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Nano-Fluids as a Coolant for Automotive Engine Radiators: Review Study

Karaar Mahdi Al-Araji[1, a,*], Dhafer Manea Hachim[1, b]&Almoussawi M A[1, c]

[1]Department of Power MechanicsEngineering, Engineering Technical Collage / Al-Najaf, Al-Furat Al-Awsat Technical University (ATU), Najaf, Iraq
[a]karaar.mahdi@student.atu.edu.iq
[b]coj.dfr@atu.edu.iq
[c]inj.mun@atu.edu.iq
[*]Corresponding Contact: karaar.mahdi@student.atu.edu.iq
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Abstract. Low-efficiency crossflow heat exchangers which are used as radiators in the automotive sector may cause engine damage. Nano-fluids are ideal coolants due to their high heat diffusion coefficient and can be added to almost any process that requires a fast reaction to thermal performance, such as the automobile. The nanofluid's thermal conductivity is greater than that of the base fluid such as water and ethylene glycol and can achieve more than 40% and enhance the heat transfer coefficient by more than 50%. The best results for heat transfer were to use carbon nanoparticles with base fluid. This article reviews previous research investigating the effect of nano-fluid in automotive radiators in which nanoparticles such as Al_2O_3, CuO, TiO_2, and MWCNT are used. The preparation and application of nano-fluid and measurement of thermal properties and the effect of volume fraction on efficiency are discussed. The review also is focused on the numerical and experimental studies of previous work related to nano-fluid performance in automobile radiators.

Keywords: Nano-Fluids, Automotive Radiator, Engine Coolant, Heat Transfer Coefficient

1. INTRODUCTION

Cooling of the engine is one of the challenges facing automobile manufacturers because the excessive heat can destroy the machine, as well as, the extra radiator weight may increase fuel consumption. The traditional methods used to improve heat transfer rates are no longer effective as the manufacturers desire. Water is considered a liquid with a high heat transfer coefficient of about 1000 W/(m^2°C) for cold water and 1000 – 6000 W/(m^2°C) for hot water [1]. Other liquids are also added to water in a different ratio to increase the boiling point and to reduce the degree of freezing, such as Ethylene Glycol (EG), for better performance of the vehicle's cooling system. The discovery of nanoparticles manufacturing techniques discovered by (Choi in 1993) [2]has led to the development of using nanoparticles in engine coolant mixtures such as water and EG to increase the thermal performance. This has helped designers to reduce the cooling system by making smaller radiators and also reducing the weight and fuel consumption. Nano-fluids are usually prepared to contain tiny nanoparticles size (< 100 nm) [3]. An ultrasonic waves device prepares the suspension by mixing a specific concentration in the base-fluids. Different nanoparticles such as Al_2O_3, MWCNT, TiO_2, CuO, MgO, Fe_3O_4, and SiO_2 can be used to increase the heat transfer rate [4].
Kole & Dey[5], carried out an experimental study and showed that 3.5 vol.% of Al_2O_3 / EG Nano-fluids had affected the maximum thermal conductivity to increase by 11.25% at 80 ° C. These particles have improved the heat transfer rate in the coolant to the right concentration compared to the base-fluid.

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2. TYPE OF NANOPARTICLES AND SURFACTANT

Many particles are presently used with the base-fluids to enhance the thermal performance of the engine coolant. The base-fluid may be water, organic-fluid like EG, biological fluids, oils, and phase change materials. Metallic materials such as silver and gold, ceramic oxides such as alumina Al_2O_3, CuO, and carbon forms like diamond, carbon nanotubes, and graphite are usually used in the nano-fluids [6]. The surfactant such as Sodium dodecyl sulfate (SDS) [$CH_3(CH_2)11SO_4Na$], sodium dodecylbenzene sulfonate (SDBS) [$C_{18}H_{29}NaO_3S$], Cetrimonium bromide (CTAB) [$(C_{16}H_{33})N(CH_3)_3$] and the Arabic Gum are added to increase the stability and homogeneity in nano-fluids [3]. Types of nanoparticles with general classifications are shown in Table 1.

Table 1. Type of base-fluid, nanoparticles, and surfactants

	Material	Surfactant
Fluid	Water Ethen Glycol Engine Oil Transmission oil	Anionic such as ([SDS] Sodium Dodecyl Sulphate) Cationic such as ([CTAB] CetylTrimethyl Ammonium Bromide) Non-ionic such as (Gum Arabic GA, Triton X-100) Amphoteric such as (lecithin, hydroxylamine)[7]
Metallic Materials	Gold Silver Cooper	
Ceramic Oxide	alumina Al_2O_3 Silica CuO Tio2	
Carbon	Diamond SWCNT MWCNT Graphene	

3. ADVANTAGES AND DISADVANTAGES OF NANO-FLUIDS

In addition to a small boost in cooling efficiency relative to pure liquid, the nanoparticle's usefulness increases the heat transfer coefficient by improving the nano-fluids thermal conductivity. There are, however, some significant disadvantages that raise questions about the use of nano-fluid in automotive radiators [8]. Table 2 shows the most common advantages and disadvantages of nano-fluid.

Table 2. Advantages and Disadvantages of Nano-Fluid

Advantages	Disadvantages
Enhanced heat transfer coefficient due to higher thermal conductivity, mainly of laminar flow	It has to raise the pumping power because of the significantly decreased pressure.
It is possible to make miniature devices available because of the improved heat transfer.	The high-cost suspension of nanoparticles, especially those requiring the addition of substances such as surfactants to improve stability[9]
	The accumulation of particles when the fluid is in a state of stagnation for a long time causing the flow pathways to close
	Corrosive damage to subsided parts due to flow

4. PREPARATION OF NANO-FLUIDS

Nano-fluids are dependent on the method and nature of the preparation. Most unstable nano-fluids reduce heat transfer and deposition of particles and may lead to sedimentation and clogging of radiator tubes and water pumps. There are two common ways of preparing the Nano-fluid [10].

4.1 One-Step Method

The one-step process consists of mixing and dispersing particles in a liquid simultaneously. Eastman et al.2001 [11] developed a one-step evaporative condensation procedure for physically preparing water / EG Nano-fluids. The drying and transporting process of the nanoparticles was avoided. However, it is challenging to prepare nano-fluids on a large scale by the one-step procedure as it is an expensive technique [10].

4.2 Two-Step Method

The two-step method represents the most common method for preparing nanoscale fluids. The first step in this method is mixing the nanoparticles in the liquid by Magnetic stirrer Figure (1). The second step is the mixing and suspension by the ultrasonic device[12]**.** Hung et al. 2011 [13] used nanoparticles of aluminum oxide (Al_2O_3) to prepare the Nano-fluids using the two-step method by mixing weight ratios (0.5, 1.1.5 wt%) with a size of 20 nm with water as base-fluid and adding a dispersing component that is (chitosan). It was mixed using ultrasonic and hot plate magnetic stirrer to create Nano-fluids (alumina). Vermahmoudi et al. 2013 [14] prepared nano-fluids from iron oxide (Fe_2O_3) nanoparticles with a purity of 99% and a diameter of 40 nm, two types of techniques have been proposing to prepare the liquid. The first technique is to use surfactants, and the second is to change the PH of the fluid for synthesis. Then added a small quantity of iron oxide 0.02 vol % in 100 ml of distilled water. They found that the nano-fluid was more stable at a PH of 11.1 and polyethylene glycol surfactant. Al-Shamani et al. 2016 [15] Prepare the nano-fluid using the two-step method and suspend the nanoparticles with base fluid using an ultrasound device. Table 3. Shows nanoparticles type and surfactant.

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Figure 1. Magnetic Stirrer Device

Table. 3. Summary of Preparation of Nano-Fluids and Type of Nanoparticles, Surfactant, and PH

Authors	**Nano-fluids**	**Surfactants / PH**	**Dispersing mothed**
Ding et al.2006 [16]	MWCNTs/Water	(GA) Gum Arabic, pH (6)	24 hours at Ultrasonic bath And 30 min at homogenizer
Li et al.2008 [17]	Cu/Water	SDBS, Ph (8.5 – 9.5)	15 min at Ultrasonic bath
Zhu et al.2009[18]	Al_2O_3-Water	SDBS, pH 8-9	One hour at Ultrasonic bath
Phuoc et al.2011 [19]	MWNT/Water	Chitosan	10 minutes at Ultrasonic processor and mixing for 20 minutes at a magnetic stirrer
Byrne et al.2012 [20]	CuO/Water	CTAB	for 7–8 hours, an ultrasonic processor with high intensity
Lotfi et al.2012 [21]	MWNT (MWNT)/water	functional groups of COOH	60 min at Ultrasonic bath and 3-hour mixing at a magnetic stirrer

5. THERMOPHYSICAL PROPERTIES

The advent of nanotechnology and the addition of nanoparticles with high thermal conductivity (8.4 - 3300 W/m.K)[22] to fluids has enhanced heat transfer in traditional liquids such as water [23]. Many researchers have been investigated particle suspension in a conventional fluid such as water, oils, and EG [24]. The most important properties are thermal conductivity, density, heat capacity, and viscosity.

5.1 Thermal conductivity

The thermal conductivity of nano-fluids is usually calculated in the laboratory using a Kapton hot disk sensor Figure 2, and the transient hot wire. It can also be calculated numerically by using the Maxwell equation (1). Maxwell's model (1881) of the thermal conductivity for a liquid-solid mixture

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works well to measure the thermal conductivity with low concentrations for solids spherical nanoparticles.[4].

$$K_{nf} = \frac{K_p + 2K_{bf}(K_p + K_{bf})\emptyset}{K_p + 2K_{bf} - (K_p - K_{bf})\emptyset} * K_{bf} \qquad (1)$$

To measure the thermal conductivity of non-spherical nanoparticles, Hamilton and Cruiser (1962) proposed a model (2) for the liquid-solid mixture which takes into account the shape coefficient, n, as its value depends on the shape of the particles, [n=3/Ψ] and [Ψ=3 for spherical, Ψ=6 for non-spherical] [25]. Equation (3) gives the most accurate thermal conductivity product of the nanofluid performed by Koo and Kleinstreuer in 2004 [26]. The summary of the thermal conductivity of nanofluids enhancement is shown in Table 4.

$$K_{nf} = \frac{K_p + (n-1)K_{bf} - (n-1)(K_{bf} + K_p)\emptyset}{K_p + (n-1)K_{bf} + (K_{bf} - K_p)\emptyset} * K_{bf} \qquad (2)$$

$$K_{nf} = \left[\frac{(K_p + 2K_{bf}) - 2\emptyset(K_p - K_{bf})}{(K_p + 2K_{bf}) + \emptyset(K_p - K_{bf})} * K_{bf}\right] + 5\times10^4\,\beta\,\emptyset\,\rho b_f\,Cpb_f\sqrt{\frac{K_B T}{\rho_p d_p}}f(T,\emptyset)(3)$$

$$f(T,\emptyset) = (-134.63 + 1722.3\emptyset) + (0.4705 - 6.04\emptyset)\left(\frac{T}{T_\circ}\right)$$

$$\beta = \begin{cases}0.0137(100\,\emptyset)^{-0.8229}, \emptyset < 0.01\\ 0.0011(100\,\emptyset)^{-07272}, \emptyset > 0.01\end{cases}$$

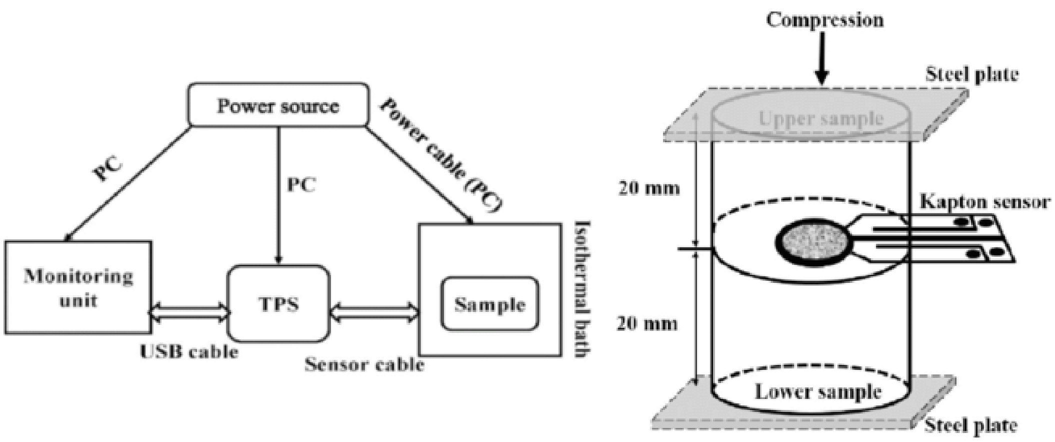

Figure 2. Schematic Diagram ofKapton Hot Disk Sensor

Table 4. Summary of Thermal Conductivity Nano-Fluids Enhancement

Authors	Nano-Fluids	Concentration (%) vol	Thermal Conductivity Enhancing (%)
Liu et al.2006 [27]	Cu/Water	0.05%vol	12%
Zhang et al. 2006 [28]	CuO/Water	7.5 %vol	52%
Ding et al. 2006 [16]	MWCNT/Water	0.05–0.5%vol	79%
Beck et al.2009 [29]	Al_2O_3/EG	2–3%vol	19%
Godson et al.2010 [30]	Ag/Water	0.3–0.9%vol	30%
Jahanshahi et al.2010[31]	SiO_2/EG	1–4%vol	23%
Paul et al.2010[32]	ZrO_2/Water	0–2.2%vol	60%
Chandrasekar et al. 2012[33]	Al_2O_3/Water	0.33–3%vol	9.7%
Karami et al. 2014 [34]	MWCNT/Water	0.015%vol	32%

5.2 Viscosity

Viscosity is the resistance to nano-fluids flow within tubes and is a significant thermal property. With an increase in fluid viscosity, the system needs more pumping force, affecting the heat transfer coefficient. [35]. The first attempt to derive an equation for calculating viscosity was carried out by Einstein (1956) using hydrodynamic equations [4]. Brinkman found an equation for knowing the viscosity of a nano-fluid of spherical nanoparticles.[36]. Esfe et al. 2014 [37] Using equation (6), the nano- fluids' viscosity was calculated from the magnesium oxide molecules of diameter 40. The units of viscosity are [Pa.s].

$$\frac{\mu_{nf}}{\mu_{bf}} = \left(1 + 2.5\emptyset_p\right),\ \emptyset < 0.05 \qquad (4)$$

$$\frac{\mu_{nf}}{\mu_{bf}} = 1/\left(1 - \emptyset_p\right)^{2.5} (5)$$

$$\frac{\mu_{nf}}{\mu_{bf}} = 1 + 11.61\,\emptyset + 109\emptyset^2 (6)$$

Lu and Fan.[38] applied a numerical simulation and experimental procedure to measure Al_2O_3/water and Al_2O_3/EG Nano-fluids viscosity. The obtained results showed that the Nano-fluids viscosity mentioned above improved the volume fraction of Al_2O_3 nanoparticles because they have a greater surface area to volume ratio. Nguyen et al. 2007 [39] experimentally analyzed the viscosity of CuO/Water, Al_2O_3/Water nanoparticles with different nanoparticle volume fractions. It was found that its viscosity counts on temperature and particle concentration. In general, the viscosity of nano-fluid increases with increasing particle size, but it decreases with increasing temperature. However, their investigations confirmed that the Nano-fluids viscosity was approximately equal when nanoparticle volume fractions were less than 4%.

5.3 Other Properties of Nano-Fluids

For the volumetric concentration of nanoparticles, all other properties are a linear relationship, which results in the equations of specific heat capacity [J/kg. k] and density [kg/m^3], respectively.

$$Cp_{nf} = (1-\varphi)Cp_{bf} + \varphi Cp_p (7)$$
$$\rho_{nf} = (1-\varphi)\rho_{bf} + \varphi\rho_p (8)$$

6. GOVERNING EQUATIONS IN HEAT TRANSFER CALCULATIONS

From the following equation, the heat transfer rate can be calculated

$$Q = \dot{m}\, Cp\, (T_{in} - T_{out}) \qquad (9)$$

$$\dot{m} = \rho\, V\, A_{in} \qquad (10)$$

Where (Q) is the heat transfer rate, (Cp)specific heat, (Tin) is the inlet temperature and (Tout) is the outlet temperature, the (m) mass flow rate be calculated the (ρ) is the density of fluid (V) velocity of the fluid and (A_{in}) the inlet area of the flat tube.

to calculate the heat transfer coefficient using the following equation

$$h = \frac{\dot{m}\, Cp\, (T_{in} - T_{out})}{A_s (T_b - T_{w)}} \qquad (11)$$

Where (A_s) the surface area of a flat tube (Tb) is the reference point for the temperature of inlet and outlet, (Tw) is the average wall temperature.

To calculate the Nusselt number, you can use the following equation

$$Nu = \frac{h * D_h}{K} \qquad (12)$$

Where the (D_h) hydraulic diameter, (k) the thermal conductivity of the fluid.

$$D_h = \frac{4 \times [\pi d^2 (D-d) * d]}{\pi\, d + 2 * (D-d)} \qquad (13)$$

7. THEORETICAL INVESTIGATION

The rapid development in computers and simulation software, in general, has led to reducing the time and cost of machine fabrication, as well as, they obtained accurate results that are close to the finding of experimental studies. The most reliable software is ANSYS Fluent and COMSOL [40].

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Pendyalaet al. 2015 [41] carried out a numerical analysis on a 3D automobile radiator using ANSYS software to calculate the thermal properties of the Nano-fluids of CuO, Al_2O_3, SiO_2; the diameters of nanoparticles was (29, 45, and 20) nm, respectively. Taking into account (Naiver- Stock equations and fluid flow and continuity equations), the entry temperature of the liquid and air was 90°C and 30°C, respectively, the air velocity is 4.4 meters per second, the hydraulic diameter is 0.0404, and the thickness of the fin is 0.001 mm. The results showed that copper oxide (CuO) and aluminum oxide (Al_2O_3) were more efficient than silicon oxide in enhancing heat transfer during laminar and turbulent flow because of the high thermal conductivity of the two mentioned nano-fluid.

Angadi et al. 2014 [42] applied a numerical study using the STAR CCM + program on automobile radiator to study the heat transfer properties of pure water to compare it with Al_2O_3 Nano-fluids at different concentrations and flow rates (2-6) l/min. They found that the heat transfer efficiency of Nano-fluids is higher than pure water because of the increase in thermal conductivity.

Vajjha et al.[43] Have been compared the dispersion of aluminum oxide (Al_2O_3) and copper oxide (CuO) nanoparticles in the vehicle coolant combination EG and Water numerically. They found that the mean heat transfer coefficient has increased to 36.6% for Al_2O_3 Nano-fluids at 3 vol% concentration and 49.7% for CuO Nano-fluids at 3 vol% concentration. The summary of the previous theoretical investigation has been organized, as shown in Table 5.

Table 5. Summary of the Theoretical Studies of Nano-Fluids

Authors	Nano-fluids	Results
Vajjha et al. 2010 [44]	Al_2O_3/W-EG, CuO/W-EG	To obtain the same amount of heat transfer in the base-fluid, Nano-fluids require less pumping force than the base-fluid with different nanoparticle concentrations.
Patel. 2012[45]	CuO/W-EG TiO_2/W-EG	Using computer programs STAR CCM+, the results were identical to the experimental results at a flow rate of 4 kg/s
Huminic et al. 2013 [46]	CuO/EG	Upon laminar flow and increasing the volume fraction of nanoparticles, the heat transfer coefficient, Reynolds number, and Brownian motion are enhanced.
Safikhani et al. 2014 [47]	Al_2O_3/Water	In flat tubes as the heat transfer of Nano-fluids led to nanoparticle distribution, a crucial case in fluid dynamics at laminar flow.
Hatami et al. 2014 [48]	TiO_2/Water Fe_2O_3/Water, CuO/Water,	By using Nano-fluids of CuO/Water and Fe_2O_3/Water, the heat transfer enhancement was lower compared to TiO_2 – Water by 10%.
Abbasi&Baniamerian. 2014 [49]	Al_2O_3, Au, CuO, TiO_2/Water-vapor	As the vapor flow rate increases, the heat transfer coefficient decreases, the enhancement of the Nano-fluids heat transfer coefficient was higher for the Al_2O_3 particles, followed by TiO_2, Au, and CuO.

8. EXPERIMENTAL INVESTIGATION

The thermophysical properties of Nano-fluids resulting from nanoparticle addition to the base-fluid have led to an improvement in heat transfer and a reduced pumping power [29]. There is much research that has been reviewed for applying Nano-fluids to automotive radiators**.** Said et al. 2019 [50]Studied automobile radiator's performance experimentally by adding Al_2O_3/Water and TiO_2/Water Nano-fluids as a coolant. It is found that the Nusselt number for a radiator at 0.3 vol% concentration was 24.21% for Al_2O_3/Water and 14.99% for TiO_2/Water. Anuar. 2016[51]Found that the coefficient of heat transfer has increased by about 93% at 10%vol, a volume fraction upon an experimental study on the effect of Cu/Water Nano-fluids. Tafakhori et al. 2020 [52]investigated the thermal properties of nano-fluids of Fe_3O_4/DW experimentally, results showed that the thermal conductivity has increased by 550.3% at a volume fraction of 0.9 vol%**.** Muruganandam & Mukesh Kumar. 2020 [53] carried out an experimental analysis on MWCNT/Water Nano-fluids, surfactants (SDBS) and found that the mechanical efficiency improved by 24% at 0.3 vol% and average fuel consumption 19% at 0.3 vol%**.** Ebrahimi et al. 2014 [54]concluded that in SiO_2 Nano-fluids when increasing the temperature of the liquid, an increase in the Nusselt number and the rate of heat transfer will occur. Nieh et al. 2013 [55] have been working on nanoparticles of aluminum and titanium oxide (Al_2O_3, TiO_2), by using the two-step method to synthesize a nano-fluid with a concentration of 0.2 wt% of nanoparticles with a base fluid consisting of water and EG at a ratio of (50:50), the results showed that the efficiency factor increased to 27.2% and the heat dissipation to 25.6% for nano-fluid. These results were higher compared to the base fluid. The summary of the experimental investigation is shown in Table 6.

Table 6. Summary of the Experimental Study of Nano-Fluids

Authors	Nano-fluids	Concentration (%) vol	Results
Leong et al. 2010[56]	CuO/EG	2%	3.8% improvement in heat transfer compared to the base-fluid
Teng and Yu. 2013[57]	MWCNT/EG - Water	0.4 %	At 0.4 vol% for MWCNT/EG -W Nano-fluids, the most significant thermal conductivity improvement was 49.6% compared to EG - W.
Peyghambarzadeh et al. 2013 [58]	Fe_2O_3/Water	0.1-1%	At a concentration of 0.65 vol% for the Fe_2O_3-Water Nano-fluids, it was found that 9% is the amount of enhancement in the heat transfer coefficient compared to water
Elias et al. 2014 [59]	Al_2O_3/Water- EG	0 -1%	At 50 ° C, the maximum improvement in the thermal conductivity of Nano-fluids using $A_{l2}O_3$ particles was 8.3% at 0.1% vol concentration.
Hussein et al. 2014 [60]	SiO_2/Water	0.1 - 2.0 %	The use of the SiO_2 Nano-fluids enhanced the heat transfer rate by up to 50% compared to pure water and at lower concentrations and flow rate of 2-8 l/min
Hussein et al. 2014 [61]	Water/TiO_2	0.1 - 2.0 %	At 0.3% vol concentration of TiO_2 nanoparticles in the basic coolant mixture, an improvement in heat transfer of 8.5% was achieved and a Nusselt number of 8.3%.
Heris et al. 2014 [62]	CuO/Water-EG	0.2 - 0.8%	At 0.8 vol% of the CuO-EG Nano-fluids, the improvement in heat transfer Compared to the base-fluid, it was around 55 %.
Ali et al. 2015 [63]	MgO/Water	0.05 - 0.12%	1.31% is the maximum obtained to enhance heat transfer with the MgO Nano-fluids at 8–16 l/min, and 0.12% vol

9. CONCLUSIONS

The review article states the numerical and experimental research conducted on the performance of nano-fluids in automotive radiators. And explain the method of calculating conductivity and viscosity by experimental and numerical approaches using equations or in the laboratory.

- The governing equations for calculating thermal properties, the equations for the analysis of heat transfer, and the Nusselt number are illustrated.
- Thermal conductivity and viscosity affect the nano-fluids, the nature of the flow, and the fluid's thermal improvement.
- Enhancement value by using nano-fluids was more than 50% compared to base-fluids
- The paper summarized the research conducted on nanoparticles of the metallic/non-metallic form, where Al2O3 nanoparticles were the most widely used because they provide good r esults and have a minimal price.
- Most researchers agreed that increasing the volume fraction more than (1 vol%) could decrease the heat transfer rate.
- However, there are problems and challenges in obtaining a stable nano-fluid for a long time; this includes low pressure and high cost for some types of nanoparticles with high conductivity coefficients such as MWCNT.

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