Nano Fluids: A New Generation Coolants

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Abstract

Today, the demand of automobile vehicles is on peak. So, it is a great challenge for automotive industries to provide an efficient and economical engine. The performance of an engine affects by various systems like fuel supply system, lubrication system, transmission system, cooling system etc. So, it becomes essential to account them while designing an engine for improves the engines performance.

Cooling system is one of the important systems amongst all. It is responsible to carry large amount of heat waste to surroundings for efficient working of an engine. It also enhances heat transfer and fuel economy which leads to maximize the performance of an engine. Most internal combustion engines are fluid cooled using either air or a liquid coolant run through a heat exchanger (radiator) cooled by air. The heat transfer through radiator can be improved by maximizing the heat transfer area and increasing the heat transfer coefficient. The heat transfer coefficient can be increased either by using more efficient heat transfer methods or by improving the thermo physical properties of the heat transfer material i.e. coolant.

Earlier, Water was widely used in radiator as a coolant for its good ability to holding heat, transfer heat and can be readily obtained. Also the mixture of water & ethylene glycol later introduced as a coolant. Both of them having certain merits & demerits.

With the advancement of nanotechnology, the new generation of heat transfer fluids called, “Nanofluids” have been developed and researchers found that these fluids offer higher thermal conductivity compared to that of conventional coolants. Nanofluids which consist of a carrier liquid, such as water, ethylene glycol dispersed with tiny nano-scale particles known as nanoparticles. This comprehensive study on cooling system importance, coolant used in automobiles and its limitations and applications and challenges of Nanofluids as a coolant have been compiled and reviewed for automobile radiator.

Keywords

Cooling System, Heat Transfer, Nanofluids

I. Introduction

Continuous technological development in automotive industries has increased the demand for high efficiency engines. A high efficiency engine is not only based on its performance but also for better fuel economy and less emission. There are many systems which influence the engine performance like fuel ignition system, emission system, cooling system, etc. one of the parameters which affects the performance of engine is the cooling rate of radiator in engine cooling system. Addition of fins is one of the approaches to increase the heat transfer rate of the radiator. It provides greater heat transfer area and enhances the air convective heat transfer coefficient. However, traditional approach of increasing the cooling rate by using fins has already reached to their limit [10]. As a result, there is a need of new and innovative heat transfer fluids for improving heat transfer rate in an automotive car radiator. In addition, heat transfer fluids at air and fluid side such as water and ethylene glycol exhibit very low thermal conductivity. With the advancement of nanotechnology, the new generation of heat transfer fluids called, “Nanofluids” have been developed and researchers found that these fluids offer higher thermal conductivity compared to that of conventional coolants. Nanofluids which consist of a carrier liquid, such as water, ethylene glycol dispersed with tiny nano-scale particles known as nanoparticles.

Nanofluids seem to be potential replacement of conventional coolants in engine cooling system. Recently there has been considerable research findings reported which highlights superior heat transfer performances of Nanofluids. Nanofluids are potential heat transfer fluids with enhanced thermo physical properties and heat transfer performance. It can be applied in many devices for better performances (i.e. energy, heat transfer and other performances). Nanofluids are formed by suspending metallic or non-metallic oxide nanoparticles in traditional heat transfer fluids. This newly introduced category of cooling fluids containing ultrafine nanoparticles (1–100 nm) has displayed interesting behavior during experiments including increased thermal conductivity and improved heat transfer coefficient compared to a pure fluid. The use of nanofluid as coolants would allow for smaller size and better positioning of the radiators. It also increases the efficiency of the system with less amount of fluid. It results that coolant pumps could be shrunk and engines could be operated at higher temperatures. These novel and advanced concepts of coolants offer exciting heat transfer characteristics compared to conventional coolants. Yu et al., [11] reported that about 15-40% of heat transfer enhancement can be achieved by using various types of Nanofluids. This translates into a better aerodynamic feature for design of an automotive car frontal area. Coefficient of drag can be minimized and fuel efficiency can be improved. Choi [12] reported a project to target fuel savings for the automotive industries through the development of energy efficient nanofluid and smaller and lighter radiators. A major goal of the nanofluid project was to reduce the size and weight of the vehicle cooling systems by greater than 10% regardless of the cooling demands of higher power engines. Nanofluids enable the potential to allow higher temperature coolants and higher heat rejection in the automotive engines. A higher temperature radiator could reduce the radiator size approximately 30%. This translates into reduced aerodynamic drag, fluid pumping and fan requirements, leading to possibly a 10% fuel savings.

A. Types of Nanofluids

There are various metallic, non metallic nanoparticles and multi-walled carbon nanotubes (MWCNT) which are currently used with base fluids to enhance the thermal performance of the cooling systems. Common base fluids are water, ethylene glycol and oil.

The metallic nanoparticles like Cu, Fe, Au, Ag etc. and non metallic particles or compounds like Al_2O_3 (Alumina), CuO, SiC, TiO_2, Fe_3O_4 (Iron Oxide), ZrO_2 (Zirconia), WO_3 (Tungsten trioxide), ZnO, SiO_2 etc. are generally used with base fluids.

II. Literature Review

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.) has 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. 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.

Leong et al. [13] attempted to investigate the heat transfer characteristics of an automotive car radiator using ethylene glycol based copper nanofluid numerically. Thermal performance of an automotive car radiator operated with nanofluid has been compared with a radiator using conventional coolants. Vajjha et al. [14] have been numerically studied a three-dimensional laminar flow and heat transfer with two different nanofluid, Al_2O_3 and CuO, in the ethylene glycol/water mixture circulating through the flat tubes of an automobile radiator to evaluate their superiority over the base fluid. Convective heat transfer coefficient along the flat tubes with the nanofluid flow showed considerable improvement over the base fluid.

Peyghambarzadeh et al. [15] have recently investigated the application of Al_2O_3/water nanofluids in the car radiator by calculating the tube side heat transfer coefficient. They have recorded the interesting enhancement of 45% comparing with the pure water application under highly turbulent flow condition. In the other study, Peyghambarzadeh et al. [6] have used different base fluids including pure water, pure ethylene glycol, and their binary mixtures with Al_2O_3 nanoparticles and once again it was proved that nanofluids improves the cooling performance of the car radiator extensively.

Eastman et al. [16] found 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 nanofluid consisting of ethylene glycol containing approximately 0.3 vol. % Cu nanoparticles of mean diameter <10 nm. Peyghambarzadeh et al. [17] have used two different water based (CuO and Fe_2O_3) nanofluid at different air and liquid velocities and liquid inlet temperatures to measure overall heat transfer coefficients in the automobile radiator. They have concluded that overall heat transfer coefficient increases while the liquid inlet temperature decreases and enhances with increasing the liquid flow rate and the air flow rate. Also, found that increasing the concentration of nanoparticles enhances the overall heat transfer coefficient especially for Fe_2O_3/water nanofluid.

Naraki et al. [18] found that thermal conductivity of CuO/water nanofluids much higher than that of base fluid water. 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.

Argonne researchers, Singh et al. [19], have determined that the use of high-thermal conductive nanofluid 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.

Choi [12] 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 nanofluid project was 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. A higher temperature radiator could reduce the radiator size by perhaps 30%. 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 Al_2O_3 nanoparticles, displayed a fairly higher thermal conductivity than the base fluid, and a maximum enhancement of 10.41% was observed at room temperature [20]. Hwang et al. [21] found that thermal conductivity of the nanofluid depends on the volume fraction of particles and thermal conductivity of base fluid and particles.

Mintsa et al. [22] investigated the effect of temperature, particle size and volume fraction on thermal conductivity of water based nanofluids of copper oxide and alumina. Authors suggested that thermal characteristics can be enhanced with increase of particles' volume fraction, temperature and particle size. Authors found that the smaller the particle size, the greater the effective thermal conductivity of the nanofluids at the same volume fraction.

Yu et al. [23] conducted heat transfer experiments of nanofluids containing 170-nm silicon carbide particles at 3.7% volume concentration. The results showed that heat transfer coefficients of nanofluids are 50-60% greater than those of base fluids at a constant Reynolds number. Kim et al. [24] investigated effect of nanofluids on the performances of convective heat transfer coefficient of a circular straight tube having laminar and turbulent flow with constant heat flux. Authors have found that the convective heat transfer coefficient of alumina nanofluids improved in comparison to base fluid by 15% and 20% in laminar and turbulent flow, respectively. This showed that the thermal boundary layer played a dominant role in laminar flow while thermal conductivity played a dominant role in turbulent flow. However, no improvement in convection heat transfer coefficient was noticed for amorphous particle nanofluids. Nguyen et al. [25] performed their experiments in the radiator type heat exchanger and at 6.8 vol. % Al_2O_3 in water obtained 40% increase in heat transfer coefficient.

Table 1: Summary of literatures

Sr. No.	Nanoparticles	Base fluid	Vol. fraction of particles	Thermal conductivity enhancement	Heat transfer enhancement	Reference
1	Al_2O_3	Water	1%	3%	45%	Peyghambarzadeh et al. [15]
2	Al_2O_3	Water	-	15%	40%	Heris et al. [26]
3	Fe_2O_3	Water	0.65%	-	9%	Peyghambarzadeh et al. [17]
4	Cu	Ethylene Glycol	0.30%	40%	-	Eastman et al. [16]
5	CuO	Water	0.40%	17%	8%	Naraki et al. [18]
6	Cu	Glycol	0.55%	21%	-	Bhogare et al. [20]
7	Fe	Water	0.0010%	17%	-	
8	Al_2O_3	Water	4.30%	30%	-	
9	Al_2O_3	Engine Coolant (HP KOOLGARD)	3.50%	10.41%	-	
10	Sic	Water	4.20%	16%	-	
11	TiO_2	Water	5%	30%	-	
12	ZnO	Ethylene Glycol	5%	26.50%	-	Yu et al. [27]
13	Cu	Ethylene Glycol	2%	-	3.8% (with Re 6000 & 5000 for air & coolant resp.)	Leong et al. [13]
			2%	-	45.2% (with Re 6000 for air)	
			2%	-	0.4% (with Re 7000 for coolant)	
14	CuO, Al_2O_3	Ethylene Glycol and water	-	-	Improvement in convective heat transfer coefficient	Vajjha et al. [14]
15	Al_2O_3	HP KOOL-GARD	3.5%	10.41%		Kole et al.[20]
16	CuO, Al_2O_3	Water	-	Enhance with increase in particle vol. fraction	-	Minsta et al. [22]
17	SiC	-	3.7%	-	50-60% enhancement in heat transfer coefficient at a constant Re	Yu et al. [23]
18	Al_2O_3	-	-	-	Enhance by 15% in laminar and 20% in turbulent flow	Kim et. al. [24]
19	Al_2O_3	Water	6.8%	-	40% enhancement in heat transfer coefficient	Nguyen et al. [25]

III. Physical Properties of Nano Fluids

By assuming that the nanoparticles are well dispersed within the base fluid, i.e. the particle concentration can be considered uniform throughout the system; the effective physical properties of the mixtures studied can be evaluated using some classical formulas [13, 15] as usually used for two phase flow. These relations have been used to predict nanofluid physical properties like density, specific heat, dynamic viscosity and thermal conductivity at different temperatures and concentrations.

$$\rho_{nf} = (1 - \varphi)\rho_f + \varphi\rho_f \tag{1}$$

$$C_{p,nf} = \frac{(1\text{-}\varphi)\rho_f C_{p.f} + \varphi\rho_p C_{p.p}}{\rho_{nf}} \tag{2}$$

$$\mu_{nf} = \mu_f \frac{1}{(1-\varphi)^{2.5}} \qquad (3)$$

$$k_{nf} = \frac{k_p + (n-1)k_{bf} - \varphi(n-1)(k_{bf}-k_p)}{k_p + (n-1)k_{bf} + (k_{bf}-k_p)}\, k_{bf} \qquad (4)$$

Where, n is empirical shape factor given by n= 3/ψ, and ψ is the particle sphericity, defined as the ratio of the surface area of a sphere with volume equal to that of the particle, to the surface area of the particle. φ is volume fraction of the nanoparticles added to the water.

For better understanding, Fig. 1 depicts variations of dimensionless physical properties of nanofluid, i.e. the ratios of physical properties of the nanofluid to those of pure water as a function of nanoparticles concentration. It is obvious that the addition of small amount of nanoparticles can change more or less all the physical properties of the base fluid.

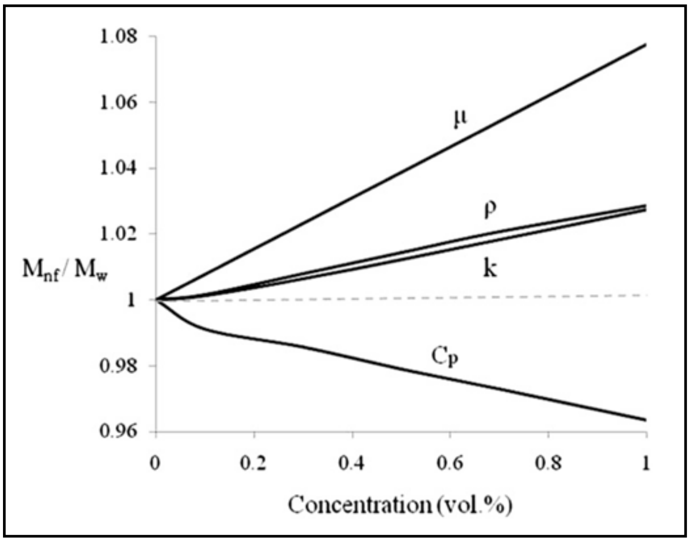

Fig. 1: Dimensionless Physical Properties of Nanofluid in Comparison With Those of Pure Water [15]

IV. Mathematical Formulation for Nanofluids

Mathematical correlations shown in this section are taken from reference [13]. Thermal performances of a radiator using nanofluid can be calculated using following equations (1)-(24). Calculations were done on air and coolant sides.

A. Air Side Calculations

Initially, air side calculations are performed to determine air heat capacity, air heat transfer coefficient, fin efficiency and total surface temperature effectiveness. These data are needed to calculate heat exchanger effectiveness, NTU number and overall heat transfer coefficient for the nanofluid side calculation. Air properties are based on temperature at 300 K. The mathematical formulations are shown below.

1. Air Heat Capacity Rate Ca can be given as Equation (1).

$C_a = m_a\, C_{p,a}$ (1)

Where, $C_{p,a}$ = 1007 J/kg K at 300 K

$$G_a = \frac{m_a}{A_{o,a}} = \frac{m_a}{\sigma_a A_{fr,a}} \qquad (2)$$

Where, $\sigma_a = \dfrac{A_{o,a}}{A_{fr,a}}$

2. Heat Transfer co-efficient can be expressed as Equation (5).

$$Re_a = \frac{G_a D_{h,a}}{\mu_a} \qquad (3)$$

$$j_a = \frac{0.174}{Re_a^{0.383}} = \frac{h_a Pr_a^{2/3}}{G_a C_{p,a}} \qquad (4)$$

$$h_a = \frac{j_a G_a C_{p,a}}{Pr_a^{2/3}} \qquad (5)$$

Where, μ_a= 0.00001846 Ns/m^2 at 300 K.

3. Fin Efficiency of Plate Fin η_{fin} can be expressed as Equation (6)

4.

$$\eta_{fin} = \frac{\tanh mL}{mL} \qquad (6)$$

Where, $m = \sqrt{\dfrac{2h_a}{k_{fin}\,\delta_{fin}}}$ (7)

5. Overall fin efficiency ηo can be expressed as Eq. (8)

$\eta_o = 1-\beta\,(1-\eta_{fin})$ (8)

Where, $\beta = \dfrac{A_{fin}}{A}$

B. Nanofluid Side Calculations

The parameters needed for nanofluid side calculation are nanofluid heat transfer coefficient, nanofluid heat capacity rate, heat exchanger effectiveness for cross-flow unmixed fluid, heat transfer coefficient based on air side, pressure drop, pumping power and total heat transfer rate.

1. Heat Transfer co-efficient can be expressed by Eq. (9)

$$h_{nf} = \frac{Nu_{nf} k_{nf}}{D_{h,nf}} \qquad (9)$$

K_{nf} can be obtained by correlation (d),

$$Nu_{nf} = 0.023\, Re_{nf}^{0.8} Pr_{nf}^{0.3} \qquad (10)$$

$$Re_{nf} = \frac{G_{nf} D_{h,nf}}{\mu_{nf}} \qquad (11)$$

Where, $G_{nf} = \dfrac{m_{nf}}{A_{o,nf}} = \dfrac{m_{nf}}{\sigma_{nf} A_{fr,nf}}$ (12)

$$m_{nf} = \rho_{nf} \dot{V}_{nf} \qquad (13)$$

$$Pr_{nf} = \frac{\mu_{nf} Cp_{nf}}{k_{nf}} \qquad (14)$$

ρ_{nf}, $C_{p,nf}$ and μ_{nf} are calculated based on correlations (a), (b) and (c) respectively.

2. Heat capacity rate, Cnf can be expressed as Eq. (15)

$C_{nf} = m_{nf}\, C_{pnf}$ (15)

3. Heat exchanger effectiveness for cross-flow unmixed fluid, ε can be expressed as Eq. (16)

$$\varepsilon = 1 - exp\,\frac{1}{R}(NTU)^{0.22}[\exp\{-R(NTU)^{0.78}\} - 1] \qquad (16)$$

Where, $R = C_{min}/C_{max}$ (17)

$NTU = U_a A_a / C_{min}$ (18)

4. Overall heat transfer coefficient, based on air side can be expressed as Eq. (19), where wall resistance and fouling factors are neglected.

$$\frac{1}{U_a} = \frac{1}{\eta_o h_a} + \frac{1}{(\frac{\alpha_{nf}}{\alpha_a})h_{nf}} \tag{19}$$

Where, $\alpha_{nf} = \frac{A_{nf}}{V}$ & $\alpha_a = \frac{A_a}{V}$ (20)

5. Pressure drop can be expressed as Eq. (21)

$$DP_{nf} = \frac{G_{nf}^2 f_{nf} H}{2\rho_{nf}(\frac{D_{h,nf}}{4})} \tag{21}$$

Where, $f_{nf} = 0.079 Re_{nf}^{-0.25}$ (22)

6. Pumping power can be expressed as Eq. (23)

$$P = \dot{V}_{nf} \, DP \tag{23}$$

7. Total heat transfer rate can be expressed as Eq. (24)

$$Q = \varepsilon C_{min}(T_{nf,in} - T_{a,in}) \tag{24}$$

V. Challenges of Nanofluids

Many interesting properties of nanofluids have been reported in the review. In the studies, thermal conductivity of nanofluids has received the maximum attention by many researchers. Conversely, 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. 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. Therefore, Bhogare et al. [20] concludes several important issues that should receive greater attention in the near future as per following.

A. 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.

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. However the dispersion behavior of the nanoparticles could be influenced by period of time. As a result, thermal conductivity of nanofluids is eventually affected.

Eastman et al. [16] 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.

B. Increased Pressure Drop & 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.

Yu et al. [11] investigated viscosity of water based Al_2O_3 nanofluids and ethylene glycol based ZnO nanofluids. Results clearly show, viscosity of nanofluids is higher than base fluid. Namburu et al. [28] in their numerical study reviewed that density of nanofluids is greater than base fluid. Both properties are found proportional with nanoparticles volume fraction. Several literatures have indicated that there is significant increase of nanofluids pressure drop compared to base fluid.

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% Al_2O_3 +H_2O nanofluids is almost double of the base fluid. Pantzali et al. [30] 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.

C. 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.

D. Lower Specific Heat

From the literatures, it is found that specific heat of nanofluids is lower than base fluid. 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 base fluids. An ideal coolant should possess higher value of specific heat which enables the coolant to remove more heat.

E. Higher Cost

Higher production cost of nanofluids is one of the main 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.

F. Difficulties in Production of Nanofluids

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.

VI. Conclusions

From the above study of nanofluids, following brief conclusions can be drawn.

1. It has been seen that nanofluids can be considered as a potential candidate for Automobile application.
2. Automobile radiators can be made energy efficient and compact as heat transfer can be improved by nanofluids. Reduced or compact shape may results in reduced drag, increase the fuel economy, and reduces the weight of vehicle.
3. Exact mechanism of enhanced heat transfer for nanofluids is still unclear as reported by many researchers.
4. 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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