A Review of Nanofluids and Their Implementation for Heat Transfer Enhancement

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Abstract- *Nanofluids, which are the colloidal suspensions of nanaomaterials, have displayed many interesting properties and distinctive features that offer unprecedented potential for many applications specifically in heat transfer equipments. This paper provides a gist on the recent progress on the research of nanofluids, such as the synthesis methods, factors affecting stability and techniques for stability enhancement of nanofluids. The notable thermal properties of nanofluids and their implementation in specific HVAC & R applications, as engine cooling, cooling of electronics, cooling of heat exchanging devices, improving heat transfer efficiency of chillers, domestic refrigerator-freezers, cooling in machining, cooling of nuclear reactors and few others have been reviewed. The paper also highlights certain desirable advantages of nanofluid based systems over conventional fluid systems, along with the challenges associated with their wide scale implementation in industrial applications. At last, future opportunities in nanofluid research are identified and directions are given to enable the achievement of the nanofluid vision.*

Keywords- Nanofluids, Applications of Nanofluids, Thermal properties, HVAC & R.

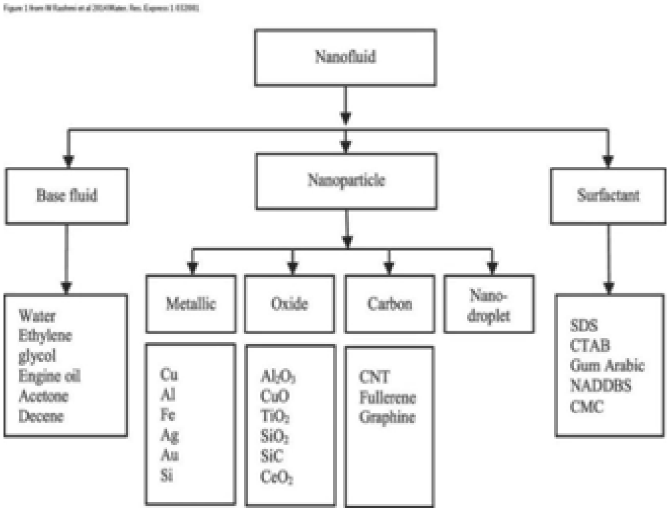
I. INTRODUCTION

Nanofluids are a novel 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 condensed nanomaterials. These are high potential heat transfer fluids, with enhanced thermophysical properties, heat transfer performance and can be applied in many applications for better performance.

In the last few decades, a strong tendency to get more and more compact and efficient heat exchangers has been observed. Smaller and more efficient devices allow to reduce energy consumption, fluids charge, and environmental impact. A new opportunity to significantly increase the heat exchange is given by paying attention on the fluid performance. Within its activity on miniaturisation of heat exchangers, Stephen Choi, at the Argonne Laboratory, had the intuition to mix nanoparticles to liquids to improve their thermal conductivity obtaining what he called "nanofluids". The idea to enhance thermal conductivity of fluids by mixing metallic particles date back to 1873, when it was first proposed by Maxwell, considering that solids have thermal conductivity orders of magnitude higher than liquids. However, millimetric or micrometric particles have a strong tendency to deposit and cannot be employed in micro channels because of possible channels obstruction. The use of nanoparticles promises to get much more stable fluids, no obstruction, low wearing and huge enhancements of thermal conductivity and eventually of heat transfer coefficients with respect to the base fluid (Choi, 1999) [1].

In recent years, nanofluids have attracted more and more attention. Eastman et al.[2], Liu et al. [3], Hwang et al. [4], Yu et al. [5] and Mintsa et al. [6], observed great enhancement of nanofluids thermal conductivity compared to conventional coolants. Although some review articles involving the progress of nanofluid investigation were published in the past several years, most of the reviews are concerned with the experimental and theoretical studies of the thermophysical properties or the convective heat transfer of nanofluids.

II. COMPOSITION OF NANOFLUIDS [7]



III. SYNTHESIS OF NANOFLUIDS

Nanoparticles are extremely interesting since the physical behaviour of materials is different at nanometric scale, the thermal, mechanical, optical, magnetic, and electrical properties are superior to those of conventional solids. Nanofluids are obtained by dispersing nanoparticles in common liquids like water, ethylene glycol, oils etc. The primary need is to obtain a stable and homogenous colloidal solution for successful reproduction of properties and interpretation of experimental data. The two commonly employed methods for the synthesis of Nanofluids are discussed as under;

3.1 Two-step method

Two-step method is the most widely used method for preparing nanofluids. Nanoparticles, nanofibers, nanotubes, or other nanomaterials used in this method are first produced as dry powders by chemical or physical methods. Then, the nanosized powder is dispersed into a fluid in the second processing step with the help of intensive magnetic force agitation, ultrasonic agitation, high-shear mixing, homogenizing, and ball milling.

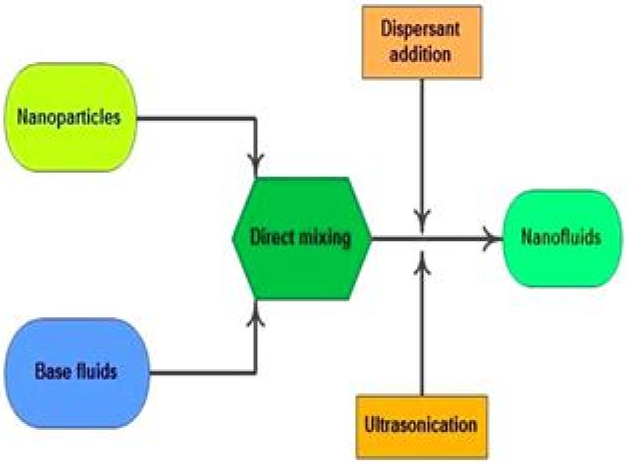


Figure 1: Two step preparation process of nanofluids [8]

However, due to the difficulty in preparing stable nanofluids by two-step method, several advanced techniques are developed to produce nanofluids, including one-step method. In the following part, we will introduce one-step method in detail.

3.2 One-step method

The one-step process consists of simultaneously making and dispersing the particles in the fluid. In this method, the processes of drying, storage, transportation, and dispersion of nanoparticles are avoided, so the agglomeration of nanoparticles is minimized, and the stability of fluids is increased. The one step process results in the production of relatively more stable nanofluids with uniform distribution of nanoparticles in the base fluid. The different morphologies are mainly influenced and determined by various thermal conductivity properties of the dielectric liquids. The nanoparticles prepared exhibit needle-like, polygonal, square, and circular morphological shapes. The method avoids the undesired particle aggregation fairly.

Figure 2:One-step preparation process of nanofluids. [8]

One-step physical method cannot synthesize nanofluids in large scale, and the cost involved in the one step process is also high, hence the one-step chemical method is developing rapidly.

Table 1.Preparation methods of few nanofluids [9]

Nanofluid	Method	Surfactant	Stability	Reference
Al2O3-Water	Two step	None	24h	Eastman et al (1997)
TiO2-Water	Two step	Oleic Acid and CTAB		Murshed et al (2010)
Cu-Water	Two step	Laurate salt	30h	Xuan and Li (2000)
MWCNT Water	Two step	SDS		Hong et al (2000)
Ag-Water	Two step	None	24h	Godson et al (2005)

IV. THERMAL CONDUCTIVITY OF NANOFLUIDS

The actual practical application of nanofluids demands sufficient acquaintance with the thermophysical properties of nanofluids. In the last decade, significant experimental as well as theoretical research has been carried out in order to determine thethermophysical characteristics of nanofluids. There are many reviews on nanofluid thermal conductivity research (Wang *et al.*, 2007; Murshed *et al.*, 2008a; Choi *et al.*, 2009; Wen *et al.*, 2009). Experimental work done by a good number of research groups worldwide has revealed that nanofluids exhibit thermal properties superior to base fluid or conventional micrometer sized particle-fluid suspensions. Authors stressed that, the thermal conductivity plays an important role in construction of energy efficient heat transfer equipment.

4.1 Factors responsible for increased Thermal conductivity of nanofluids

This increase in the thermal conductivity is predicted to be because of thefollowing reasons:

1. Brownian motion
2. Interfacial layer
3. Volume fraction of particles

Table 2: Summary of literature review on thermal conductivity of nanofluids. Main source [11]

	Particle	Base fluid	Average particle size	Volume fraction	Thermal conductivity enhancement
Metallic nanofluids	Cu	Ethylene glycol	10 nm	0.3%	40%
	Cu	Water	100 nm	7.5%	78%
	Fe	Ethylene glycol	10 nm	0.55%	18%
	Au	Water	10–20 nm	0.026%	21%
	Ag	Water	60–80 nm	0.001%	17%
Non-metallic nanofluids	Al_2O_3	Water	13 nm	4.3%	30%
	Al_2O_3	Water	33 nm	4.3%	15%
	Al_2O_3	Water	68 nm	5%	21%
	CuO	Water	36 nm	3.4%	12%
	CuO	Water	50 nm	0.4%	17%
	SiC	Water	26 nm	4.2%	16%
	TiO_2	Water	15 nm	5%	30%
	MWCNT	Synthetic oil	25 nm in diameter 50 μm in length	1%	150%
	MWCNT	Decene/ethylene glycol/water	15 nm in diameter 30 μm in length	1%	20%/13%/7%
	MWCNT	Water	100 nm in diameter 70 μm in length	0.6%	38%

V. OVERVIEW OF APPLICATIONS OF NANOFLUID

The advent of high heat flow processes has created significant demand for new technologies to enhance heat transfer. For example, microprocessors have continually become smaller and more powerful, and as a result heat flow demands have steadily increased over time leading to new challenges in thermal management. Furthermore, there is increasing interest in improving the efficiency of existing heat transfer processes. An example is in automotive systems where improved heat transfer could lead to smaller heat exchangers for cooling resulting in reduced weight of the vehicle.

Many methods are available to improve heat transfer in processes. The flow of heat in a process can be calculated as follows:

$$Q=hA\Delta T$$

Where; Q is the heat flow, h is the heat transfer coefficient, A is the heat transfer area, and ΔT is the temperature difference that results in heat flow. It can be stated from this equation that increased heat transfer can be achieved by:

(i) increasing ΔT;
(ii) increasing A;
(iii) increasing h.

A greater temperature difference ΔT can lead to increase in heat flow, but ΔT is often limited by process or materials constraints. For example, the maximum temperature in a nuclear reactor must be kept below a certain value to avoid runaway reactions and meltdown. Therefore, increased ΔT can only be achieved by decreasing the temperature of the coolant. However, this would reduce the rate of the nuclear reaction and decrease the efficiency of the process. Maximizing the heat transfer area A is a common strategy to improve heat transfer, and many heat exchangers such as radiators and plate-and-frame heat exchangers are designed to maximize the heat transfer area. However, this strategy cannot be employed in microprocessors and microelectromechanical systems (MEMS) because the area cannot be increased. In

aerospace and automotive systems, increasing the heat transfer area can only be achieved by increasing the size of the heat exchanger which can lead to unwanted increases in weight.
Heat transfer improvements can also be achieved by increasing the heat transfer coefficient h either by using more efficient heat transfer methods, or by improving the transport properties of the heat transfer material.

Some of the areas of Nanofluids applications are listed below:

- Engine cooling.
- Engine transmission oil.
- In diesel electric generator as water coolant
- Boiler exhaust flue gas recovery.
- Heating and cooling of buildings.
- Cooling of electronics.
- Cooling of welding.
- Nanofluids in transformer cooling oil.
- Nuclear systems cooling.
- Solar water heating.
- Nanofluids in drilling.
- Refrigeration (domestic refrigerator, chillers).
- Defence.
- Space.
- High-power lasers, microwave tubes.
- Biomedical applications.
- Drilling.
- Lubrications

VI. APPLICATIONS OF NANOFLUIDS FOR HEAT TRANSFER ENHANCEMENT

This section of the paper highlights certain specific engineering applications of nanofluids particularly aimed at heat transfer enhancement. These are briefly discussed as under;

6.1 Cooling of electronics

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.

Micro scale 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 electro wetting. It is discovered that nanofluids are effective in engineering the wettability of the surface and possibly of surface tension.

6.2 Application in chillers

Many reported that 40% increase in thermal conductivity for 0.4% volume fraction of nanofluids. This gives an opportunity for improving performance of chillers in air conditioning systems. Surprisingly, the cooling capacity of the nanofluids could be increased by 4.2% at the standard rating conditions. A 6.7% increase in the capacity was encountered at a flow rate of 60L/min. The unexpected rise in the cooling capacity of the nanofluids was related to the dynamic interaction of the flow field and the nanopowder. The nano powders were capable of absorbing the fluctuation of the turbulent kinetic energy, giving rise to a better heat transfer characteristic under dynamic conditions, thereby leading to better system performance. At the standard rating conditions, the introduction of nanofluids gave rise to an increase in the COP by 5.15%, relative to a condition without nanofluids. Furthermore, the pressure drop penalty of the addition of nanofluids was almost negligible.

6.3 Transportation

Nanofluids possess great potential 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.

Ethylene glycol-based nanofluids have attracted great attention in the application as engine coolant 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 have a high boiling point, and can be used to increase the normal coolant operating temperature and then reject more heat through the existing coolant system. Kole et al. prepared car engine coolant (Al2O3 nanofluid) using a standard car engine coolant (HP KOOLGARD) as the base fluid and studied the thermal conductivity and viscosity of the coolant. The prepared nanofluid, containing only 3.5% volume fraction of Al2O3 nanoparticles, displayed a fairly higher thermal conductivity than the base fluid, and a maximum enhancement of 10.41% was observed at room temperature.

The researchers of Argonne National Laboratory have assessed the applications of nanofluids for transportation. 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.

In fact, nanofluids not only enhance the efficiency and economic performance of car engine, but also will greatly influence the structure design of auto motives. For example, the engine radiator cooled by a nanofluid will be smaller and lighter. It can be placed elsewhere in the vehicle, allowing for the redesign of a far more aerodynamic chassis. By reducing the size and changing the location of the radiator, a reduction in weight and wind resistance could enable greater fuel efficiency and subsequently lower exhaust Journal emissions.

Computer simulations from the US department of energy’s office of vehicle technology showed that nanofluid coolants could reduce the size of truck radiators by 5%. This would result in a 2.5% fuel saving at highway speeds. The practical applications are on the road. In USA, car manufacturers GM and Ford are running their own research programs on nanofluid applications. A C8.3 million FP7 project, named NanoHex (Nanofluid Heat Exchange), began to run. It involved 12 organizations from Europe and Israel ranging from Universities to SMEs and major companies. NanoHex is overcoming the technological challenges faced in development and application of reliable and safe nanofluids for more sophisticated, energy efficient, and environmentally friendly products and services.

6.4 Application in domestic refrigerator

The experimental results by Jiang et.al showed that the thermal conductivities of carbon nanotube (CNT) nanorefrigerants are much higher than those of CNT–water nano fluids or spherical nanoparticle-R113 nanorefrigerants. Some investigations were carried out with nanoparticles in refrigeration systems to use advantageous properties of nanoparticles to enhance the efficiency and reliability of refrigerators.

Li et.al. investigated the pool boiling heat transfer characteristics of R11 refrigerant with TiO_2 nanoparticles and showed that the heat transfer enhancement reached 20% at a particle loading of 0.01g/L. Parkand Jung investigated the effects of carbon nanotubes(CNTs) on the nucleate boiling heat transfer of R123 and HFC134 a refrigerants. Authors test results showed that CNTs increase the nucleate boiling heat transfer coefficients for these refrigerants.

Thus, the use of nanoparticles in refrigeration systems is a new, innovative way to enhance the efficiency and reliability of refrigerators.

6.5 Mechanical applications:

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 behaviour 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.

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 nonpolar and polar carrier liquids. 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.

6.6 Heat Exchangers

The increases in effective thermal conductivity are important in improving the heat transfer behaviour of fluids. A number of other variables also play key roles. For example, the heat transfer coefficient for forced convection in tubes depends on many physical quantities related to the fluid or the geometry of the system through which the fluid is flowing. These quantities include intrinsic properties of the fluid such as its thermal conductivity, specific heat, density, and viscosity, along with extrinsic system parameters such as tube diameter and length and average fluid velocity. Therefore, it is essential to measure the heat transfer performance of nanofluids directly under flow conditions. Researchers have shown that nanofluids have not only better heat conductivity but also greater convective heat transfer capability than that of base fluids.

6.7 Application in Nuclear systems:

Nuclear system cooling:

The researchers are exploring the nuclear applications of nanofluids, specifically the following three areas:

1. Main reactor coolant for pressurized water reactors (PWRs). It could enable significant power uprates in current and future PWRs, thus enhancing their economic performance.
2. Coolant for the emergency core cooling systems (ECCSs) of both PWRs and boiling water reactors. The use of a nanofluid in the ECCS accumulators and safety injection can increase the peak-cladding-temperature margins (in the nominal-power core) or maintain them in uprated cores if the nanofluid has a higher post-CHF heat transfer rate;

6.8 Engine Cooling

Vehicle thermal management is a crosscutting technology because it directly or indirectly affects engine performance, fuel economy, safety and reliability, aerodynamics, driver/passenger comfort, materials selection, emissions, maintenance, and component life. It follows that an effective and responsive thermal management system is critical to the design and operation of over- the-road trucks that are fuel-efficient and that meet increasingly stringent emissions standards.

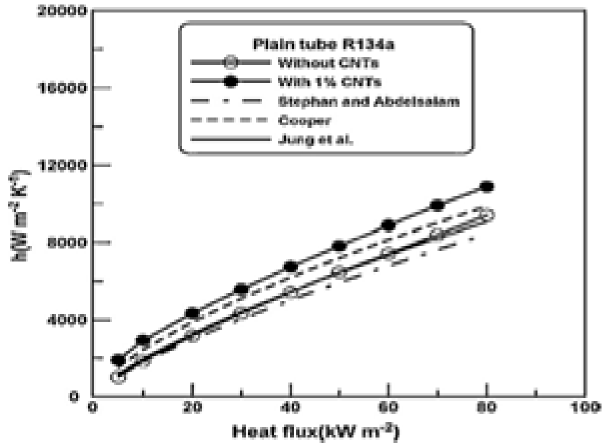


Figure 3: Convective heat transfer coefficient v/s Heat flux.

Choi et al (1995) showed that nanofluids have the potential of being recognized as a new generation of coolants for vehicle thermal management due to their significantly higher thermal conductivities than the base fluids. The heat rejection requirements of automobiles and trucks are continually increasing due to trends toward more power output.

Olivier et al numerically investigated the possible application of nanofluids as a jacket water coolant in a gas spark ignition engine. Authors performed numerical simulations of unsteady heat transfer through the cylinder and inside the coolant flow. Authors reported that because of higher thermal diffusivity of nanofluids, the thermal signal variations for knock detection increased by 15% over that predicted using water alone. Thermal management of heavy vehicle engines and support systems is a technology that addresses reduction in energy usage through improvements in engine thermal efficiency and reductions in parasitic energy uses and losses. An ethylene glycol and water mixture, the nearly universally used automotive coolant, is a relatively poor heat transfer fluid compared to water alone. Engine oils perform even worse as a heat transfer medium. The addition of nanoparticles to the standard engine coolant has the potential to improve automotive and heavy-duty engine cooling rates. Such improvement can be used to remove engine heat with a reduced-size coolant system. Smaller coolant systems result in smaller and lighter radiators, which in turn benefit almost every aspect of car and economy. This may reduce the coefficient of drag and thus resulting in less fuel consumption. Alternatively, improved cooling rates for automotive and truck engines can be used to remove more heat from higher horse-power engines with the same size of coolant system.

A promising nanofluids engine coolant is pure ethylene glycol with nanoparticles. Tzengetal. Dispersed CuOandAl2O3 nanoparticles into engine transmission oil. The experimental platform was the transmission of a four- wheel-drive vehicle. The temperature distribution on the exterior of the rotary blade coupling transmission was measured at four engine operating speeds. The temperature distribution on the exterior of the rotary blade-coupling transmission was measured at four engine operating speeds (400, 800, 1200, and1600rpm), and the optimum composition of nanofluids with regards to heat transfer performance was investigated. Authors reported that CuO nanofluid- ids produced the lowest transmission temperatures at both high and low rotating speeds .Thus, use of nanofluids in the transmission has a clear advantage from the thermal performance viewpoint.

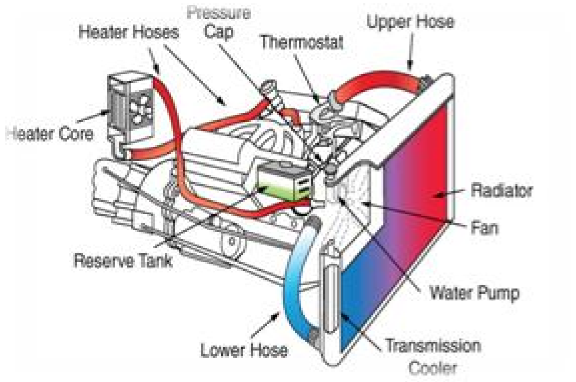


Figure 4: Radiator of an I.C Engine

Choi reported that in US a project was initiated to target fuel savings for the HV industry through the development of energy efficient nanofluids and smaller and lighter radiators. A major goal of the nanofluids project is to reduce the size and weight of the HV cooling systems by > 10% thereby increasing fuel efficiency by>5%, despite the cooling demands of higher- power engines and EGR. Nanofluids enable the potential to allow higher temperature coolants and higher heat rejection in HVs.

6.9. Heating Buildings and Reducing Pollution

Nanofluids can be applied in the building heating systems. Kulkarni et al. evaluated how they perform heating buildings in cold regions. In cold regions, it is a common practice to use ethylene or propylene glycol mixed with water in different proportions as a heat transfer fluid. So, 60: 40 ethylene glycol/water (by weight) was selected as the base fluid. The results showed that using nanofluids in heat exchangers could reduce volumetric and mass flow rates, resulting in an overall pumping power savings. Nanofluids necessitate smaller heating systems, which are capable of delivering the same amount of thermal energy as larger heating systems but are less expensive. This lowers the initial equipment cost excluding nanofluid cost. This will also reduce environmental pollutants, because smaller heating units use less power, and the heat transfer unit has less liquid and material waste to discard at the end of its life cycle.

6.10Space, Defence and Ships

Due to the restriction of space, energy, and weight in space station and aircraft, there is a strong demand for high efficient cooling system with smaller size. You et al. and Vassalo et al. have reported order of magnitude increases in the critical heat flux in pool boiling with nanofluids compared to the base fluid alone. Further research of nanofluids will lead to the development of next generation of cooling devices that incorporate nanofluids for ultrahigh-heat-flux electronic systems, presenting the possibility of raising chip power in electronic components or simplifying cooling requirements for space applications. A number of military devices and systems require high-heat flux cooling to the level of tens of MW/m2. At this level, the cooling of military devices and system is vital for the reliable operation. Nanofluids with high critical heat fluxes have the potential to provide the required cooling in such applications as well as in other military systems, including military vehicles, submarines, and high-power laser diodes. Therefore, nanofluids have wide application in space and defence fields, where power density is very high and the components should be smaller and weight less.

VII. BENEFITS AND CHALLENGES ASSOCIATED WITH THE USE OF NANOFLUIDS

Nanofluids are dilute suspensions of functionalized nanoparticles composite materials developed about a decade ago with the specific aim of increasing the thermal conductivity of heat transfer fluids, which have now evolved 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. Compared to conventional solid–liquid suspensions for heat transfer intensifications, Nanofluids possess the following advantages:

Benefits of nanofluids over conventional fluids

- 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.

Limitation of using Nanofluids as challenges associated with use of Nanofluids

Nanofluids attracts wide range of applications in various fields. But still the development in the area of nanofluid is hindered by various factors as the present challenges associated with the use of Nanofluids. Some of the important factors are:

1. Long term stability of Nanofluids: A long term stable Nanofluids needs to be prepared which could sustain all its properties and also be efficient under changing thermal and physical conditions. Long term physical and chemical stability of nanofluids is an important practical issue because of aggregation of nanoparticles due to very strong Vander waals interactions so the suspension is not homogeneous. Physical or chemical methods have been applied to get stable nanofluids such as: (i) an addition of surfactant; (ii) surface modification of the suspended particles; (iii) applying strong force on the clusters of the suspended particles.

2.Increased pressure drop and pumping power: Pressure drop development and required pumping power during the flow of coolant determines the efficiency of nanofluid application. It is known that higher density and viscosity leads to higher pressure drop and pumping power. There are many studies showing significant increase of nanofluids pressure drop compared to base fluid. One of the experimental study by Choi (2009) calculated 40% increase of pumping power compared to water for a given flow rate.

3. Low specific heat: In order to have an enhanced or higher rate of heat flow an ideal heat transfer fluid must possess higher value of specific heat so the fluid can transfer more heat .Previous studies show that Nanofluids exhibit lower value of specific heat, which limits its application.

4. Thermal conductivity of Nanofluids: The existing models for predicting thermal conductivities of CNT nanofluids, including Hamilton–Crosser model, Yu–Choi model and Xue model, cannot predict the thermal conductivities of CNT nanorefrigerants within a mean deviation of less than 15%.

5. Difficulties in production processes: Both the one step and the two step methods possess certain undesirable limitations, which prevent their wider application.

6. Higher cost of nanofluids: Both synthesis methods of nanofluids are highly expensive

VIII. CONCLUSION

The present preview gives a comprehensive overview of fascinating research and progress in area relating to nanofluids. From research point of view, the number of papers published in this field has increased exponentially, and a clear picture about the future direction of research in this area can be depicted at this point of time.

The first major conclusion that can be drawn from the reviewed studies is that nanofluids show great promise for use in cooling technology and other mechanical applications. Metallic nanoparticles seem to enhance thermal conductivity anomalously, with very large enhancement at very low volume fraction .However more research and study needs to be done on achieving stability of nanofluids, most importantly particle size must be studied.

Form theoretical perspective, the mechanism of thermal conductivity is still unclear. Many attempts to identify and model this mechanism have been carried out with only very limited success. Until now only few ceramic (Al2O3, CuO, TiO2, SiC and SiO2) and a few metallic particles (Cu, Fe, Au and Ag) have been studied in differing concentration ranges. Some of the studies modelled both oxide nanofluids and carbon nanofluids. These studies are commendable. Also the effort to include particle motion in form of Brownian motion appears to be controversial and these efforts needs to be revisited, particularly with respect to ‘temperature effect’. A very encouraging effect is the nano-convection of fluids around particles due to their motion. It is important that any model that is developed in future be tested against much more data on ceramics, metallic and nanotube based nanofluids and that should be with respect to temperature rather than present practice of testing with a limited range of measurement. Also if model contains adjustable parameters, their values should be justified by physics of problem rather than by simple empirical treatment.

Finally, studies on convective energy transport of nanofluids, both with and without phase changes, have just began. Experimental work in convective heat transfer of nanofluids is still scarce. As all convective studies have been performed with oxide particles, and it should be interesting to know the energy transport with low concentration nanofluid with metallic particles as well as additional effects, such as application of microwaves.

Future convective studies should be performed with metallic nanoparticles in standard geometries to consider heat transfer enhancement; transition to turbulence and hydraulic behaviour. The studies can be expanded to include complex geometries and methods of computational modelling.

Application oriented future work/research in nanofluids in its infancy and is expected to grow at a faster rate in future, only this will define the future of nanofluids and its present promises.

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