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Kaufui Vincent Wong
University of Miami

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Review Article

Applications of Nanofluids: Current and Future

Kaufui V. Wong and Omar De Leon

Mechanical and Aerospace Engineering Department, University of Miami, Coral Gables, FL 33124, USA

Correspondence should be addressed to Kaufui V. Wong, kwong@miami.edu

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Nanofluids are suspensions of nanoparticles in fluids that show significant enhancement of their properties at modest nanoparticle concentrations. Many of the publications on nanofluids are about understanding their behavior so that they can be utilized where straight heat transfer enhancement is paramount as in many industrial applications, nuclear reactors, transportation, electronics as well as biomedicine and food. Nanofluid as a smart fluid, where heat transfer can be reduced or enhanced at will, has also been reported. This paper focuses on presenting the broad range of current and future applications that involve nanofluids, emphasizing their improved heat transfer properties that are controllable and the specific characteristics that these nanofluids possess that make them suitable for such applications.

1. Introduction

Nanofluids are dilute liquid suspensions of nanoparticles with at least one of their principal dimensions smaller than 100 nm. From previous investigations, nanofluids have been found to possess enhanced thermophysical properties such as thermal conductivity, thermal diffusivity, viscosity and convective heat transfer coefficients compared to those of base fluids like oil or water [1–6]

From the current review, it can be seen that nanofluids clearly exhibit enhanced thermal conductivity, which goes up with increasing volumetric fraction of nanoparticles. The current review does concentrate on this relatively new class of fluids and not on colloids which are nanofluids because the latter have been used for a long time. Review of experimental studies clearly showed a lack of consistency in the reported results of different research groups regarding thermal properties [7, 8]. The effects of several important factors such as particle size and shapes, clustering of particles, temperature of the fluid, and dissociation of surfactant on the effective thermal conductivity of nanofluids have not been studied adequately. It is important to do more research so as to ascertain the effects of these factors on the thermal conductivity of wide range of nanofluids.

Classical models cannot be used to explain adequately the observed enhanced thermal conductivity of nanofluids. Recently most developed models only include one or two postulated mechanisms of nanofluids heat transfer. For instance, there has not been much fundamental work reported on the determination of the effective thermal diffusivity of nanofluids nor heat transfer coefficients for nanofluids in natural convection [9].

There is a growth is the use of colloids which are nanofluids in the biomedical industry for sensing and imaging purposes. This is directly related to the ability to design novel materials at the nanoscale level alongside recent innovations in analytical and imaging technologies for measuring and manipulating nanomaterials. This has led to the fast development of commercial applications which use a wide variety of manufactured nanoparticles. The production, use and disposal of manufactured nanoparticles will lead to discharges to air, soils and water systems. Negative effects are likely and quantification and minimization of these effects on environmental health is necessary. True knowledge of concentration and physicochemical properties of manufactured nanoparticles under realistic conditions is important to predicting their fate, behavior and toxicity in the natural aquatic environment. The aquatic colloid and atmospheric ultrafine particle literature both offer evidence as to the likely behavior and impacts of manufactured nanoparticles [10], and there is no pretense that a review duplicating similar literature about the use of colloids which are also nanofluids is attempted in the current review.

Owing to their enhanced properties as thermal transfer fluids for instance, nanofluids can be used in a plethora of engineering applications ranging from use in the automotive industry to the medical arena to use in power plant cooling systems as well as computers.

2. Heat Transfer Applications

2.1. Industrial Cooling Applications. Routbort et al. [11] started a project in 2008 that employed nanofluids for industrial cooling that could result in great energy savings and resulting emissions reductions. For U.S. industry, the replacement of cooling and heating water with nanofluids has the potential to conserve 1 trillion Btu of energy. For the U.S. 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.

For Michelin North America tire plants, the productivity of numerous industrial processes is constrained by the lack of facility to cool the rubber efficiently as it is being processed. This requires the use of over 2 million gallons of heat transfer fluids for Michelin's North American plants. It is Michelin's goal in this project to obtain a 10% productivity increase in its rubber processing plants if suitable water-based nanofluids can be developed and commercially produced in a cost-effective manner.

Han et al. [12] have used phase change materials as nanoparticles in nanofluids to simultaneously enhance the effective thermal conductivity and specific heat of the fluids. As an example, a suspension of indium nanoparticles (melting temperature, 157°C) in polyalphaolefin has been synthesized using a one-step, nanoemulsification method. The fluid's thermophysical properties, that is, thermal conductivity, viscosity, and specific heat, and their temperature dependence were measured experimentally. The observed melting-freezing phase transition of the indium nanoparticles significantly augmented the fluid's effective specific heat.

This work is one of the few to address thermal diffusivity; similar studies allow industrial cooling applications to continue without thorough understanding of all the heat transfer mechanisms in nanofluids.

2.2. Smart Fluids. In this new age of energy awareness, our lack of abundant sources of clean energy and the widespread dissemination of battery operated devices, such as cell-phones and laptops, have accented the necessity for a smart technological handling of energetic resources. Nanofluids have been demonstrated to be able to handle this role in some instances as a smart fluid.

In a recent paper published in the March 2009 issue of Physical Review Letters, Donzelli et al. [13] showed that a particular class of nanofluids can be used as a smart material working as a heat valve to control the flow of heat. The nanofluid can be readily configured either in a "low" state, where it conducts heat poorly, or in a "high" state, where the dissipation is more efficient. To leap the chasm to heating and cooling technologies, the researchers will have to show more evidence of a stable operating system that responds to a larger range of heat flux inputs.

2.3. Nuclear Reactors. Kim et al. [14, 15] at the Nuclear Science and Engineering Department of the Massachusetts Institute of Technology (MIT), performed a study to assess the feasibility of nanofluids in nuclear applications by improving the performance of any water-cooled nuclear system that is heat removal limited. Possible applications include pressurized water reactor (PWR) primary coolant, standby safety systems, accelerator targets, plasma divertors, and so forth, [16].

In a pressurized water reactor (PWR) nuclear power plant system, the limiting process in the generation of steam is critical heat flux (CHF) between the fuels rods and the water—when vapor bubbles that end up covering the surface of the fuel rods conduct very little heat as opposed to liquid water. Using nanofluids instead of water, the fuel rods become coated with nanoparticles such as alumina, which actually push newly formed bubbles away, preventing the formation of a layer of vapor around the rod and subsequently increasing the CHF significantly.

After testing in MIT's Nuclear Research Reactor, preliminary experiments have shown promising success where it is seen that PWR is significantly more productive. The use of nanofluids as a coolant could also be used in emergency cooling systems, where they could cool down overheat surfaces more quickly leading to an improvement in power plant safety.

Some issues regarding the use of nanofluids in a power plant system include the unpredictability of the amount of nanoparticles that are carried away by the boiling vapor. One other concern is what extra safety measures that have to be taken in the disposal of the nanofluid. The application of nanofluid coolant to boiling water reactors (BWR) is predicted to be minimal because nanoparticle carryover to the turbine and condenser would raise erosion and fouling concerns.

From Jackson's study [17], it was observed that considerable enhancement in the critical heat flux can be achieved by creating a structured surface from the deposition of nanofluids. If the deposition film characteristics such as the structure and thickness can be controlled it may be possible to increase the CHF with little decrease in the heat transfer. Whereas the nanoparticles themselves cause no significant difference in the pool-boiling characteristics of water, the boiling of nanofluids shows promise as a simple way to create an enhanced surface.

The use of nanofluids in nuclear power plants seems like a potential future application [16]. Several significant gaps in knowledge are evident at this time, including, demonstration of the nanofluid thermal-hydraulic performance at prototypical reactor conditions and the compatibility of the nanofluid chemistry with the reactor materials.

Another possible application of nanofluids in nuclear systems is the alleviation of postulated severe accidents during which the core melts and relocates to the bottom of the reactor vessel. If such accidents were to occur, it is desirable to retain the molten fuel within the vessel by removing the decay heat through the vessel wall. This process is limited by the occurrence of CHF on the vessel outer surface, but analysis indicates that the use of nanofluid can increase the in-vessel retention capabilities of nuclear reactors by as much as 40% [18].

Many water-cooled nuclear power systems are CHF-limited, but the application of nanofluid can greatly improve the CHF of the coolant so that there is a bottom-line economic benefit while also raising the safety standard of the power plant system.

2.4. Extraction of Geothermal Power and Other Energy Sources. The world's total geothermal energy resources were calculated to be over 13000 ZJ in a report from MIT (2007) [19]. Currently only 200 ZJ would be extractable, however, with technological improvements, over 2,000 ZJ could be extracted and supply the world's energy needs for several millennia. When extracting energy from the earth's crust that varies in length between 5 to 10 km and temperature between 500°C and 1000°C, nanofluids can be employed to cool the pipes exposed to such high temperatures. When drilling, nanofluids can serve in cooling the machinery and equipment working in high friction and high temperature environment. As a "fluid superconductor," nanofluids could be used as a working fluid to extract energy from the earth core and processed in a PWR power plant system producing large amounts of work energy.

In the sub-area of drilling technology, so fundamental to geothermal power, improved sensors and electronics cooled by nanofluids capable of operating at higher temperature in downhole tools, and revolutionary improvements utilizing new methods of rock penetration cooled and lubricated by nanofluids will lower production costs. Such improvements will enable access to deeper, hotter regions in high grade formations or to economically acceptable temperatures in lower-grade formations.

In the sub-area of power conversion technology, improving heat-transfer performance for lower-temperature nanofluids, and developing plant designs for higher resource temperatures to the supercritical water region would lead to an order of magnitude (or more) gain in both reservoir performance and heat-to power conversion efficiency.

Tran et al. [20], funded by the United States Department of Energy (USDOE), performed research targeted at developing a new class of highly specialized drilling fluids that may have superior performance in high temperature drilling. This research is applicable to high pressure high temperature drilling, which may be pivotal in opening up large quantities of previously unrecoverable domestic fuel resources. Commercialization would be the bottleneck of progress in this sub-area.

3. Automotive Applications

Engine oils, automatic transmission fluids, coolants, lubricants, and other synthetic high-temperature heat transfer fluids found in conventional truck thermal systems—radiators, engines, heating, ventilation and air-conditioning (HVAC)—have inherently poor heat transfer properties. These could benefit from the high thermal conductivity offered by nanofluids that resulted from addition of nanoparticles [2, 21].

3.1. Nanofluid Coolant. In looking for ways to improve the aerodynamic designs of vehicles, and subsequently the fuel economy, manufacturers must reduce the amount of energy needed to overcome wind resistance on the road. At high speeds, approximately 65% of the total energy output from a truck is expended in overcoming the aerodynamic drag. This fact is partly due to the large radiator in front of the engine positioned to maximize the cooling effect of oncoming air.

The use of nanofluids as coolants would allow for smaller size and better positioning of the radiators. Owing to the fact that there would be less fluid due to the higher efficiency, coolant pumps could be shrunk and truck engines could be operated at higher temperatures allowing for more horsepower while still meeting stringent emission standards.

Argonne researchers, Singh et al. [22], have determined that the use of high-thermal conductive nanofluids in radiators can lead to a reduction in the frontal area of the radiator by up to 10%. This reduction in aerodynamic drag can lead to a fuel savings of up to 5%. The application of nanofluid 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. It is conceivable that greater improvement of savings could be obtained in the future.

In order to determine whether nanofluids degrade radiator material, they have built and calibrated an apparatus that can emulate the coolant flow in a radiator and are currently testing and measuring material loss of typical radiator materials by various nanofluids. Erosion of radiator material is determined by weight loss-measurements as a function of fluid velocity and impact angle.

In their tests, they observed no erosion using nanofluids made from base fluids ethylene and tri-cloroethylene gycols with velocities as high as 9 m/s and at 90°–30° impact angles. There was erosion observed with copper nanofluid at a velocity of 9.6 m/s and impact angle of 90°. The corresponding recession rate was calculated to be 0.065 mils/yr of vehicle operation.

Through preliminary investigation, it was determined that copper nanofluid produces a higher wear rate than the base fluid and this is possibly due to oxidation of copper nanoparticles. A lower wear and friction rate was seen for alumina nanofluids in comparison to the base fluid. Some interesting erosion test results from Singh et al. [22] are shown in Tables 1 and 2.

Shen et al. [23] researched the wheel wear and tribological characteristics in wet, dry and minimum quantity lubrication (MQL) grinding of cast iron. Water-based alumina and diamond nanofluids were applied in the MQL grinding process and the grinding results were compared with those of pure water. Nanofluids demonstrated the benefits of reducing grinding forces, improving surface roughness, and preventing burning of the workpiece. Contrasted to

Table 1: Erosion Test Results for 50% Ethlyene Glycol, 50% H2O Aluminum 3003 - 50°C Rig [22].

Impact Angle (*)	Velocity (m/s)	Time (hrs)	Weight Loss (mg)
90	8.0	236	0 ± 0.2
90	10.5	211	0 ± 0.2
50	6.0	264	0 ± 0.2
50	10.0	244	0 ± 0.2
30	8.0	283	0 ± 0.2
30	10.5	293	0 ± 0.2

Table 2: Erosion Test Results for Cu Nanoparticles in Trichloroethylene Glycol on Al 3003 - 50°C Rig [22].

Impact Angle (*)	Velocity (m/s)	Time (hrs)	Weight Loss (mg)
90	4.0	217	0 ± 0.2
30	4.0	311	0 ± 0.2
90	7.6	341	0 ± 0.2
30	7.6	335	0 ± 0.2
30	9.6	336	0 ± 0.2

dry grinding, MQL grinding could considerably lower the grinding temperature.

More research must be conducted on the tribological properties using nanofluids of a wider range of particle loadings as well as on the erosion rate of radiator material in order to help develop predictive models for nanofluid wear and erosion in engine systems. Future research initiatives involve nanoparticles materials containing aluminum and oxide-coated metal nanoparticles. Additional research and testing in this area will assist in the design of engine cooling and other thermal management systems that involve nanofluids.

Future engines that are designed using nanofluids' cooling properties would be able to run at more optimal temperatures allowing for increased power output. With a nanofluids engine, components would be smaller and weigh less allowing for better gas mileage, saving consumers money and resulting in fewer emissions for a cleaner environment.

3.2. Nanofluid in Fuel. The aluminum nanoparticles, produced using a plasma arc system, are covered with thin layers of aluminum oxide, owing to the high oxidation activity of pure aluminum, thus creating a larger contact surface area with water and allowing for increased decomposition of hydrogen from water during the combustion process. During this combustion process, the alumina acts as a catalyst and the aluminum nanoparticles then serve to decompose the water to yield more hydrogen. It was shown that the combustion of diesel fuel mixed with aqueous aluminum nanofluid increased the total combustion heat while decreasing the concentration of smoke and nitrous oxide in the exhaust emission from the diesel engine [24, 25].

3.3. Brake and Other Vehicular Nanofluids. As vehicle aerodynamics is improved and drag forces are reduced, there is a higher demand for braking systems with higher and more efficient heat dissipation mechanisms and properties such as brake nanofluid.

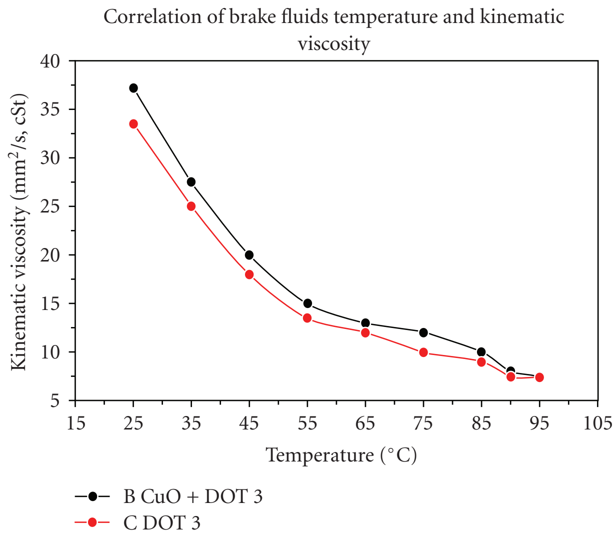

Figure 1: CBN Temperature and Viscosity Fluctuations [24, 25].

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. If the heat causes the brake fluid to reach its boiling point, a vapor-lock is created that retards the hydraulic system from dispersing the heat caused from braking. Such an occurrence will in turn will cause a brake malfunction and poses a safety hazard in vehicles. Since brake oil is easily affected by the heat generated from braking, nanofluids with enhanced characteristics maximize performance in heat transfer as well as remove any safety concerns.

Copper-oxide brake nanofluid (CBN) is manufactured using the method of arc-submerged nanoparticle synthesis system (ASNSS). Essentially this is done by melting bulk copper metal used as the electrode which is submerged in dielectric liquid within a vacuum-operating environment and the vaporized metals are condensed in the dielectric liquid [24, 25].

Aluminum-oxide brake nanofluid (AOBN) is made using the plasma charging arc system. This is performed in a very similar fashion to that of the ASNSS method. The aluminum metal is vaporized by the plasma electric arc at a high temperature and mixed thoroughly with the dielectric liquid [24, 25].

CBN has a thermal conductivity 1.6 times higher than that of the brake fluid designated DOT3, while AOBN's thermal conductivity is only 1.5 times higher than DOT3. This enhanced thermal conductivity optimizes heat transmission and lubrication.

CBN and AOBN both have enhanced properties such as a higher boiling point, higher viscosity and a higher conductivity than that of traditional brake fluid (DOT3). By yielding a higher boiling point, conductivity and viscosity, CBN and AOBN reduce the occurrence of vapor-lock and offer increased safety while driving. Important findings of Kao et al. [24, 25] are shown in Figure 1 and Table 3.

Table 3: CBN and AOBN Boiling Point and Thermal Conductivity Fluctuations [24, 25].

	DOT3*	CBN 2 wt% (CuO + DOT3)	DOT3*	AOBN 2 wt% (Al_2O_3+ DOT3)
Boiling Point	270^{o}C	278^{o}C	240^{o}C	248^{o}C
				-
Conductivity (25^{o}C)	0.03 W/m^{o}C	0.05 W/m^{o}C	0.13 W/m^{o}C	0.19 W/m^{o}C

* Different DOT3 brake fluids were used.

In the nanofluid research applied to the cooling of automatic transmissions, Tzeng et al. [26] dispersed CuO and Al_2O_3 nanoparticles into engine transmission oil. The experimental setup was the transmission of a four-wheel-drive vehicle. The transmission had an advanced rotary blade coupling, where high local temperatures occurred at high rotating speeds. Temperature measurements were taken on the exterior of the rotary-blade-coupling transmission at four engine operating speeds (range from 400 to 1600 rpm), and the optimum composition of nanofluids with regard to heat transfer performance was studied. The results indicated that CuO nanofluids resulted in the lowest transmission temperatures both at high and low rotating speeds. Therefore, the use of nanofluid in the transmission has a clear advantage from the thermal performance viewpoint. As in all nanofluid applications, however, consideration must be given to such factors as particle settling, particle agglomeration, and surface erosion.

In automotive lubrication applications, Zhang [27] reported that surface-modified nanoparticles stably dispersed in mineral oils are effective in reducing wear and enhancing load-carrying capacity. Results from a research project involving industry and academia points to the use of nanoparticles in lubricants to enhance tribological properties such as load-carrying capacity, wear resistance, and friction reduction between moving mechanical components. Such results are promising for enhancing heat transfer rates in automotive systems through the use of nanofluids.

4. Electronic Applications

Nanofluids are used for cooling of microchips in computers and elsewhere. They are also used in other electronic applications which use microfluidic applications.

4.1. Cooling of Microchips. A principal limitation on developing smaller microchips is the rapid heat dissipation. However, nanofluids can be used for liquid cooling of computer processors due to their high thermal conductivity. It is predicted that the next generation of computer chips will produce localized heat flux over 10 MW/m^2, with the total power exceeding 300 W. In combination with thin film evaporation, the nanofluid oscillating heat pipe (OHP) cooling system will be able to remove heat fluxes over 10 MW/m^2 and serve as the next generation cooling device that will be able to handle the heat dissipation coming from new technology [28, 29].

In order to observe the oscillation, researchers had to modify the metal pipe system of the OHP to use glass or plastic for visibility. However, since OHP systems are usually made of copper, the use of glass or plastic changes the thermal transfer properties of the system and subsequently altering the performance of the system and the legitimacy of the experimental data [28, 29].

So as to obtain experimental data while maintaining the integrity of the OHP system, Arif [30] employed neutron imaging to study the liquid flow in a 12-turn nanofluid OHP. As a consequence of the high intensity neutron beam from an amorphous silicon imaging system, they were able to capture dynamic images at 1/30th of a second. The nanofluid used was composed of diamond nanoparticles suspended in water.

Even though nanofluids and OHPs are not new discoveries, combining their unique features allows for the nanoparticles to be completely suspended in the base liquid increasing their heat transport capability. Since nanofluids have a strong temperature-dependent thermal conductivity and they show a nonlinear relationship between thermal conductivity and concentration, they are high performance conductors with an increased CHF. The OHP takes intense heat from a high-power device and converts it into kinetic energy of fluids while not allowing the liquid and vapor phases to interfere with each other since they flow in the same direction.

In their experiment, Ma et al. [28, 29] introduced diamond nanoparticles into high performance liquid chromatography (HPLC) water. The movement of the OHP keeps the nanoparticles from settling and thus improving the efficiency of the cooling device. At an input power of 80 W, the diamond nanofluid decreased the temperature difference between the evaporator and the condenser from 40.9°C to 24.3°C.

However, as the heat input increases, the oscillating motion increases and the resultant temperature difference between the evaporator and condenser does not continue to increase after a certain power input. This phenonmenon inhibits the effective thermal conductivity of the nanofluid from continuously increasing. However, at its maximum power level of 336 W, the temperature difference for the nanofluid OHP was still less than that for the OHP with pure water, Figure 2. Hence, it has been shown that the nanofluid can significantly increase the heat transport capability of the OHP.

Lin et al. [31] investigated nanofluids in pulsating heat pipes by using silver nanoparticles, and discovered encouraging results. The silver nanofluid improved heat transfer characteristics of the heat pipes.

Nguyen et al. [32] investigated the heat transfer enhancement and behavior of Al_2O_3-water nanofluid with the

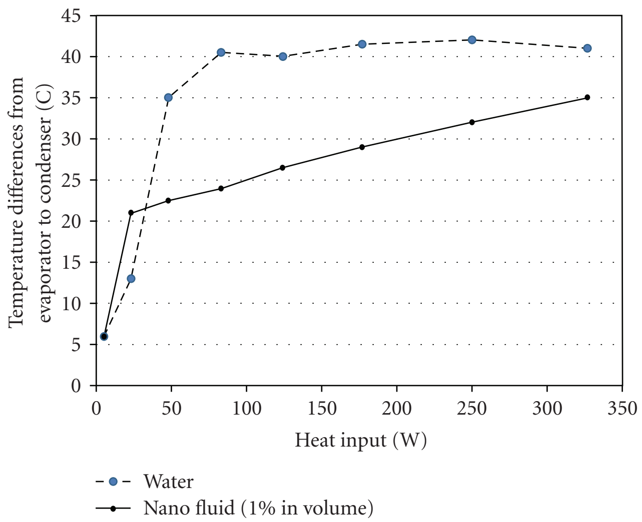

Figure 2: Effect of nanofluid on heat transport capability in an OHP [28, 29].

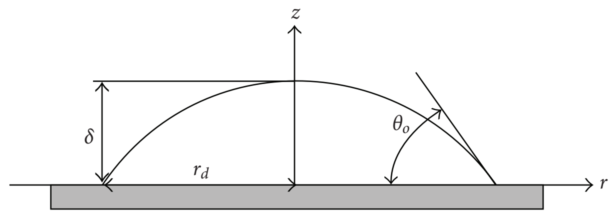

Figure 3: Schematic diagram of droplet shape.

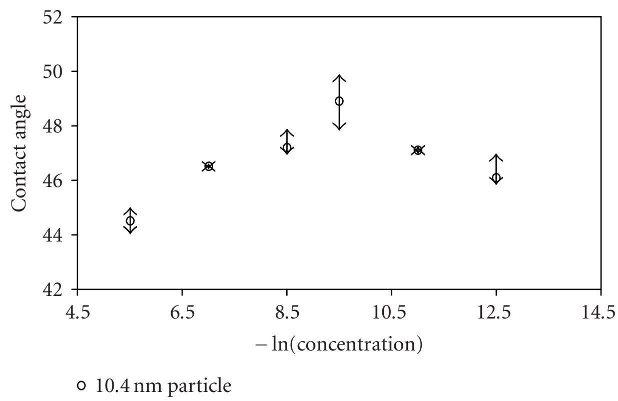

Figure 4: Variation of contact angle for 10 nm bismuth telluride nanoparticles concentration on a glass substrate [34].

intention of using it in a closed cooling system designed for microprocessors or other electronic devices. The experimental data supports that the inclusion of nanoparticles into distilled water produces a significant increase of the cooling convective heat transfer coefficient. At a given particle concentration of 6.8%, the heat transfer coefficient increased as much as 40% compared to the base fluid of water. Smaller Al_2O_3 nanoparticles also showed higher convective heat transfer coefficients than the larger ones.

Further research of nanofluids in electronic cooling applications will lead to the development of the next generation of cooling devices that incorporate nanofluids for ultrahigh-heat-flux electronic systems.

4.2. Microscale Fluidic Applications. The manipulation of small volumes of liquid is necessary in fluidic digital display devices, optical devices, and microelectromechanical systems (MEMS) such as lab-on-chip analysis systems. This can be done by electrowetting, or reducing the contact angle by an applied voltage, the small volumes of liquid. Electrowetting on dielectric (EWOD) actuation is one very useful method of microscale liquid manipulation.

Vafaei et al. [33] discovered that nanofluids are effective in engineering the wettability of the surface and possibly of surface tension. Using a goniometer, it was observed that even the addition of a very low concentration of bismuth telluride nanofluid dramatically changed the wetting characteristics of the surface. Concentrations as low as 3×10^{-6} increased the contact angle to over 40°, distinctly indicating that the nanoparticles change the force balance in the vicinity of the triple line. The contact angle, $\theta°$, Figure 3 rises with the concentration of the nanofluid, reaches a maximum, and then decreases, Figure 4 [34].

The droplet contact angle was observed to change depending on the size of the nanoparticles as well. Smaller nanoparticles are more effective in increasing the contact angle. The reason for this effect is that smaller particles would provide more surface-to-volume area, for the same concentration.

Dash et al. used the EWOD effect to demonstrate that nanofluids display increased performance and stability when exposed to electric fields, Figure 5. The experiment consisted of placing droplets of water-based solutions containing bismuth telluride nanoparticles onto a Teflon-coated silicon wafer. A strong change in the angle at with the droplet contacted the wafer was observed when an electric field was applied to the droplet. The change noticed with the nanofluids was significantly greater than when not using nanofluids. The bismuth telluride nanofluid also displayed enhanced droplet stability and absence of the contact angle saturation effect compared to solutions of 0.01 N Na_2SO_4 and thioglycolic acid in deionized water.

That the contact angle of droplets of nanofluids can be changed has potential applications for efficiently moving liquids in microsystems, allowing for new methods for focusing lenses in miniature cameras as well as for cooling computer chips.

5. Biomedical Applications.

5.1. Nanodrug Delivery. Most bio-MEMS studies were done in academia in the 1990s, while recently commercialization of such devices have started. Examples include an electronically activated drug delivery microchip [35]; a controlled delivery system via integration of silicon and electroactive polymer technologies; a MEMS-based DNA sequencer developed by Cepheid [36]; and arrays of in-plane and out-of-plane hollow micro-needles for dermal/transdermal drug

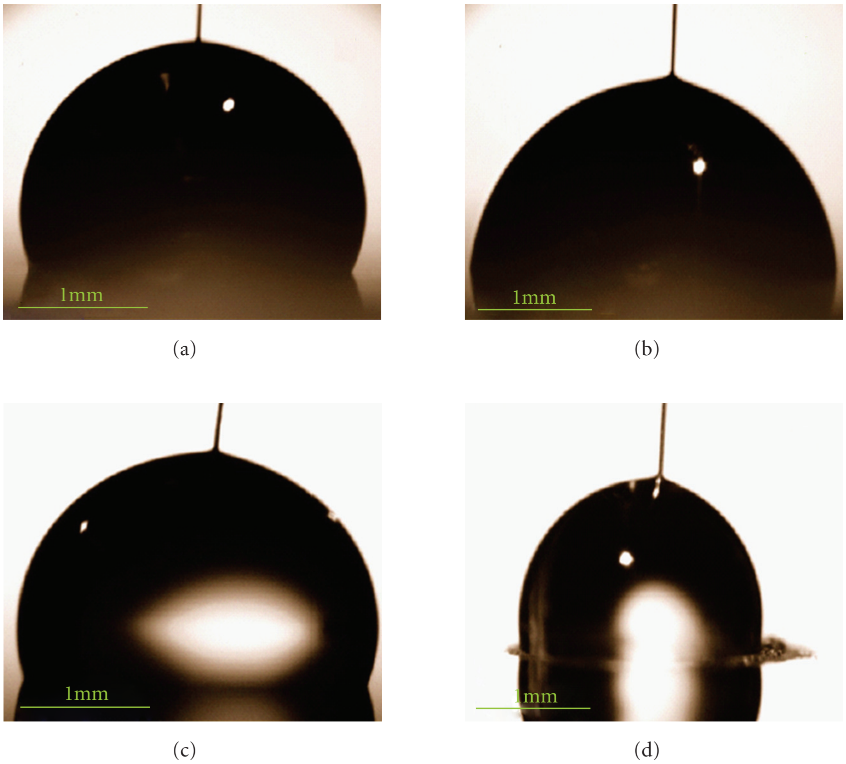

Figure 5: Nanofluid droplet with applied voltage (a) 0 V and (b) 64.5 V 0.01 M Na_2SO_4 droplet under (c) 0 V and (d) 40 V. The Na_2SO_4 droplet becomes unstable at approximately 40 V seen by the gas bubbles forming in the contact line, [34].

delivery [37, 38] as well as nanomedicine applications of nanogels or gold-coated nanoparticles [39]. An objective of the advanced endeavors in developing integrated micro- or nano-drug delivery systems is the interest in easily monitoring and controlling target-cell responses to pharmaceutical stimuli, to understand biological cell activities, or to enable drug development processes.

While conventional drug delivery is characterized by the "high-and-low" phenomenon, microdevices facilitate precise drug delivery by both implanted and transdermal techniques. This means that when a drug is dispensed conventionally, drug concentration in the blood will increase, peak and then drop as the drug is metabolized, and the cycle is repeated for each drug dose. Employing nano-drug delivery (ND) systems, controlled drug release takes place over an extended period of time. Thus, the desired drug concentration will be sustained within the therapeutic window as required.

A nanodrug-supply system, that is, a bio-MEMS, was introduced by Kleinstreuer et al. [40]. Their principal concern were the conditions for delivering uniform concentrations at the microchannel exit of the supplied nano-drugs. A heat flux which depends on the levels of nano-fluid and purging fluid velocity was added to ascertain that drug delivery to the living cells occurs at an optimal temperature, that is, 37°C. The added wall heat flux had also a positive influence on drug-concentration uniformity. In general, the nano-drug concentration uniformity is affected by channel length, particle diameter and the Reynolds number of both the nanofluid supply and main microchannels. Since the transport mechanisms are dependent on convection—diffusion, longer channels, smaller particle diameters as well as lower Reynolds numbers are desirable for best, that is, uniform drug delivery.

5.2. Cancer Theraupetics. There is a new initiative which takes advantage of several properties of certain nanofluids to use in cancer imaging and drug delivery. This initiative 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. It will allow doctors to deliver high local doses of drugs or radiation without damaging nearby healthy tissue, which is a significant side effect of traditional cancer treatment methods. In addition, magnetic nanoparticles are more adhesive to tumor cells than non-malignant cells and they absorb much more power than microparticles in alternating current magnetic fields tolerable in humans; they make excellent candidates for cancer therapy.

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 [41]. 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. The nanofluid containing magnetic nanoparticles also acts as a super-paramagnetic fluid which in an alternating electromagnetic field absorbs energy producing a controllable hyperthermia. By enhancing the chemotherapeutic efficacy, the hyperthermia is able to produce a preferential radiation effect on malignant cells [42].

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 [43, 44].

Nanofluids could be applied to almost any disease treatment techniques by reengineering the nanoparticles' properties. In their study, the nanoparticles were laced with the drug docetaxel to be dissolved in the cells' internal fluids, releasing the anticancer drug at a predetermined rate. The nanoparticles contain targeting molecules called aptamers which recognize the surface molecules on cancer cells preventing the nanoparticles from attacking other cells. In order to prevent the nanoparticles from being destroyed by macrophages—cells that guard against foreign substances entering our bodies—the nanoparticles also have polyethylene glycol molecules. The nanoparticles are excellent drug-delivery vehicles because they are so small that living cells absorb them when they arrive at the cells' surface.

For most biomedical uses the magnetic nanoparticles should be below 15 nm in size and stably dispersed in water. A potential magnetic nanofluid that could be used for biomedical applications is one composed of FePt nanoparticles. This FePt nanofluid possesses an intrinsic chemical stability and a higher saturation magnetization making it ideal for biomedical applications. However, before magnetic nanofluids can be used as drug delivery systems, more research must be conducted on the nanoparticles containing the actual drugs and the release mechanism.

5.3. Cryopreservation. Conventional cryopreservation protocols for slow-freezing or vitrification involve cell injury due to ice formation/cell dehydration or toxicity of high cryoprotectant (CPA) concentrations, respectively. In the study by X. He et al. [45], they developed a novel cryopreservation technique to achieve ultra-fast cooling rates using a quartz micro-capillary (QMC). The QMC enabled vitrification of murine embryonic stem (ES) cells using an intracellular cryoprotectant concentration in the range used for slowing freezing (1–2 M). More than 70% of the murine ES cells post-vitrification attached with respect to non-frozen control cells, and the proliferation rates of the two groups were alike. Preservation of undifferentiated properties of the pluripotent murine ES cells post-vitrification cryopreservation was verified using three different types of assays. These results indicate that vitrification at a low concentration (2 M) of intracellular cryoprotectants is a viable and effective approach for the cryopreservation of murine embryonic stem cells.

5.4. 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 [46] 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 cyrosugery 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. Additionally, introduction of nanoparticle enhanced freezing could also make conventional cyrosurgery more flexible in many aspects such as artificially interfering in the size, shape, image and direction of iceball formation. The concepts of nanocyrosurgery may offer new opportunities for future tumor treatment.

With respect to the choice of particle for enhancing freezing, magnetite (Fe_3O_4) and diamond are perhaps the most popular and appropriate because of their good biological compatibility. Particle sizes less than 10 μm are sufficiently small to start permitting effective delivery to the site of the tumor, either via encapsulation in a larger moiety or suspension in a carrier fluid. Introduction of nanoparticles into the target via a nanofluid would effectively increase the nucleation rate at a high temperature threshold.

5.5. Sensing and Imaging. Colloidal gold has been used for several centuries now, be it as colorant of glass ("Purple of Cassius") and silk, in medieval medicine for the diagnosis of syphilis or, more recently, in chemical catalysis, non-linear optics, supramolecular chemistry, molecular recognition and the biosciences. Colloidal gold is often referred to as the most stable of all colloids. Its history, properties and applications have been reviewed extensively. For a thorough and up-to-date overview the paper by Daniel and Astruc [48] and the references cited therein may be consulted. As stated in the introduction, no attempt is made here to review the use of colloids which are also nanofluids. An increase of colloids which are nanofluids is expected in this category.

6. Other Applications

6.1. Nanofluid Detergent. Nanofluids do not behave in the same manner as simple liquids with classical concepts of spreading and adhesion on solid surfaces [7, 49, 50]. This fact opens up the possibility of nanofluids being excellent candidates in the processes of soil remediation, lubrication, oil recovery and detergency. Future engineering applications could abound in such processes.

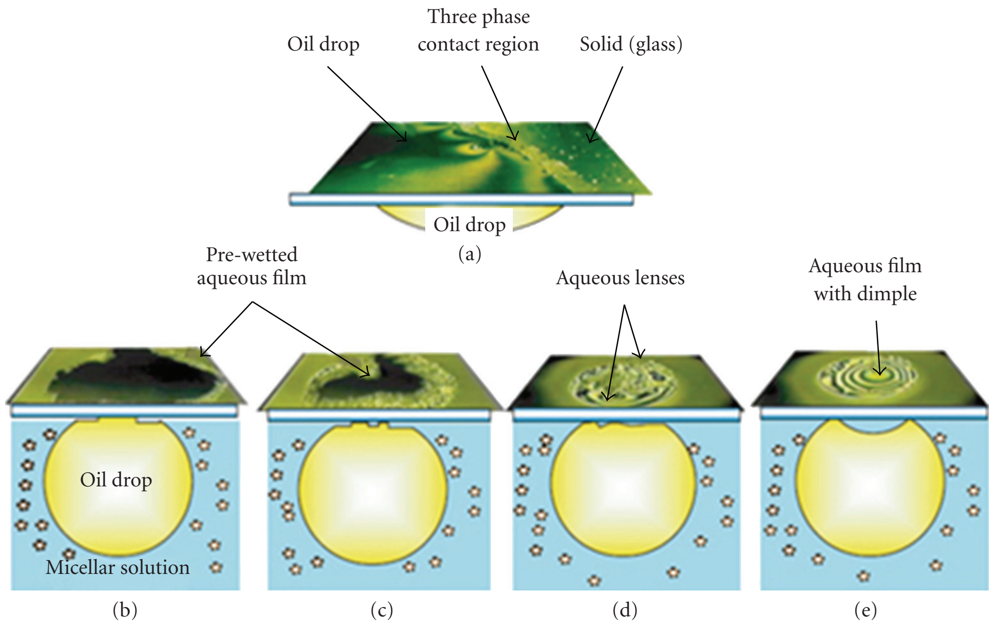

FIGURE 6: (a) Photomicrograph showing the oil drop placed on a glass surface and differential interference patterns formed at the three-phase contact region [47]. (b), Photomicrographs taken after addition of the nanofluid at (b), 30 s; 2 minutes; (d), 4 minutes; (e), 6 minutes region [47].

Wasan and Nikolov [47] of Illinois Institute of Technology in Chicago were able to use reflected-light digital video microscopy to determine the mechanism of spreading dynamics in liquid containing nanosized polystyrene particles, Figure 6. They were able to demonstrate the two-dimensional crystal-like formation of the polystyrene spheres in water and how this enhances the spreading dynamics of a micellar fluid at the three-phase region [47].

When encountering an oil drop, the polystyrene nanoparticles concentrate and rearrange around the drop creating a wedge-like region between the surface and the oil drop. The nanoparticles then diffuse into the wedge film and cause an increase in concentration and subsequently an increase in disjoining pressure around the film region. Owing to the increase in pressure, the oil-solution interface moves forward allowing the polystyrene nanoparticles to spread along the surface. It is this mechanism that causes the oil drop to detach completely from the surface.

Wasan and Nikolov [47] performed an additional experiment where they introduced an electrolyte into the process in order to decrease the interfacial tension at the interface of the oil and the nanofluid, but found that the drop did not become detached from the surface. They actually observed a diminished disjoining pressure contrary to the logical prediction. Additional work must be done in this area to determine such behavior of the nanofluid.

Overall, this phenomenon which involves the increased spreading of the detergent surfactants, which are not only limited to polystyrene nanoparticles, and enhanced oil removal process offers a new way of removing stains and grease from surfaces. This type of nanofluid also has potential in the commercial extraction of oil from the ground as well as the remediation of oil spills.

7. Conclusion

Nanofluids are important because they can be used in numerous applications involving heat transfer, and other applications such as in detergency. Colloids which are also nanofluids have been used in the biomedical field for a long time, and their use will continue to grow. Nanofluids have also been demonstrated for use as smart fluids. Problems of nanoparticle agglomeration, settling, and erosion potential all need to be examined in detail in the applications. Nanofluids employed in experimental research have to be well characterized with respect to particle size, size distribution, shape and clustering so as to render the results most widely applicable. Once the science and engineering of nanofluids are fully understood and their full potential researched, they can be reproduced on a large scale and used in many applications. Colloids which are also nanofluids will see an increase in use in biomedical engineering and the biosciences.

Further research still has to be done on the synthesis and applications of nanofluids so that they may be applied as predicted. Nevertheless, there have been many discoveries and improvements identified about the characteristics of nanofluids in the surveyed applications and we are a step closer to developing systems that are more efficient and smaller, thus rendering the environment cleaner and healthier.

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