of PCMs [27].

For composites with 1 wt % copper nanoparticle, the heating and cooling times could be reduced by 30.3 and 28.2%, respectively. The latent heats and phase-change temperatures changed very little after 100 thermal cycles.

2) Solar absorption

Solar energy is one of the best sources of renewable energy with minimal environmental impact. The conventional direct absorption solar collector is a well established technology, and it has been proposed for a variety of applications such as water heating; however the efficiency of these collectors is limited by the absorption properties of the working fluid, which is very poor for typical fluids used in solar collectors. Recently this technology has been combined with the emerging technologies of nanofluids and liquid-nanoparticle suspensions to create a new class of nanofluid-based solar collectors.

Otanicar et al. reported the experimental results on solar collectors based on nanofluids made from a variety of nanoparticles (CNTs, graphite, and silver) [28]. The efficiency improvement was up to 5% in solar thermal collectors by utilizing nanofluids as the absorption media. In addition they compared the experimental data with a numerical model of a solar collector with direct absorption nanofluids. The experimental and numerical results demonstrated an initial rapid increase in efficiency with volume fraction, followed by a leveling off in efficiency as volume fraction continues to increase.

Theoretical investigation on the feasibility of using a nonconcentrating direct absorption solar collector showed that the presence of nanoparticles increased the absorption of incident radiation by more than nine times over that of pure water [29]. Under the similar operating conditions, the efficiency of an absorption solar collector using nanofluid as the working fluid was found to be up to 10% higher (on an absolute basis) than that of a flat-plate collector.

Otanicar et al. evaluated the overall economic and environmental impacts of the technology in contrast with conventional solar collectors using the life cycle assessment methodology [30]. Results showed that for the current cost of nanoparticles the nanofluid based solar collector had a slightly longer payback period but at the end of its useful life has the same economic saving as a conventional solar collector.

Sani et al. investigated the optical and thermal properties of nanofluids consisting in aqueous suspensions of single wall carbon nanohorns [31]. The observed nanoparticle-induced differences in optical properties appeared promising, leading to a considerably higher sunlight absorption. Both these effects, together with the possible chemical functionalization of carbon nanohorns, make this new kind of nanofluids very interesting for increasing the overall efficiency of the sunlight exploiting device.

- **Mechanical applications**

Nanoparticles in nanofluids form a protective film with low hardness and elastic modulus on the worn surface can be considered as the main reason that some nanofluids exhibit excellent lubricating properties. Magnetic fluids are kinds of special nanofluids.

Magnetic liquid rotary seals operate with no maintenance and extremely low leakage in a very wide range of applications, and it utilizing the property magnetic properties of the magnetic nanoparticles in liquid.

1) Friction reduction

Advanced lubricants can improve productivity through energy saving and reliability of engineered systems. Tribological research heavily emphasizes reducing friction and wear. Nanoparticles have attracted much interest in recent years due to their excellent load-carrying capacity, good extreme pressure and friction reducing properties. Zhou *et al.* evaluated the tribological behavior of Cu nanoparticles in oil on a four-ball machine. The results showed that Cu nanoparticles as an oil additive had better friction-reduction and antiwear properties than zinc dithiophosphate, especially at high applied load.

Meanwhile, the nanoparticles could also strikingly improve the load-carrying capacity of the base oil [32]. Dispersion of solid particles was found to play an important role, especially when a slurry layer was formed. Water-based Al_2O_3 and diamond nanofluids were applied in the minimum quantity lubrication (MQL) grinding process of cast iron. During the nanofluid MQL grinding, a dense and hard slurry layer was formed on the wheel surface and could benefit the grinding performance.

Nanofluids showed the benefits of reducing grinding forces, improving surface roughness, and preventing workpiece burning. Compared to dry grinding, MQL grinding could significantly reduce the grinding temperature [33]. Wear and friction properties of surface modified Cu nanoparticles as 50CC oil additive were studied. The higher the oil temperature applied, the better the tribological properties of Cu nanoparticles were. It could be inferred that a thin copper protective film with lower elastic modulus and hardness was formed on the worn surface, which resulted in the good tribological performances of Cu nanoparticles, especially when the oil temperature was higher [34].

Yu et al. firstly reported that Room Temperature Ionic Liquid /Multi-Walled Carbon Nanotubes composite was evaluated as lubricant additive in ionic liquid due to their excellent dispersibility, and the composite showed good friction-reduction and anti-wear properties in friction process [35].

Wang *et al.* studied the tribological properties of ionic liquid-based nanofluids containing functionlized MWNTs under loads in the range of 200-800 N [36], indicating that the nanofluids exhibited preferable friction-reduction properties under 800 N and remarkable antiwear properties with use of reasonable concentrations. Magnetic nanoparticle $Mn_{0.78}$ $Zn_{0.22}$ Fe_2O_4 was also an efficient lubricant additive. When used as a lubricant additive in 46# turbine oil, it could improve the wear resistance, load-carrying capacity, and antifriction ability of base oil, and the decreasing percentage of wear scar diameter was 25.45% compared to the base oil. This was a typical self-repair phenomenon [37].

2) Magnetic sealing

Magnetic fluids (Ferromagnetic fluid) are kinds of special nanofluids. They are stable colloidal suspensions of small magnetic particles such as magnetite (Fe_3O_4). The properties of the magnetic nanoparticles, the magnetic component of magnetic nanofluids, may be tailored by varying their size and adapting their surface coating in order to meet the requirements of colloidal stability of magnetic nanofluids with non-polar and polar carrier liquids [38]. Comparing with the mechanical sealing, magnetic sealing offers a cost-effective solution to environmental and hazardous-gas sealing in a wide variety of industrial rotation equipment with high speed capability, low friction power losses and long life and high reliability [39]. A ring magnet forms part of a magnetic circuit in which an intense magnetic field is established in the gaps between the teeth on a magnetically permeable shaft and the surface of an opposing pole block.

Ferrofluid introduced into the gaps forms discrete liquid rings capable of supporting a pressure difference while maintaining zero leakage. The seals operate without wear as the shaft rotates because the mechanical moving parts do not touch. With these unique characteristics, sealing liquids with magnetic fluids can be applied in many application areas. It is reported that an iron particle dispersed magnetic fluids was utilized in the sealing of a high rotation pump. The sealing holds pressure of 618 kPa with a 1800 r/min [40]. Mitamura et al. studied the application of a magnetic fluid seal to rotary blood pumps. The developed magnetic fluid seal worked for over 286 days in a continuous flow condition, for 24 days (on-going) in a pulsatile flow condition and for 24 h (electively terminated) in blood flow [41].

- **Biomedical application**

Some special kinds of nanoparticles have antibacterial activities or drug delivery properties, so the nanofluids containing these nanoparticles will exhibit some relevant properties.

1) Antibacterial activity against

An Organic bacteriostatic materials are often less stable particularly at high temperatures or pressures. As a consequence, inorganic materials such as metal and metal oxides have attracted lots of attention over the past decade due to their ability to withstand harsh process conditions. The antibacterial behaviour of ZnO nanofluids shows that the ZnO nanofluids have bacteriostatic activity against [42]. The antibacterial activity of suspensions of ZnO nanoparticles against Escherichia coli (E. coli) has been evaluated by estimating the reduction ratio of the bacteria treated with ZnO. Survival ratio of bacteria decreases with increasing the concentrations of ZnO nanofluids and time [43]. The antibacterial activity of ZnO may be dependent on the size and the presence of normal visible light [44].

Recent research showed that ZnO nanoparticles exhibited impressive antibacterial properties against an important food-borne pathogen, E. coli O_{157}:H_7, and the inhibitory effects increased as the concentrations of ZnO nanoparticles increased , and ultimately the death of cells, considered as an effective antibacterial agent for protecting agricultural and food safety [45]. CuO nanoparticles could be hypothesized that these nanoparticles formed stable complexes with vital enzymes inside cells which hampered cellular functioning resulting in their death [46]. Bulk equivalents of these products showed no inhibitory activity, indicating that particle size was determinant in activity [47].

Lee et al. reported the antibacterial efficacy of nanosized silver colloidal solution on the cellulosic and synthetic fabrics [48]. A very low concentration of silver gave antibacterial performance [49]. The aqueous suspensions of fullerenes and nano-TiO2 can produce reactive oxygen species (ROS). Bacterial (E. coli) toxicity tests suggestted that, unlike nano-TiO2 which was exclusively phototoxic, the antibacterial activity of fullerene suspensions was linked to ROS production. However, fullerol and PVP/C60 may be useful as water treatment agents targeting specific pollutants or microorganisms that are more sensitive to either superoxide or singlet oxygen [50]. Lyon et al. proposed that C60 suspensions exerted ROS- independent oxidative stress in bacteria, with evidence of protein oxidation, changes in cell membrane potential, and interruption of cellular respiration[51].

2) Nanodrug delivery

Over the last few decades, colloidal drug delivery systems have been developed in order to improve the efficiency and the specificity of drug action [52]. The small size, customized surface, improved solubility, and multi-functionality of nanoparticles open many doors and create new biomedical applications. The novel properties of nanoparticles offer the ability to interact with complex cellular functions in new ways [53]. Gold nanoparticles provide non-toxic carriers for drug and gene delivery applications.

With these systems, the gold core imparts stability to the assembly, while the monolayer allows tuning of surface properties such as charge and hydrophobicity. Another attractive feature of gold nanoparticles is their interaction with thiols, providing an effective and selective means of controlled intracellular release [54].

Nakano et al. proposed the drug delivery system using nano-magnetic fluid [55], which targetted and concentrated drugs using a ferrofluid cluster composed of magnetic nanoparticles , with their drug loading capability and the biochemical properties that can be bestowed on them by means of a suitable coating. CNT has emerged as a new alternative and efficient tool for transporting and translocating therapeutic molecules. The functionalised CNT display low toxicity and are not immunogenic, such systems hold great potential in the field of nanobiotechnology and nanomedicine [56, 57].

Pastorin et al. have developed a novel strategy for the functionalisation of CNTs with two different molecules using the 1,3-dipolar cycloaddition of azomethine ylides [58]. The attachment of molecules that will target specific receptors on tumour cells will help improve the response to anticancer agents. Liu et al. have found that prefunctionalized CNTs can adsorb widely used aromatic molecules by simple mixing, forming "forest–scrub"-like assemblies on CNTs with PEG extending into water to impart solubility and aromatic molecules densely populating CNT sidewalls[59].

In recent years, graphene based drug delivery systems have attracted more and more attention. In 2008, Sun et al. firstly reported the application of nano-graphene oxide (NGO) for cellular imaging and drug delivery [60]. They have developed functionalization chemistry in order to impart solubility and compatibility of NGO in biological environments. Simple physicosorption via π-stacking can be used for loading doxorubicin, a widely used cancer drug onto NGO functionalized with antibody for selective killing of cancer cells in vitro. Functional nanoscale graphene oxide is found to be a novel nanocarrier for the loading and targeted delivery of anticancer drugs [61, 62]. The PEGylated (PEG: polyethylene glycol) nanographene oxide could be used for the delivery of water-insoluble cancer drugs [63]. PEGylated NGO readily complexes with a water insoluble aromatic molecule SN38, a camptothecin analogue, via noncovalent van der Waals interaction.Yang et al. found GO-Fe_3O_4 hybrid could be loaded with anti-cancer drug doxorubicin hydrochloride with a high loading capacity [64]. This pH-triggered controlled magnetic behavior makes this material a promising candidate for controlled targeted drug delivery.

- **Cancer Theraupetics**

A new initiative , which takes advantage of several properties of certain nanofluids to use in cancer imaging and drug delivery is there. This involves the use of iron-based nanoparticles as delivery vehicles for drugs or radiation in cancer patients. Magnetic nanofluids are to be used to guide the particles up the bloodstream to a tumor with magnets. Magnetic nanoparticles are used because as compared to other metal-type nanoparticles, these provide a characteristic for handling and manipulation of the nanofluid by magnetic force [65]. This combination of targeted delivery and controlled release will also decrease the likelihood of systemic toxicity since the drug is encapsulated and biologically unavailable during transit in systemic circulation. By enhancing the chemotherapeutic efficacy, the hyperthermia is able to produce a preferential radiation effect on malignant cells [66].

- **Nanocryosurgery**

Cryosurgery is a procedure that uses freezing to destroy undesired tissues. This therapy is becoming popular because of its important clinical advantages. Although it still cannot be regarded as a routine method of cancer treatment, cryosurgery is quickly becoming as an alternative to traditional therapies.

Simulations were performed by Yan and Liu [67] on the combined phase change bioheat transfer problems in a single cell level and its surrounding tissues, to explicate the difference of transient temperature response between conventional cyro sugery and nanocyrosurgery. According to theoretical interpretation and existing experimental measurements, intentional loading of nanoparticles with high thermal conductivity into the target tissues can reduce the final temperature, increase the maximum freezing rate, and enlarge the ice volume obtained in the absence of nanoparticles.

- **Medicine**

In medicine, ferrofluids are used as contrast agents for magnetic resonance imaging and can be used for cancer detection. The ferrofluids are in this case composed of iron oxide nanoparticles and called SPION, for "Superparamagnetic Iron Oxide Nanoparticles". There is also much experimentation with the use of ferrofluids in an experimental cancer treatment called magnetic hyperthermia. It is based on the fact that a ferrofluid placed in an alternating magnetic field releases heat.

Most common applications of ferrofluids in biomedicine involve highly dilute colloidal suspensions of magnetic nanoparticles. Their widest commercial use is as MRI contrast agents (68). When properly coated with targeting antibodies, they can also be used in hyperthermia therapy for cancer or as sensors to detect pathogens (69).

- **Magnetic Drug Targeting**

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Latest research on cancer is partly focused on localized delivery of cancer medicine to the affected part of the body. To achieve the same the medicine is bound to magnetic particles (e.g. ferrofluids) which are biologically compatible. For targeting the same permanent magnets can be used by positioning them at suitable locations of the external body.

More on Biomedical Applications

Nanoparticles of iron(III) oxide are biocompatible, non-toxic, are chemically active on their surface, and are paramagnetic at particle sizes above a critical limit of about 5 nanometers. They find wide use in biomedical applications , used as contrast agents in magnetic resonance imaging, in labeling of cancerous tissues, magnetically controlled transport of pharmaceuticals, localized thermotherapy (where the tissue is labeled by iron oxide nanoparticles, then heated by application of AC field to particles), and preparation of ferrofluids.

Ayse et al presented a simple microfluidic platform that uses biocompatible ferrofluids for the controlled manipulation and rapid separation of both microparticles and live cells. Using microspheres, we demonstrate size-based separation with 99% separation efficiency and sub-10-μm resolution in <45 s. It also shows continuous manipulation and shape-based separation of live red blood cells from sickle cells and bacteria. These initial demonstrations reveal the potential of ferromicrofluidics in significantly reducing incubation times and increasing diagnostic sensitivity in cellular assays through rapid separation and delivery of target cells to sensor arrays.[70].

There are numerous biomedical applications that involve nanofluids such as magnetic cell separation, drug delivery, hyperthermia, and contrast enhancement in magnetic resonance imaging. Depending on the specific application, there are different chemical syntheses developed for various types of magnetic nanofluids that allow for the careful tailoring of their properties for different requirements in applications. Surface coating of nanoparticles and the colloidal stability of biocompatible water-based magnetic fluids are the two particularly important factors that affect successful application [67, 68].

Finally, there is much hope for future biomedical applications of ferrofluids. For example, researchers are attempting to design ferrofluids that can carry medications to specific locations in the body through the use of applied magnetic fields. Other ongoing work is investigating the use of ferrofluids as contrast agents for magnetic resonance imaging (MRI).

Other applications

1) Intensify microreactors

The discovery of high enhancement of heat transfer in nanofluids can be applicable to the area of process intensification of chemical reactors through integration of the functionalities of reaction and heat transfer in compact multifunctional reactors. Fan et al. studied a nanofluid based on benign TiO2 material dispersed in ethylene glycol in an integrated reactor-heat exchanger [71]. The overall heat transfer coefficient increase was up to 35% in the steady state continuous experiments. This resulted in a closer temperature control in the reaction of selective reduction of an aromatic aldehyde by molecular hydrogen and very rapid change in the temperature of reaction under dynamic reaction control.

2) Nanofluids as vehicular brake fluids

A vehicle's kinetic energy is dispersed through the heat produced during the process of braking and this is transmitted throughout the brake fluid in the hydraulic braking system [72], and now there is a higher demand for the properties of brake oils. Copper-oxide and aluminum-oxide based brake nanofluids were manufactured using the arc-submerged nanoparticle synthesis system and the plasma charging arc system, respectively [73, 74].

The two kinds of nanofluids both have enhanced properties such as a higher boiling point, higher viscosity and a higher conductivity than that of traditional brake fluid. By yielding a higher boiling point, conductivity and viscosity, the nanofluid brake oil will reduce the occurrence of vapor-lock and offer increased safety while driving.

3) MFC

Nanofluids based microbial fuel cell Microbial fuel cells (MFC) that utilize the energy found in carbohydrates, proteins and

other energy rich natural products to generate electrical power have a promising future. The excellent performance of MFC depends on electrodes and electron mediator. Sharma et al. constructed a novel microbial fuel cell (MFC) using novel electron mediators and CNT based electrodes [75]. The novel mediators are nanofluids which were prepared by dispersing nanocrystalline platinum anchored CNTs in water. They compared the performance of the new E. coli based MFC to the previously reported E. coli based microbial fuel cells with Neutral Red and Methylene Blue electron mediators. The performance of the MFC using CNT based nanofluids and CNT based electrodes has been compared against plain graphite electrode based MFC.

CNT based electrodes showed as high as ~6 fold increase in the power density compared to graphite electrodes. The work demonstrates the potential of noble metal nanoparticles dispersed on CNT based MFC for the generation of high energies from even simple bacteria like E. coli.

4) Nanofluids with unique optical properties

Optical filters are used to select different wavelengths of light. The ferrofluid based optical filter has tunable properties. The desired central wavelength region can be tuned by an external magnetic field. Philip et al. developed a ferrofluid based emulsion for selecting different bands of wavelengths in the UV, visible and IR regions [76]. The desired range of wavelengths, bandwidth and percentage of reflectivity could be easily controlled by using suitably tailored ferrofluid emulsions.

Mishra et al. developed nanofluids with selective visible colors in gold nanoparticles embedded in polymer molecules of polyvinyl pyrrolidone (PVP) in water [77]. They compared the developments in the apparent visible colors in forming the Au-PVP nanofluids of 0.05, 0.10, 0.50, and 1.00 wt% Au-contents. The surface plasmon bands, which occurs over 480-700 nm, varies sensitively in its position as well as the intensity when varying the Au-content 0-1 wt%.

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