A Review on applications and challenges of Nano-fluids as coolant in Automobile Radiator

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Abstract **-**Nanofluids are potential heat transfer fluids with enhanced thermo physical properties and heat transfer performance can be applied in many devices for better performances (i.e. energy, heat transfer and other performances). Evaluating the heat transfer enhancement due to the use of nanofluids has recently become the center of interest for many researchers. This newly introduced category of cooling fluids containing ultrafine nanoparticles (1–100 nm) has displayed fascinating behavior during experiments including increased thermal conductivity and augmented heat transfer coefficient compared to a pure fluid. In this paper, a comprehensive literature on the applications and challenges of nanofluids have been compiled and reviewed in Automobile sector.

Latest up to date literatures on the applications and challenges in terms of PhD and Master thesis, journal articles, conference proceedings, reports and web materials have been reviewed and reported. Recent researches have indicated that substitution of conventional coolants by nanofluids appears promising in Automobile radiator. Nanofluids have 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. Alternatively, it is beneficial to design more compact cooling system with smaller and lighter automobile radiators.

Index Terms- applications and challenges of Nano-fluids as coolant in Automobile Radiator

I. Introduction

The automotive industry is continuously involved in a strong competitive career to obtain the best automobile design in multiple aspects (performance, fuel consumption, aesthetics, safety, etc.). The air-cooled heat exchangers found in a vehicle (radiator, AC condenser and evaporator, charge air cooler, etc.) have an important role in its weight and also in the design of its front-end module, which also has a strong impact on the car aerodynamic behavior. Looking at these challenges, an optimization process is mandatory to obtain the best design compromise between performance, size/shape and weight. This optimization objective demands advanced design tools that can indicate not only the better solution but also the fundamental reason of a performance improvement**.**

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.

These novel and advanced concepts of coolants offer intriguing heat transfer characteristics compared to conventional coolants. There are considerable researches on the superior heat transfer properties of nanofluids especially on thermal conductivity and convective heat transfer. Eastman et al [40], Liu et al.[41], Hwang et al.[42], Yu et al[43]. and Mintsa et al.[44] , observed great enhancement of nanofluids' thermal conductivity compared to conventional coolants. Enhancement of convective heat transfer was reported by Zeinali Heris et al.[45] , Kim et al., Jung et al.[46] and Sharma et al.[47] . Applications of nanofluids in industries such as heat exchanging devices appear promising with these characteristics. However, the development and applications of nanofluidsm may be hindered by several factors such as long term stability, increase pumping power and pressure drop, nanofluids' thermal performance in turbulent flow and fully developed region, lower specific heat of nanofluids and higher production cost of nanofluids.

This paper review application of nanofluids as coolant in Automobile radiator as a coolant and challenges related to the it. The Below figure 1 shows the the different types of Nano-particles with Length scale and some examples related to it

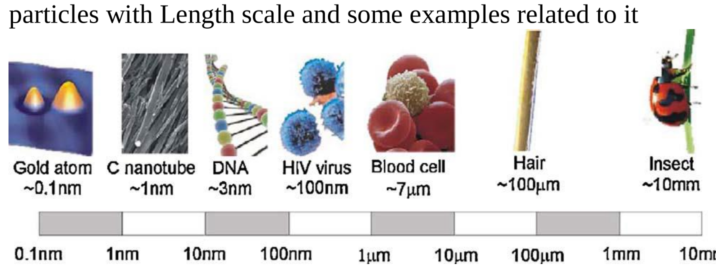

Fig. 1. Length scale and some examples related [50]

II. Overview application 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 based on [49].

$$\mathbf{Q = hA\Delta T}$$

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 the 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[49].

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 micro electro mechanical 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 [49].

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. For example, heat transfer systems which employ forced convection of a gas exhibit a greater heat transfer coefficient than systems which employ free convection of a gas. Alternatively, the heat transfer coefficient can be increased by enhancing the properties of the coolant for a given method of heat transfer. Additives are often added to liquid coolants to improve specific properties. For example, glycols are added to water to depress its freezing point and to increase its boiling point. The heat transfer coefficient can be improved via the addition of solid particles to the liquid coolant (i.e. nanofluids).[49-57]

Nanofluids can be used for a wide variety of industries, ranging from transportation to energy production and in electronics systems like microprocessors, Micro-Electro-Mechanical Systems (MEMS) and in the field of biotechnology. Recently, the number of companies that observe the potential of nanofluids technology and their focus for specific industrial applications is increasing. In the transportation industry, nanocars, GM and Ford, among others are focusing on nanofluids research projects[54-56].

Nanofluids can be used to cool automobile engines and welding equipment and to cool high heat-flux devices such as high power microwave tubes and high-power laser diode arrays. A nanofluid coolant could flow through tiny passages in MEMS to improve its efficiency. The measurement of nanofluids critical heat flux (CHF) in a forced convection loop is useful for nuclear applications. If nanofluids improve chiller efficiency by 1%, a saving of 320 billionkWh of electricity or an equivalent 5.5 million barrels of oil per year would be realized in the US alone. Nanofluids find potential for use in deep drilling application. A nanofluid can also be used for increasing the dielectric strength and life of the transformer oil by dispersing nanodiamond particles[56,57].

Kostic [59] reported that nanofluids can be used in following specific areas:

• Heat-transfer nanofluids.
• Tribological nanofluids.
• Surfactant and coating nanofluids.
• Chemical nanofluids.
• Process/extraction nanofluids.
• Environmental (pollution cleaning) nanofluids.
• Bio- and pharmaceutical-nanofluids.
• Medical nanofluids (drug delivery and functional tissue–cell interaction).

Figure 2 shows the market volume of nanomaterials, tools and devices in past , present and future.

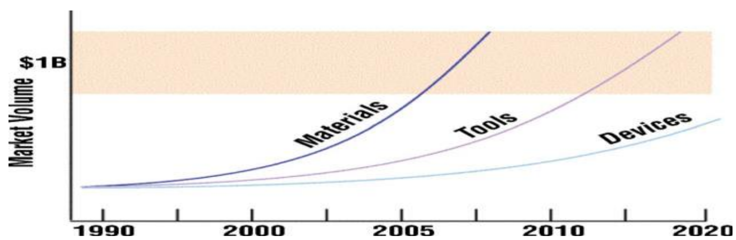

Fig. 2. Nanotechnology is poised to impact dramatically on all sectors of industry[60].

III. Thermal Conductivity of Nanofluids

Numerous studies have shown that nanofluids have superb physical properties, among which thermal conductivity has been studied most extensively but remains controversial. Considerable research has been carried out on this topic. Eastman et al found [3] that a "nanofluid" consisting of copper nanometer-sized particles dispersed in ethylene glycol has a much higher effective thermal conductivity than either pure ethylene glycol or ethylene glycol containing the same volume fraction of dispersed oxide nanoparticles. Thermal conductivity of ethylene glycol can be increased by 40 % for a nanofluids consisting of ethylene glycol containing approximately 0.3 vol% Cu nanoparticles of mean diameter <10 nm. S.M. Peyghambarzadeh [1] found that nano fluid consisting of Copper oxide (CuO) and Iron oxide (Fe_2O_3) nono particles dispersed in water has much higher heat transfer coefficient than pure water. In this paper ,the heat transfer performance of the automobile radiator is evaluated experimentally by calculating the overall heat transfer coefficient (*U*) according to the conventional ε-NTU technique. Copper oxide (CuO) and Iron oxide (Fe_2O_3) nanoparticles are added to the water at three concentrations 0.15, 0.4, and 0.65 vol.% with considering the best pH for longer stability. In these experiments, the liquid side Reynolds number is varied in the range of 50–1000 and the inlet liquid to the radiator has a constant temperature which is changed at 50, 65 and 80 °C. The ambient air for cooling of the hot liquid is used at constant temperature and the air Reynolds number is varied between 500 and 700. From these experiments he found that nanofluids show greater overall heat transfer coefficient in comparison with water up to 9%.

M. Naraki,[4] found that thermal conductivity of CuO/water nanofluids much higher than that of base fluidwater. He found that the overall heat transfer coefficient increases with the enhancement in the nanofluid concentration from 0 to 0.4 vol.%. Conversely. The implementation of nanofluid increases the overall heat transfer coefficient up to 8% at nanofluid concentration of 0.4 vol.% in comparison with the base fluid. Liu et al. [5], investigated the thermal conductivity of copper–water nanofluids produced by chemical reduction method. Results showed 23.8% improvement at 0.1% volume fraction of copper particles. Higher thermal conductivity and larger surface area of copper nanoparticles are attributed to this improvement. It is also noted that thermal conductivity increases with particles volume fraction but decreases with elapsed time. Lee et al. [6] revealed thermal conductivity of nanofluids is affected by pH level and addition of surfactant during nanofluids preparation stage. Better dispersion of nanoparticles is achieved with addition of surfactant such as sodium dodecylbenzenesulfonate. Optimum combination of pH and surfactant leads to 10.7% thermal conductivity enhancement of 0.1% Cu/H2O nanofluids. Thermal conductivity of ethylene glycol based ZnO nanofluids measured by transient short hot wire technique is found to be increased non-linearly with nanoparticles volume fraction.

Vajjha and Das [7] also agreed that thermal conductivity is dependent not only on the nanoparticles concentration but also on the temperature. Authors concluded that, it will be more beneficial if nanofluids are used in high temperature applications. It has been noticed that most authors agreed that nanofluids provide higher thermal conductivity compared to basefluids. Its value increases with particles concentration. Temperature, particles size, dispersion and stability do play important role in determining thermal conductivity of nanofluids [8]. Fig. 3 shows the comparison of thermal conductivity of heat transfer fluids and nanofluids. Figs. 4 and 5 show the thermal conductivity of nanofluids at different temperatures. Table 1 also shows the enhanced thermal conductivities of metallic and non-metallic nanofluids as reported by Shen [9]. Table 2 shows the thermal conductivity ratio (i.e. thermal conductivity of solid to liquids) of nanofluids.The ratios are found to be in the range of 3–17,100. This shows an indication that when solid particles are added in conventional liquids/coolants, thermal conductivity can be increased tremendously.

Choi et al.observed that the thermal conductivity of this nanofluid was 150% greater thanthat of the oil alone. Tables 1–6 show the thermal performances of different types (metallic, non-metallic, MWCNT) and concentrations of nanofluids. Recently, tribology research shows that lubricating oils with nanoparticles additives (MoS2, CuO, TiO2, diamond, etc.) exhibit improved load-carrying capacity, anti-wear and friction-reduction properties.These features made nanofluids very attractive in some cooling and/or lubricating application in many industries including manufacturing, transportation, energy, and electronics, etc.

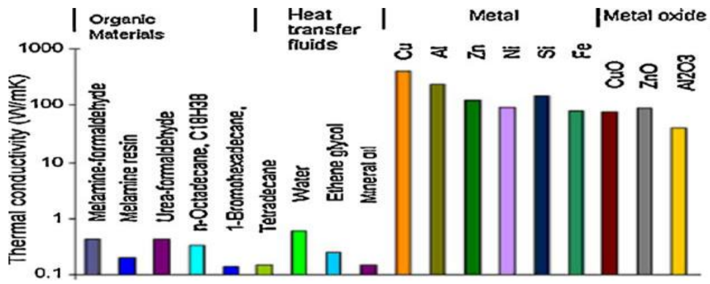

Fig. 3. Comparison of the thermal conductivity of common liquids, polymers and solids [10]

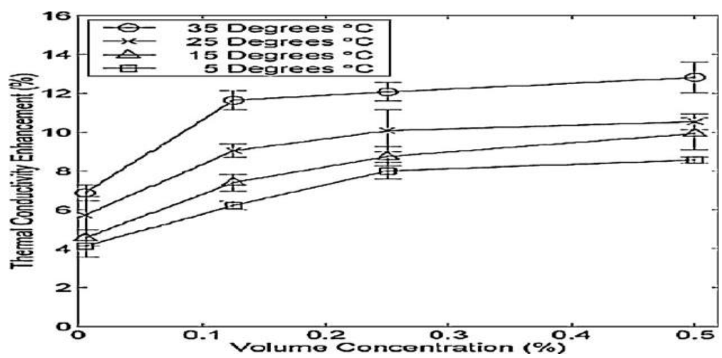

Fig. 4. Thermal conductivity enhancement of 2 nm gold nanoparticle in water as afunction of volume concentration [11].

Table no =1
Summary of literature review for thermal conductivity of nanofluids.[9]

	Particle	Base fluid	Average particle size	Volume fraction	Thermal conductivity enhancement
Met	Cu	Ethyle	10 nm	0.3%	40%
alli		ne		7.5%	78%
c	Cu	glycol	100nm	0.55%	21%
nan	Fe	Water		0.001%	17%
oflu	Au	Ethyle	10-20 nm		
ids		ne			
	Ag	glycol	60-80 nm		
		Water			
		Water			
No	Al_2O_3	Water	13 nm	4.3%	30%
n-	Al_2O_3	Water	33nm	4.3%	15%
met	Al_2O_3	Water	68nm	5%	21%
alli	CuO	Water	36nm	3.4%	12%
c	CuO	Water	50 nm	0.4%	17%
nan	SiC	Water	26 nm	4.2%	16%

ISSN 2250-3153

ofluids	TiO_2	Water	15 nm	5%	30%
	MWCNT	Synthetic oil	25nm in diameter 50μm in length	1%	150%
	MWCNT	Decene/ethylene glycol/water	15nm in diameter 30μm in length	1%	20%/13%/7%
	MWCNT	Water	100nm in diameter 70μm in length	0.6%	38%

Table 2 : Thermal conductivities ratio of different types of nanofluids.[9]

Nano particles	k_2/k_1 (K_1 Thermal conductivity for liquid and k_2 Thermal conductivity for solid	Fluid
Al_2O_3	66 156 140 342	Water Ethylene Glycol Glycerol Water
CuO	127 300	Water Ethylene Glycol
TiO_2	14 33	Water Ethylene Glycol
Fe_3O_4	11.5	water
ZrO_2		water
WO_3		Ethylene Glycol
ZnO	48 113	Water Ethylene Glycol
SiO_2	2.2 5.2	Water Ethylene Glycol
Cu	655 1550	Water Ethylene Glycol Water+ Ethylene Glycol
Ag	697	Water
Au	518 1830 2370	Water Ethanol Toluene
Fe	132 311	Water Ethylene Glycol
Alxcuy		Water Ethylene Glycol Oil
Alxcuy		Water Ethylene Glycol
Carbon nonotubes	3290 7780 17100 14300	Water Antifreeze Oil
Carbon nonotubes	21 111 3	Water Oil Toluene
Graphite	1020	Oil
Diamond	3500	Ethylene Glycol

Table no 3
The augmentation factor (α_{cond}) of A12O3 nanofluids. [9]

Practical Material	Particle size (nm)	Base Fluid Material	α_{cond}
Al_2O_3	33	Water	6
Al_2O_3	24.4	Water	2.5
Al_2O_3	28	Water	4
Al_2O_3	38.4	Water	2.5
Al_2O_3	36	Water	6
Al_2O_3	47	Water	5
Al_2O_3	20	Water	1.3
Al_2O_3	11	Water	12
Al_2O_3	47	Water	6
Al_2O_3	150	Water	3
Al_2O_3	Not reported	Water	4.6
Al_2O_3	24.4	Ethylene Glycol	3
Al_2O_3	28	Ethylene Glycol	3.4
Al_2O_3	Not reported	Ethylene Glycol	6
Al_2O_3	28	Pump Fluid	2.4
Al_2O_3	Not reported	Engine oil	7.6
Al_2O_3	Not reported	Glycerol	5.4

Table 4
The augmentation factor (α_{cond}) of Oxide nanofluids[9]

Practical Material	Particle size (nm)	Base Fluid Material	α_{cond}
CuO	36	Water	12
CuO	18.6	Water	50
CuO	23	Water	3.8
CuO	28.6	Water	3.8
CuO	33	Water	3
CuO	18.6	Ethylene glycol	5
CuO	23	Ethylene glycol	3.9
CuO	12	Ethylene	6

		glycol	
CuO	29	Ethylene glycol	4.5
TiO_2	15	water	6
TiO_2	40	water	2.4
ZrO_2	20	water	2.5
Fe_3O_4	9.8	water	8

Table 5
The augmentation factor (α_{cond}) for metal nanofluids [9]

Practical Material	Particle size (nm)	Base Fluid Material	α_{cond}
Cu	18	Water	6
Cu	100	Water	10.1
Cu	100-200	Water	232
Cu	10	Ethylene Glycol	133
Cu	100	Transformer	5.9
Au	10-20	Toluene	818
Fe	10	Ethylene glycol	32.7
$B_{i2}Te_3$	100	FC72	10

Table 6
The augmentation factor (α_{cond}) for metal nanofluids[9]

Practical Material	Particle size (nm)	Base Fluid Material	α_{cond}
CNT	15/30	Water	7.5
CNT	150/10	Water	44
CNT	40/50	Water	37
CNT	15/30	Ethylene	12
CNT	15/30	Decene	818

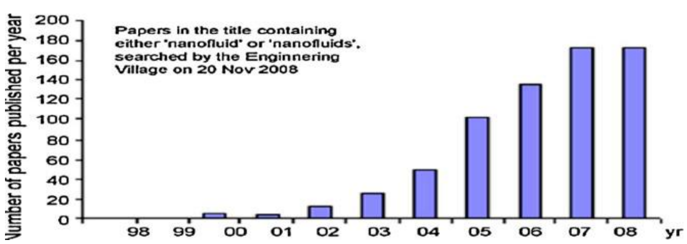

Fig. 6. Growth of publications by the nanofluids community [10]

USES OF NANOFLUIDS AS A COOLANTS IN AUTOMOBILE RADIATOR

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 [56-58], 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 [13].

Argonne researchers, Singh et al. [12], 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 9m/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. [12] are shown in Tables 7 & 8.

Table 7. Erosion Test Results for 50% Ethlyene Glycol, 50% H_2O [12].

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 8. Erosion Test Results for Cu Nanoparticles in Trichloroethylene [12].

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

Shen et al. [14] 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 work piece. Contrasted to 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 aluminium 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.

Choi et al. [15] 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.

Ollivier et al. [16] 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 horsepower engines with the same size of coolant system.

A promising nanofluids engine coolant is pure ethylene glycol with nanoparticles. Pure ethylene glycol is a poor heat transfer fluid compared to a 50/50 mixture of ethylene glycol and water, but the addition of nanoparticles will improve the situation. If the resulting heat transfer rate can approach the 50/50 mixture rate, there are important advantages. Perhaps one of the most prominent is the low pressure operation of an ethylene-glycol-based nanofluids compared with a 50/50 mixture of ethylene glycol and water. This nanofluid also has a high boiling point, which is desirable for maintaining single-phase coolant flow. In addition, a higher boiling point coolant can be used to increase the normal coolant operating temperature and then reject more heat through the existing coolant system. More heat rejection allows a variety of design enhancements including engines with higher horsepower.

Ollivier et al.[16] found that the use of the nanofluids leads to increased thermal signal variations by around 15% over that predicted using water alone. Authors employed a CFD numerical simulation method to analyze the application value of nanofluids in engine cooling. The simulation results indicated that nanofluids could enhance engine heat dissipating capacity and Cu–water nanofluids had better heat-transfer capability. It was also found that the more concentrations of the nanoparticles, the more enhancement of the engine heat dissipating capacity. When the concentration reached 5%, the heat dissipating capacity increased by 44.1%. With a remarkable enhancement on heat-transfer capability, the workload of the pump of engine cooling system only increased by 6%, which could be acceptable.

Tzeng et al. [17] dispersed CuO and Al_2O_3 nanoparticles into engine transmission oil. The experimental platform was the transmission of a fourwheel- 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, and 1600 rpm), and the optimum composition of nanofluids with regard to heat transfer performance was investigated. Authors reported that CuO nanofluids 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.

As in all nanofluids applications, however, consideration must be given to such factors as particle setting, particle agglomeration, and surface erosion. In automotive lubrication applications, surface modified nanoparticles stably dispersed in mineral oils are reported to be effective in reducing wear and enhancing load-carrying capacity. Results from a research project involving industry and university 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 encouraging for improving heat transfer rates in automotive systems through the use of nanofluids.

The trend toward higher engine power and EGR inevitably leads to larger radiators and increased frontal areas, resulting in additional aerodynamic drag and increased fuel consumption. Therefore, cooling is one of the top technical challenges facing the truck industry [11].

Choi [11] reported the limitations of existing technologies as follows:

• Liquid-side: traditional coolants and oils have inherently poor heat transfer properties.

• Air-side: current radiator designs for increasing air-side heat transfer have already adopted extended surface technology to its limits.

• Therefore, there is a steadily increasing need for new concepts and technology for improving HV cooling system performance.

Choi [11] 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 higherpower engines and EGR. Nanofluids enable the potential to allow higher temperature coolants and higher heat rejection in HVs. A higher temperature radiator could reduce the radiator size by perhaps 30%. This translates into reduced aerodynamic drag and fluid pumping and fan requirements, leading to perhaps a 10% fuel savings.

The new radiator design will be used in new general motors hybrid vehicles. These hybrid vehicles have multiple cooling systems for the internal combustion engine, electric engine, and batteries. The popularity of these hybrid vehicles is on the rise due to the decreasing fossil fuel supply, increasing the importance of a new radiator design that can possibly replace these multiple cooling systems.

These properties would be very beneficial to allow for an increased amount of heat to be removed from the engine. This is important because it will allow for a greater load to be placed on the fluid for cooling. However, these nanofluids do not show considerable improvement in heat transfer when used with current radiator designs. This is because there are several limitations to current radiator designs.

A steady-state heat exchanger consists of a fluid flowing through a pipe or system of pipes, where heat is transferred from one fluid to another. Heat exchangers are very common in everyday life and can be found almost anywhere. Some common examples of heat exchangers are air conditioners, automobile radiators, and a hot water heater. A schematic of a simple heat exchanger is shown in Figs. 7 and 8. Fluid flows through a system of pipes and takes heat from a hotter fluid and carries it away. Essentially it is exchanging heat from the hotter fluid to the cooler fluid as can be seen in Fig. 7.

Almost all automobiles in the market today have a type of heat exchanger called a radiator. The radiator is part of the cooling system of the engine as shown in Fig. 8. As can be can be seen in the figure, the radiator is just one of the many components of the complex cooling system.

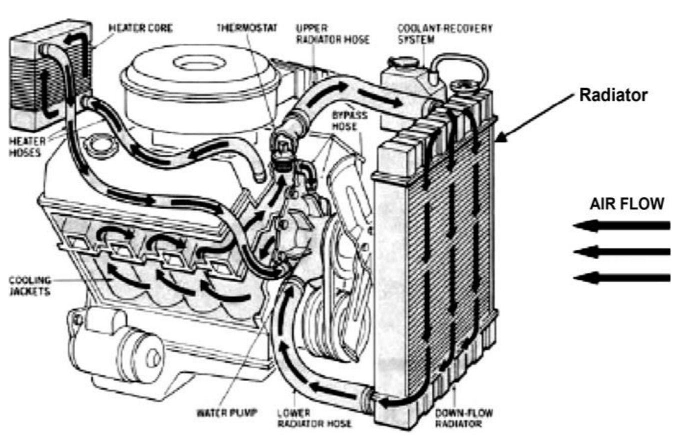

Fig. 7. Radiator of an engine.

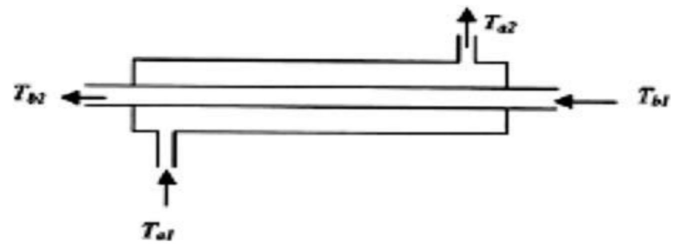

Fig. 7. Fluid flows in a radiator

Kole *et al.* prepared car engine coolant (Al_2O_3 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 [13].

Tzeng *et al*. 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 Al2O3 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 [13].

IV. CHALLENGES OF NANOFLUIDS

Many interesting properties of nanofluids have been reported in the review. In the previous studies, thermal conductivity has received the maximum attention, but many researchers have recently initiated studies on other heat transfer properties as well. The use of nanofluids in a wide variety of applications appears promising. But the development of the field is hindered by (i) lack of agreement of results obtained by different researchers; (ii) poor characterization of suspensions; (iii) lack of theoretical understanding of the mechanisms responsible for changes in properties. Therefore, this paper concludes several important issues that should receive greater attention in the near future. Experimental studies in the convective heat transfer of nanofluids are needed. Many issues, such as thermal conductivity, the Brownian motion of particles, particle migration, and thermo physical property change with temperature, must be carefully considered with convective heat transfer in nanofluids. Though, all the convective studies have been performed with oxide particles in high concentrations (for example Pak and Cho [18] used 10 vol.% of Al_2O_3 which increased the viscosity and pumping power of the fluid, it is interesting to know the energy transport in low concentration(<1 vol.%) nanofluids with metallic particles since the thermal conductivity of pure metallic nanoparticles is more than 100 times higher than that of the oxide nanoparticles.

Future convective studies must be performed with metallic nanoparticles with different geometries and concentrations to consider heat transfer enhancement in laminar, transition and turbulent regions. The use of nanofluids in heat pipes has shown enhancement in performance and considerable reduction in thermal resistance. However, recent studies indicate particle aggregation and deposition in micro-channel heat sinks.

Further study is required in these areas to identify the reasons for and the effects of particle deposition. Finally, there appears to be hardly any research in the use of nanofluids as refrigerants. Nanoparticle refrigerant dispersions in two-phase heat transfer applications can be studied to explore the possibility of improving the heat transfer characteristics of evaporators and condensers used in refrigeration and air-conditioning appliances. Applied research in nanofluids which will define their future in the field of heat transfer is expected to grow at a faster pace in the near future [19].

4.1. Long term stability of nanoparticles dispersion-

Preparation of homogeneous suspension remains a technical challenge since the nanoparticles always form aggregates due to very strong van der Waals interactions. To get stable nanofluids, physical or chemical treatment have been conducted such as an addition of surfactant, surface modification of the suspended particles or applying strong force on the clusters of the suspended particles. Dispersing agents, surface-active agents, have been used to disperse fine particles of hydrophobic materials in aqueous solution [20]. On the other hand, if the heat exchanger operates under laminar conditions, the use of nanofluids seems advantageous, the only disadvantages so far being their high price and the potential instability of the suspension [21].

Generally, long term stability of nanoparticles dispersion is one of the basic requirements of nanofluids applications. Stability of nanofluids have good corresponding relationship with the enhancement of thermal conductivity where the better dispersion behavior, the higher thermal conductivity of nanofluids [22]. However the dispersion behavior of the nanoparticles could be influenced by period of time as can be seen in Figs. 8 and 9. As a result, thermal conductivity of nanofluids is eventually affected. Eastman et al. [23] revealed that, thermal conductivity of ethylene glycol based nanofluids containing 0.3% copper nanoparticles is decreased with time. In their study, the thermal conductivity of nanofluids was measured twice: first was within 2 days and second was two months after the preparation. It was found that fresh nanofluids exhibited slightly higher thermal conductivities than nanofluids that were stored up to two months. This might due to reduced dispersion stability of nanoparticles with respect to time. Nanoparticles may tend to agglomerate when kept for long period of time. Lee and Mudawar [24] compared the Al2O3 nanofluids stability visually over time span. It was found that nanofluids kept for 30 days exhibit some settlement and concentration gradient compared to fresh nanofluids. It indicated long term degradation in thermal performance of nanofluids could be happened. Particles settling must be examined carefully since it may lead to clogging of coolant passages.

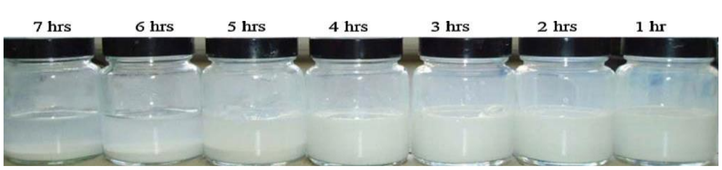

Fig. 8**.** Samples of Al_2O_3 nanofluids (without any stabilizer) stability change with time [22].

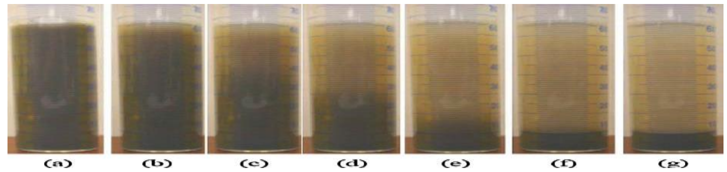

Fig. 9. The sedimentation of diamond nanoparticles at settling times of (a) 0 min, (b) 1min, (c) 2min, (d) 3min, (e) 4min, (f) 5min, and (g) 6min [39].

Choi et al. [25] reported that the excess quantity of surfactant has a harmful effect on viscosity, thermal property, chemical stability, and thus it is strongly recommended to control the addition of the surfactant with great care. However, the addition of surfactant would make the particle surface coated, thereby resulting in the screening effect on the heat transfer performance of nanoparticles. Authors also mentioned that the surfactant may cause physical and/or chemical instability problems.

4.2. Increased pressure drop and pumping power-

Pressure drop developed during the flow of coolant is one of the important parameter determining the efficiency of nanofluids application. Pressure drop and coolant pumping power are closely associated with each other. There are few properties which could influence the coolant pressure drop: density and viscosity. It is expected that coolants with higher density and viscosity experience higher pressure drop. This has contributed to the disadvantages of nanofluids application as coolant liquids. Lee et al. [26] and Yu et al. [27] investigated viscosity of water based Al2O3 nanofluids and ethylene glycol based ZnO nanofluids. Results clearly show, viscosity of nanofluids is higher than basefluid. Namburu et al. [28] in their numerical study reviewed that density of nanofluids is greater than basefluid. Both properties are found pro portional with nanoparticles volume fraction. Several literatures have indicated that there is significant increase of nanofluids pressure drop compared to basefluid. Lee and Mudawar [24] revealed that single phase pressure drop of Al2O3 nanofluids in microchannel heat sink increases with nanoparticles concentration. Vasu et al. [29] studied the thermal design of compact heat exchanger using nanofluids. In this study, it is found that pressure drop of 4% Al2O3 +H2O nanofluids is almost double of the basefluid. Pantzali et al. [31] reported there was substantial increase of nanofluids pressure drop and pumping power in plate heat exchanger. About 40% increase of pumping power was observed for nanofluids compared with water.

Peng et al. [30] reported that the frictional pressure drop of refrigerant-based nanofluids flow boiling inside the horizontal smooth tube is larger than that of pure refrigerant, and increases with the increase of the mass fraction of nanoparticles. The maximum enhancement of frictional pressure drop can reach 20.8% under the experimental conditions.

An important parameter in the application of nanofluids in heat exchanging equipment is the pressure drop developed during the flow through the Plate Heat Exchanger (PHE). In Fig. 10 the total pressure drop P,measured inside the PHE, is plotted versus the cooling liquid volumetric flow rate for both the water and the nanofluid. Pantzali et al. [31] observed that the measured viscosity of the suspension (i.e. nanofluids) exhibits a twofold increase compared to water. This leads to a significant increase in the measured pressure drop and consequently in the necessary pumping power when the nanofluids are applied. Authors calculated that the pumping power increased about 40% compared to water for a given flow rate. Authors observed that for a given heat duty the required volumetric Flow rates for both the water and the nanofluid are practically equal, while the necessary pumping power in the case of the nanofluid is up to two times higher than the corresponding value for water due to the higher kinematic viscosity of the fluid [31].

4.3. Nanofluids thermal performance in turbulent flow and fully developed region-

Apart from thermal conductivity, convective heat transfer performance of the nanofluids also attracted maximum attention from the researchers. Most of the literatures reported that this property is greatly enhanced with the application of nanofluids. However, there is an issue that must be addressed carefully especially on the thermal performance of nanofluids in turbulent flow. Recently, there was inconsistence of results reported by the researchers. For instance [32] revealed that no convective heat transfer improvement was noticed for amorphous carbonic nanofluids in turbulent flow despite 8% improvement in laminar flow. However, Duangthongsuk and Wong wises[33] reported that heat transfer coefficient of TiO2–water nanofluids is higher than basefluid. This property increases with the increase of Reynold numbers and particle concentrations ranging from 0.2% to 2%. Although the study revealed that 26% enhancement can be observed for nanofluids with 1% of TiO2 nanoparticles, it showed contradictory results at 2.0% volume fraction. Study indicated that heat transfer coefficient of nanofluids at this condition was 14% lower than basefluid. Pantzali et al. [31] added substitution of conventional coolants by nanofluids seemed beneficial for laminar flow compared to turbulent flow. Another weakness of nanofluids is its thermal performance at fully developed region. Ding et al. [33] found that convective heat transfer coefficient of nanofluids at low Reynold number has the highest value at the entrance length of the tube, starts decreasing with axial distances and eventually reaches constant value in fully developed region.

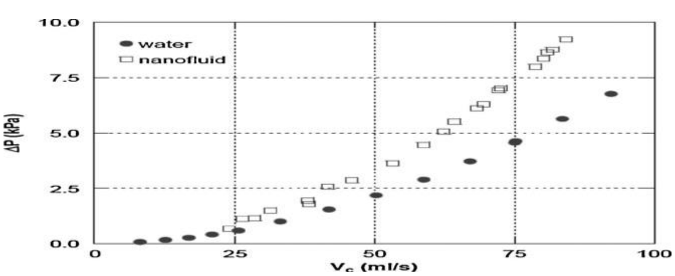

Fig. 10**.** Pressure drop of the cooling liquid inside the PHE versus the respective volumetric flow rate [31].

4.4. Higher viscosity-

The viscosity of nanoparticle–water suspensions increases in accordance with increasing particle concentration in the suspension. So, the particle mass fraction cannot be increased unlimitedly [34]. Pantzali et al. [31] concluded that in industrial heat exchangers, where large volumes of nanofluids are necessary and turbulent flow is usually developed, the substitution of conventional fluids by nanofluids seems inauspicious. Lee [35] reported that the viscosity increased so rapidly with increasing particle loading that volume percentages of CNTs are limited to less than 0.2% in practical systems.

4.5. Lower specific heat-

From the literatures, it is found that specific heat of nanofluids is lower than basefluid. Namburu et al. [28] reported that CuO/ethylene glycol nanofluids, SiO_2/ethylene glycol nanofluids and Al_2O_3/ethylene glycol nanofluids exhibit lower specific heat compared to basefluids. An ideal coolant should possess higher value of specific heat which enable the coolant to remove more heat.

4.6. Thermal conductivity-

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 Nano refrigerants within a mean deviation of less than 15% [36].

4.7. High cost of nanofluids-

Higher production cost of nanofluids is among the reasons that may hinder the application of nanofluids in industry. Nanofluids can be produced by either one step or two steps methods. However both methods require advanced and sophisticated equipments. Lee and Mudawar [24] and Pantzali et al. [31] stressed that high cost of nanofluids is among the drawback of nanofluids applications.

4.8. Difficulties in production process-

Previous efforts to manufacture nanofluids have often employed either a single step that simultaneously makes and disperses the nanoparticles into base fluids, or a two-step approach that involves generating nanoparticles and subsequently dispersing them into a base fluid. Using either of these two approaches, nanoparticles are inherently produced from processes that involve reduction reactions or ion exchange. Furthermore, the base fluids contain other ions and reaction products that are difficult or impossible to separate from the fluids.

Another difficulty encountered in nanofluid manufacture is nanoparticles' tendency to agglomerate into larger particles, which limits the benefits of the high surface area nanoparticles. To counter this tendency, particle dispersion additives are often added to the base fluid with the nanoparticles. Unfortunately, this practice can change the surface properties of the particles, and nanofluids prepared in this way may contain unacceptable levels of impurities. Most studies to date have been limited to sample sizes less than a few hundred milliliters of nanofluids. This is problematic since larger samples are needed to test many properties of nanofluids and, in particular, to assess their potential for use in new applications [37].

Yet the fact that nano-fluids have more points in favor of them than against, for usage as cooling fluid, has emerged as an undisputed view. This calls for amore intensified effort in the research on nano-fluids. In contrast to the traditional unilateral approach, this research needs to examine closely a variety of issues, such as synthesis, characterization, thermo-physical properties, heat and mass transport, modeling, and device- as well as system-level applications. Hence, amulti-disciplinary approach comprising researchers such as thermal engineers, chemical technologists, material scientists, chemists, and physicists needs to be undertaken. Only such an approach can ensure a "cooler future" with nano-fluids [38].

V. Conclusion

- It has been seen that nanofluids can be considered as a potential candidate for Automobile application.
- As heat transfer can be improved by nonofluids, in Automobile radiators can be made energy efficient and compact . Reduced or compact shape may results in reduced drag ,increase the fuel economy ,reduce the weight of vehicle**.**
- Exact mechanism of enhanced heat transfer for nanofluids is still unclear as reported by many researchers.
- There are different challenges of nanofluids which should be identified and overcome for Automobile radiators application.

Nanofluids stability and its production cost are major factors that hinder the commercialization of nanofluids. By solving these challenges, it is expected that nanofluids can make substantial impact as coolant in heat exchanging devices.

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