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ARTICLE

Hybrid nano-coolants in automotive heat transfer – an updated report

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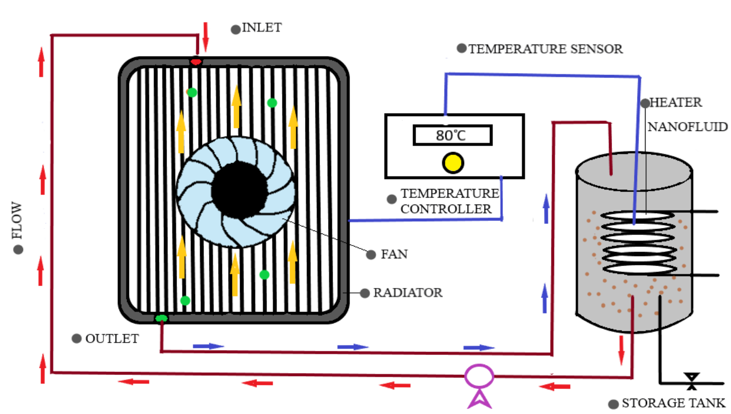
ABSTRACT

Nano coolants have been attracting various researchers for efficient heat transfer agents. The efficacy of nanofluids as nano coolants is reviewed in the present study. The addition of nanoparticles to existing coolant fluids can enhance their heat transfer performance. Conventionally water and ethylene glycol are used as engine radiator coolants. The addition of ethylene glycol is needed to increase the boiling point of the water and decrease the freezing point. The convention also seems to be a crucial factor for heat exchanger performance. This is a requirement for vehicles that are being used under harsh weather conditions. Different types of nanoparticles used as nano coolants SiO_2, TiO_2, Al_2O_3, Cu/CuO, G/GO, CNT, and Hybrid nanoparticles, were extensively illustrated. Finally, nanofluids applications in the past decade were included. As many researchers have shown, they can be used to enhance radiator performance as well. In this review paper, studies of heat transfer performance of various Nanofluids as nano coolants conducted by researchers are studied. Finally, a conclusion is presented.

Graphical Representation



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Content

1. Introduction

Since the last few decades' different base fluids with nanoparticles have become the most important and firmly investigated nanoparticles for engineering applications, there are several advantages found in fluid-based nanoparticles, such as higher mobility, low erosion, thermal connectivity, and high stability. Hybrid nanofluid is a novel period of nanofluids contrived by dissolving two, unlike nanoparticles, into straight high-temperature handover fluid. Hybrid nanofluids are potential solutions that reduced restored heat transference routine and thermo-physical assets than conventional heat transferal solutions and nanofluids through single nanoparticles. Systematic results have specified that mixture nanofluid can exchange single nanofluid; meanwhile, it offers more temperature delivery augmentation, particularly in the vehicle's parts, electro-mechanical, engineering process, HVAC, and solar vigor.

Nanofluids are the most influential invention in science and engineering (Dietz et al., 2011). Nanofluids can be best suitable in heat transfer applications such as fluid. Nanofluids can be industrialized via two means: one-step and two-step methods. Theoretically, the improvement can be up to 350 % because metal has a much higher thermal conductivity irrespective of the state of the metal compared to fluids such as water and various organic fluids. Therefore, a much higher cooling ability is accomplished if a liquid metal or its alloys with a low melting point the fluid. Nanofluids (Nanoparticle fluid suspensions) are coined by Choi et al. (1995) to describe this new class of nanotechnology-based fluids that exhibit thermal properties superior to those of their base fluids.

Similarly, it can be stated that Graphene is relatively considered an excellent heat conductor, and several studies have talked about different potentials of heat conduction. Different studies have identified that Graphene has unlimited heat conduction potential based on the size of the sample and contradicts the ultimate law of thermal conduction in the form micrometre scale. From the theoretical point of view, it has been identified that Graphene could easily absorb unlimited amounts of heat. On the other hand, amongst other fillers, it has become eventually clear that Graphite features unique properties such as electrical conductivity and high thermal conductivity. Moreover, a low coefficient of thermal expansion along with exceptional thermal resistance is the major considerable factor of Graphene. The one-step method associates nanoparticles' incorporation and its scattering into the base fluid in a solitary step. The nanofluids produced past this process are extra invariable, and fewer particles sedimentation is experimental. More compact and efficient cooling systems can be found with the help of technological advancement. Efficient cooling systems are necessary to ensure engineering devices and systems (Ali et al., 2017).

The current research review encompasses different reports with the overview of experimental investigation of base fluids and nanometer-sized particles with various bases that host fluids for engineering applications of energy transfer systems. Different tribological and rheological properties are discussed below. Various metal nanoparticles are summarized.

2. Nanofluids

Nanofluid is produced by dissolving Nanoscaled particles into a base liquid such as water and ethylene glycol. The use of nanofluid significantly improves the input energy of the mechanical system. Nanofluids can change the properties and characteristics of the transport medium (Ganvir et al., 2017) when the base fluid is mixed with metal nanoparticles such as aluminium oxide, titanium dioxide, and silicon powder. The thermal properties of the nanofluid are mainly reliant on the metal nanoparticle properties. The thermal conductivity of base fluids is lesser than that of metal nanoparticles. Metal nanoparticles enhance the thermal properties, especially the thermal conductivity of the base fluids they are mixed. When metal nanoparticles are dispersed into the carrier/base liquids, the heat transfer efficiency of the fluid compared to the carrier liquid increases itself (Peng et al., 2008). Due to their small size, usually less than 100 nm, nanoparticles fluidize easily inside the base fluid, and therefore, clogging and erosion in channels are no longer a problem. These particles contain only a few thousand atoms and possess substantially different properties from their nurture materials. The goal of nanofluids is to achieve the highest possible thermal properties at the possible minor concentration by uniform dispersion and stable suspension of nanoparticles in base fluids. Recently there have been several advancements that have made the nanofluids more stable and ready for use. Nanofluids find potential applications in electronic devices as they have higher denser chips with a compact design which makes heat dissipation difficult, heat pipes in the computer devices to improve heat dissipation, industrial cooling applications resulting in significant energy savings and emission. Reduction for cooling nuclear systems, space and defence due to the restriction of space and heat exchangers to improve heat transfer rates in the fuel cell, Solar water heaters, chillers, domestic refrigerators, and lubricants in machining.

2.1. Preparation of nanofluids

Nanofluids are not simply liquid-solid mixtures but are produced by dispersing nanometer-scale solid particles into base liquids such as water, ethylene glycol (EG), oils, etc., without agglomeration. The two methods used to prepare nanofluids are (i) one-step and (ii) two-step methods. The one-step method combines the production and dispersion of nanoparticles in the base fluid in a single step. The limitations of this method are the low production capacities and residual reactants left in the nanofluid due to incomplete chemical reactions. In two-step methods, nanoparticles are synthesized and then dispersed in the base fluids. The two-step method is advantageous when mass production of nanofluids is considered. The disadvantage of the two-step technique is that the nanoparticles form clusters without proper dispersion during the nanofluid preparation. Generally, ultrasonic equipment is used to disperse the particles and reduce clustering intensively. Besides applying ultrasonic waves, other techniques such as control of pH of base fluid or the addition of surface-active agents (surfactants) are used.

2.2 Tribological and rheological properties of nanofluids

I. Tribological properties

Different desirable tribological properties have made nanofluids attractive in the field. The desirable properties that are present are extreme strength, sheer capability, and high thermal stability. Copper nanoparticles that research groups have found ultimately group the friction surface as per EDS and AFM analysis and fill the scars when deposition of nanoparticles suddenly happens between the friction surfaces. Similarly, another study proved that nanoparticles provide a protective film that ultimately reduces abrasive actions that agglomerate on the surface (Pourpasha et al., 2020). A new thing has been observed in the graphitized nanodiscs due to their high structure and organized property compared to the other nano-carbons. Like graphitized carbon black, the friction coefficient is lower, which leads to the contact area of the Graphene forming a film of protection in the sliding metal duty on its surface which ultimately fills it in the earth in atomic size thickness Graphene. Sanukrishna and Prakash have studied and found that the tribological properties of Graphene are as additives as diamond-like carbon/ionic liquid hybrid films indifferent lubricating stating at a high vacuum level (Sanukrishna et al., 2018).

The surface-modified that Graphene enhances the wear resistance and the load-carrying capacity present in the machine. This might be because Graphene must be allowed to enter quickly with the help of the contact area because of the fragile laminated structure; this has been shown by the SEM and EDX results. To reduce wear scar diameter by 70% and 14% and increase enhanced performance with a high friction coefficient, scientists used liquid-phase Graphene modified by oleic acid as there are additives present in the oil, which ultimately showed the expected result (Sanukrishna et al., 2018). It is attributed that the nano bearing mechanism presented in the Graphene is the main reason behind these enhancements. This is one of the reasons Graphene oxide nanoparticles were added in the water-dependent coolant and found that by doing this in the testing, the coefficient of friction was reduced to 0.5, and there was no surface wear found for more than 6000 cycles (Pamies et al. 2018).

II. Rheological properties

Researchers worldwide are predicting that properties of nanofluids such as thermal conductivity are applied to nanofluids like drilling fluids and are higher in range to the base fluid on a similar idea. A possible way of enhancing the heat transfer rate in the spiral plate heat exchanger is by employing nanofluids, as it often works in the medium context. A countercurrent SPHE can be designed and modelled, and then the employment of conventional fluid can simulate SPHE along with hybrid nanofluids for investigating the heat transfer rates. Ionic liquid-based nanofluids comprising functionalized multi-walled carbon nanotubes (F-MWCNTs) remained devised. Transmission electron microscopy (TEM), field emission electron microscopy (FE-SEM), Fourier transmission Infrared analysis (FT-IR), and X-ray photoelectron fields revealed the morphology and biochemical assembly of the found F-MWCNTs. The rheological actions of the F-MWCNTs/1-butyl-3-methylimidazolium hexafluorophosphate nanofluids remained calculated, representative of the retreating behaviour of nanofluids at slightly low absorptions, which might be due to the all-precise relation, suppleness of F-MWCNTs, and the formation of a transitory finished nanotube–nanotube and nanotube–matrix communications. It originated that the rheological behaviour of the F-MWCNTs (0.1 wt %) / nanofluid was similar to that of the surfactant worm-like micelle organizations. Therefore, the quick system assembly of the F-MWCNTs (0.1 wt %)/(Bmim)(PF6) nanofluid might be renewed in a bit of time after shearing armies were an effort.

With enhanced mechanical performance, Graphene, which has an intrinsic fracture strength of 130 GPa mechanical properties, can be measured up to 1 TPa. Large quantities of nanofluids can be produced, and the two-step methods are usually way more economical because they utilize the physical agitation to produce nanofluids that have dispersed nanoparticles in dry powder form into their respective base fluid. That is why ball milling methods, homogenization, high shearing mixing are consistent in this ultrasonication method. The novel combination of hydrodynamic cavitation dispersion and ultrasonication can be used to homogenize and produce stable nanofluids.

Nanofluids that include graphene and carbon nanotubes-based suspensions have different rheological behaviour. In a recent observation, it is found that the sheet shape of Graphene oxide could be the main factor in the relationship between thermal conductivity 'k' and viscosity of nanofluids. An increase in temperature was found when the viscosity was decreased. It was observed that temperature and concentration of Graphene, if increased non-Newtonian behaviour, can be found. In models by Kriegar and Dougherty, Brinkman, Einstein, and Kitano the enhancement in viscosity could not be predicted. An investigation found that the Brownian motion is more active for small-sized cylindrical-shaped particles (Rasheed et al., 2016).

2.3. Thermal conductivity of nanofluids

The fluid used in heat transfer applications needs the following properties: thermal conductivity, viscosity, specific heat, and density. The enhancement in thermal conductivity of nanofluid is due to the random movement of nanoparticles called Brownian motion. The enhancement in heat transfer is because of the increase in the thermal conductivity of nanofluids. The viscosity of nanofluids influences heat transfer as it suffers pressure drop during the flow. Specific heat of a nanofluid is essential to estimate fluidic temperature changes at a heat transfer rate and fluid flow. The density of nanofluids influences the flow behaviour and hence must be found out. The enhancement in thermal conductivity of nanofluid increased convective heat transfer coefficients. The thermal conductivity and specific heat of nanofluids are calculated using the hot plate method, viscosity can be estimated using viscometer-I and density is obtained with a specific method. Mathematical correlations are developed based on the experimental data obtained to predict these properties under different situations (Chougule et al., 2016).

The effect of particle volume fraction, which is the volumetric concentration of the nanoparticles in the nanofluid, on the thermal conductivity of nanofluids. Japan was the first to report thermal conductivity enhancement with nanofluids. They showed that as little as 4.3% particle volume fraction of silica, alumina and other oxides in water increased the nanofluid thermal conductivity by 30% (Turgut et al., 2009). Reported thermal conductivity enhancements for the same oxides considered, not only in water but also in ethylene glycol. They reported that the thermal conductivity enhancement increases as the size of the particles decreases and is almost proportional to the volume fraction of the particles. A maximum thermal conductivity enhancement of 12% was observed when alumina particles were used with a volume fraction of just 3% (Patel et al., 2010). An exciting conclusion is that thermal conductivity has a linear dependence on volume fraction. However, as the particle volume fraction increased, the trend of conductivity enhancement varies more like the square root of temperature (Murshed et al., 2005). Used the transient hot-wire method to estimate the thermal conductivity of Al_2O_3 nanofluids and observed a substantial increase at different volume fractions. Studied Al_2O_3 nanofluids and observed a 4% enhancement in thermal conductivity at 1% volume concentration (PANG ET AL., 2012). Prepared aqueous nanofluids containing low volume concentration of Al_2O_3 nanoparticles and observed a 2% enhancement in thermal conductivity at a lower volume percent for 35-nm-sized Al_2O_3 particles (Sridhara et al., 2011). Investigated the effects of variations in the temperature and volume fraction on thermal conductivity by adding Copper- Aluminum oxide and CuO- Al_2O_3 nanoparticles in 2%, 4%, 6%, and 10% volume fractions to the distilled water at various temperatures. The results indicated that the nanoparticle material, diameter, volume fraction, and bulk temperature significantly impact the thermal conductivity of these suspensions.

2.4. Factors influencing the thermal conductivity

2.4.1. Volume concertation

The volume concentration of a nanoparticle is set between the range of 0 to 1 vol. % and a variety of temperatures starting from 10°C to 50°C to verify the influence of volume concentration on viscosity, specific heat, density, and thermal conductivity of nanofluid as in Figure 1 and Figure 2, the result verified that thermal conductivity as well as viscosity, the density of a nanofluid increase proportionally with the increment in volume concentrations (Elias et al., 2014). The particle volume fraction of base fluid and particles greatly influences the thermal conductivity of the nanofluid. Apart from that, the thermal conductivity of particles and base fluid also plays a vital role in determining the thermal conductivity of nanofluid (Dhaiban, 2016). A study was carried on Zinc Dioxide-Ethylene Glycol (ZnO_2EG) based nanofluids to investigate their thermal properties. In addition, the result obtained shows an approximately 26.5% improvement of thermal conductivity of a 5% volume fraction of Zinc Dioxide nanoparticles in ethylene glycol (Nguyen et al., 2007). Investigated experiment on Alumina water (Al_2O_3/water) nanofluids regarding its convective heat transfer in laminar flow as it flows through a circular tube with stagnant wall temperature under different concentrations of nanoparticles shows attained augmentation of heat transfer coefficient of nanofluid as the concentration of nanoparticles rises (Zeinali Heris et al., 2007). Nanofluids of 3.7% volume concentration containing 170-nm Silicon Carbide particles proves that the conducted heat transfer experiments lead to the conclusion that at stable Reynolds number, heat transfers coefficients of nanofluid are bigger by 50-60% when compared to base fluid (Mintsa et al., 2009).

Copper Oxide/water-based nanoparticles are experimentally tested under a laminar flow regime in an automobile radiator. The overall heat transfer leads to finding that the total heat transfer coefficient of base fluid was less than nanofluid at a concentration of 0 to 4 vol. % (Naraki et al., 2013).

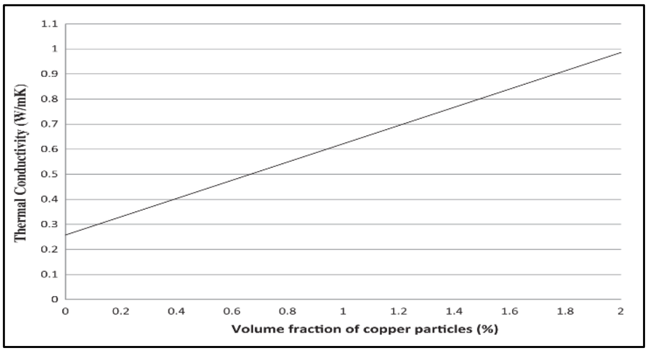

Fig. 1. Thermal Conductivity of Ethylene Glycol based Copper Nanofluids (Leong et al., 2010).

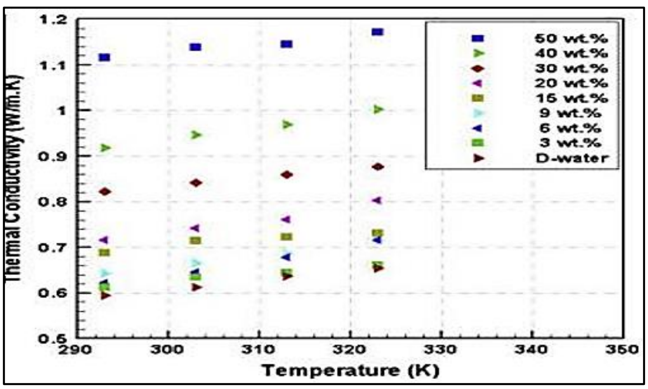

Fig. 2. Thermal Conductivity of Al_2O_3-Water Nanofluids at Different Concentration (Ghanbarpour et al., 2014).

2.4.2. Particle size

Particle size is one of the crucial factors in nanofluids. Several researches were done to verify the influence of particles size in improving the thermal conductivity of nanofluid. Although previous studies provide proof that the addition of small particles in fluid causes wearing of instruments and blockage, but promising studies done by few researchers provide sufficient results that combination of nanoparticles with a base fluid can increase the thermal conductivity of a fluid. It was also able to reduce the problem arising from wearing and deposition of the heat exchangers. This is mainly due to the size of added nanoparticles are extremely small. Apart from that, the increment of thermal conductivity due to the usage of nanoparticles of larger size that leads to a reduction in volume fraction is much higher compared to the increment in thermal conductivity due to the effect of temperature on nanofluids.

Brownian motion is a motion that occurs within a bulk liquid due to the random motion of nanoparticles. As the particles and molecules collide endlessly within the bulk liquid, this results in thermal conductivity. The Brownian diffusion coefficient, DB can be used to display the Brownian motion and can be illustrated using the Einstein-Stokes equation:

$$DB = KBT/[3\pi(dp/109)] \quad (1)$$

Einstein- Strokes equation (Eq. 1) relates that the Brownian diffusion coefficient is proportional to temperature; however it is reciprocal to the particle's diameter. This shows that the addition of particles with a small size diameter at higher temperatures can cause more vigorous collisions, which yield better thermal conductivity. Thus, based on this obtained result, it can be concluded that increasing the temperature and reducing the particles size can amplify the possibilities of vigorous collision among molecules within a bulk fluid. It can be verified that the thermal conductivity decreases under large-sized particles and low-temperature conditions than thermal conductivity values under elevated temperature and small particle size.

(Mintsa et al., 2009) investigated factors that affect the thermal conductivity of water-based nanofluid of alumina and copper oxide. The variables factors are the influence of temperature, volume of fraction, and size of particles. It was found that the thermal characteristics of the nanofluid can be boosted by increasing the temperature, size of particles, and volume of the fraction. The authors verified that the larger size of particles leads to a decrease in the effectiveness of thermal conductivity of a nanofluid at an equal volume of the fraction. Area of contact and vigorous collision during Brownian motion can be elevated by applying particles of smaller size under the equal volume of the fraction, which leads to the better thermal conductivity of nanofluids.

The thermal conductivity increases rapidly for particles less than 50 nm approximately and decreases rather slowly after that. The viscosity increases with a decrease in particle size due to a larger surface area. Observation illustrates that the heat transfer coefficient rises together with nanofluid concentration and is influenced by particle size and operating temperatures. Hence particle size influences the properties and hence heat transfer coefficients (Sharma et al., 2012). The results presented in Figures 3 to 5 reveal the relationship between the regression result and experimented data of thermal conductivity ratio of Aluminium Oxide/ water-based nanofluid that varies according to different sizes of particles under different weight fractions and temperature. The temperature range is set at 10, 30, and 50 °C, whereby the size of nanoparticles is varied among 20, 50, and 100 nm, respectively.

The result leads to the understanding that decreasing the size of particles and elevating the temperature boosts a nanofluid's thermal conductivity. As the temperature of the specimen was 10°C, the possibilities of increasing the thermal conductivity ratios were by 1.8-6.5%, 0.8-6.0%, and 0.4-5.6%. Moreover, when the temperature of the three is elevated up to 30°C, the enhancement in thermal conductivity ratios was by 5.1-12-8%, 1.4-6.9%, and 0.7-5.3%. When the temperature of the three samples was increased to 50°C, the enhancement in thermal conductivity ratios by 6.7-14.7%, 2.3-7.3%, and 1.2-5.6% prove that the size of nanoparticles indeed influences the increment in thermal conductivity ratio. Increasing the temperature leads to the movement of a particle to elevate rapidly, resulting in a high value of kinetic energy. Therefore, the movement velocity of larger particles can be slower than the movement of smaller particles. This incident may decrease the chance of collision among molecules. Thus, it can be concluded that temperature plays a minor role in increasing the fluid thermal conductivity when combined with particles of larger size. Furthermore, particles of smaller size result in a higher area of the solid-liquid interface exercised under identical concentration conditions. Hence, the size of particles plays an essential role in the thermal conductivity of a nanofluid.

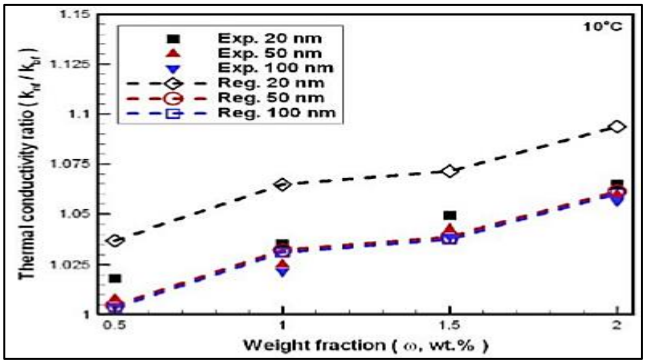

Fig. 3. Dependence Relationship between Weight Fraction and Thermal conductivity Ratio of Al_2O_3/Water Nanofluid with Different Particle Sizes at 10°C. Source: (Teng et al., 2010).

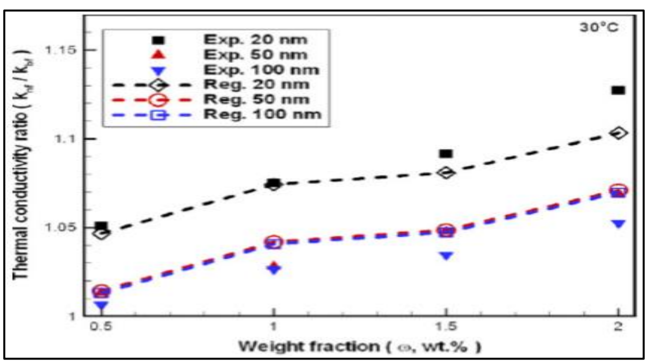

Fig. 4. Dependence Relationship between Weight Fraction and Thermal conductivity Ratio of Al_2O_3/Water Nanofluid with Different Particle Sizes at 30°C. (Teng et al., 2010).

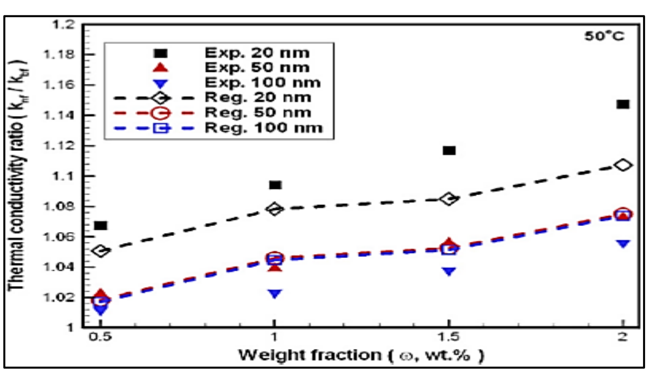

Fig. 5. Dependence Relationship between Weight Fraction and Thermal conductivity Ratio of Al_2O_3/Water Nanofluid with Different Particle Sizes at 50°C. Source: (Teng et al., 2010).

2.4.3. convention

Convection is defined as a transfer of energy between an adjacent fluid such as gas or liquid thath is in motion, and a solid surface that comprises effects of fluid motion and conduction, as shown in Figure 6. The fast motion of fluids achieves more outstanding heat transfer through convection. Pure conduction of heat transfer between an adjacent fluid and a solid surface is accomplished during the absence of bulk fluid motion. Although the presence of bulk motion stimulates the elevation of heat transfer among fluids and a solid surface, the determination of the heat transfer rate becomes complicated.

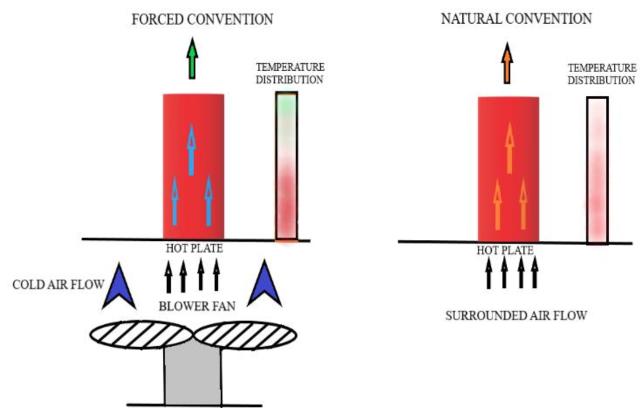

Fig. 6. Heat transfer to the surrounding fluid by convection Source: (Cengel et al., 2011).

Newton's law of cooling conveniently expresses the rate of heat transfer through convection as in Eq. 2:

$$Q_{Convection} = hAS\ (TS - T\infty) \qquad (2)$$

Where h represents the convection heat transfer coefficient in W/m^2, K, the surface area is noted as A, and the surface temperature is represented using the symbol TS, whereas $T\infty$ is the ambient temperature. Heat transfer coefficient, h, is a parameter that is experimentally determined and does not represent the property of the fluid. Its values vary based on conditions such as nature of fluid motion, surface geometry and bulk fluid velocity, and properties of the fluid. Table 1 shows the values of h based on types of convection.

Forced convection is a condition that occurs when the flow of a fluid is forced over a surface by the application of external force such as a fan, pump, or blower. Forced convection can be divided into two main situations: external force convection and internal force convection. External force convection occurs when fluid flows over a surface such as wire, plate, and pipe, whereas internal forced convection occurs in duct or pipe or can be described as an entirely confined place (Azad, 2016).

Table 1 Typical value of Convection Heat Transfer Coefficient (et al., 2011).

Type of Convection	h, W/m^2. °C
Free Convention of Liquids	10 - 1000
Forced Convention of Liquid	50 - 20000

3. Nano Coolants and Cooling System

Coolant is used to fill the engine's cooling system, act as a heat exchange fluid, lower the freezing point of water, and increase the boiling point of water. It is confined to the cooling circuit, which runs through rubber hoses from the radiator to the engine. It is not present in air-cooled engines.

Nanoparticles are particles that range between 1 and 100 nanometres (nm) in size. In nanotechnology, a particle is defined as a small object that behaves as a whole unit concerning its transport and properties. Choi et al. (2020) first used the term "nanofluid" for fluids with suspended nanoparticles. Experimentally investigated the effect of convective heat transfer in nanofluids under laminar and turbulent flow regimes. However, surprisingly, a few researchers have found a minor improvement in thermal conductivity, as shown. Recently, have provided an excellent review on the effects of several parameters to determine the effective thermal conductivity of nanofluids.

For cooling purposes in ICEs can be considered radiator cooling, exhaust EGR cooling, and cylinder coolant. In the first and second applications, the base fluid must be water or ethylene glycol, which nanoparticles can be added to it, while for the third application, the nano-oils can be considered as well as the water-based nano-coolants.

3.1. Types of nano coolant

3.1.1. water-based

Nano-coolant has the main effects on ICEs: energy savings, reduced vehicular emissions due to lower fuel consumption and minimized global warming (Naraki et al., 2013). Peyghambarzadeh et al. (2011) used nanometer (nm) sized Single (SWCNT) and multi-walled carbon nanotubes (MWCNT) for water-based and oil-based nano-coolants to find the best performance of nano-coolants in engines applications. In this section, most researches on radiator coolants based on water nanofluids are gathered in Table 1. Based on Table 1's data for water-based nano-coolants, MWCNT had maximum mechanical efficiency and total fuel consumption improvement (18%), while maximum heat transfer coefficient occurred for Al_2O_3 (78.67%) and TiO_2 (20%) and minimum friction factor increment between these two nanoparticles occurred for TiO_2 (12%). Ahmed et al. (2018) used TiO_2 –water nanofluid as a substitution to the conventional coolant system with flow rates of 0.097 and 0.68 m3/h to check the aspects of heat transfer of the laminar flow region, where Reynolds number ranged from 560 to 1650 and found a maximum 47% improvement on radiator effectiveness (Sahoo, 2020). Salimi et al. (2015) reported that the temperature reduction in CuO-water nano-coolant is a function of nanoparticles concentration and the engine load. Maximum temperature reductions of 13.6% at VS1 position were achieved at the maximum engine load and nanofluid at 2.5% vol. (Salimi et al., 2015). Hussein et al. (2014) used the Al_2O_3-water nano-coolant and found that the convective heat transfer coefficient significantly increased with flow velocity, where the maximum enhancement was 43.54% (Selvam et al., 2017). Also, Peyghambarzadeh et al. (2011), by using the Al_2O_3-water nano-coolant, reported that increasing the fluid circulating rate can increase the heat transfer performance, while the fluid inlet temperature to the radiator has an unimportant effect. Figure 1, which is depicted from Peyghambarzadeh et al. (2011) study, shows the standard circuit for the radiator cooling process, which contains a reservoir tank, two heaters, a centrifugal pump, a liquid flow meter, a variable speed forced draft fan, an airflow channel, a PID controller for temperature adjustment, chemoresistance for temperature measurement and a cross-flow heat exchanger as an automobile radiator (Peyghambarzadeh et al., 2011). Many researchers also used the same setup and instruments for their study in this field.

3.1.2. Ethylene glycol-based

Ethylene glycol (EG) as a powerful anti-freeze and anti-boiling is used in car radiators; some researchers worked on the pure EG properties with nano-additives presented here and summarized in Table 2. Li et al. (2016) used the synthesized β-CD-TiO_2-Ag nanoparticles by modifying TiO_2 nanoparticles with β-cyclodextrin and Ag elementary substance through building the bridge of coupling agent, respectively (Yan et al., 2018). They found that the thermal conductivity of nano-coolant significantly enhanced with an increase in the percentage of the solid volume fraction, as also found for MgO-FMWCNTs nano-additives. Goudarzi et al. (2017) reported that Al_2O_3-EG nano-coolant with different volume concentration caused 1–11.8% higher friction factor than the radiator with tube inserts and 20–47.5% higher friction factor than the radiator without tube inserts, also enhanced Nusselt numbers were observed by 11%, 12.5% and 13% for 0.08%, 0.5%, and 1% vol., respectively. By using Cu nanoparticles additives to EG, Leong et al. (2010) indicated 3.8% heat transfer enhancement for 2% Cu, but 12.13% extra pumping power was needed for that situation. Furthermore, about 42.7% and 45.2% heat transfer enhancement were observed for pure EG and EG with 2% Cu nanoparticles, respectively.

3.1.3. Mixed

Based on this review, most of the application papers in ICEs used the mixture of Water/EG as an anti-freeze for the radiator. MWCNTs and TiO_2 as an additive to Water/EG mixture and found that in low solid volume fractions, adding 10% excess nanoparticles did not affect the viscosity of the nano-coolant, which this subject can be considered as an important achievement in industrial and engineering applications. Also, Teng et al. (2010) reported that high concentrations of MWCNTs could not achieve significant heat exchange improvements due to the uneven density of NC in the flow state increases the thermal resistance of the solid liquid. Compared the Al_2O_3 and CuO nanoparticles outcomes in the W/EG mixture and recorded the heat transfer coefficient at 36384.41 W/m^2 K, the thermal conductivity 1.241 W/m K, Nusselt number 208.71, and the rate of heat transfer at 28.45W for CuO, while for the Al_2O_3 nano-coolant heat transfer coefficient was 31,005.9 W/ m2K, thermal conductivity 1.287 W/mK, Nusselt number 173.19 and the rate of heat transfer was at 28.25W. A different study investigated the effect of nanoparticles types and shapes (Brick, Cylindrical, Platelet, and Spherical) for TiO_2 and CuO in EG and water-based radiator nano-coolant by numerical modelling in four different Reynolds numbers (500, 1000, 1500 and 2000) as shown in Figure 2. As seen, EG-TiO_2 with the platelet shapes had the maximum Nusselt numbers due to the larger surface/volume ratio and more turbulence created due to its particular shape. Based on Peyghambarzadeh et al. (2011) outcomes, the heat transfer behaviours of the nanofluids are highly dependent on the particle concentration and the flow conditions, while weakly is related to the temperature. Reviewing the nano-coolants revealed that the enhancement in the heat transfer was averagely about 15–20%, and maximum, it was noted about 193%. Furthermore, investigated the usage of aluminium oxide (Al_2O_3) doped with unmilled silicon carbide (SiCUM) nanoparticles and milled Silicon carbide (SiCM) nanoparticles dispersed in DWand EG and found overall thermal performance improvements of 28.34% for Al_2O_3 doped with milled Silicon carbide. Based on Table 3 data, for EG-water nano-coolants, maximum heat transfer coefficient improvements occurred forMWCNT (196.3%), Graphene (104%), and Al_2O_3 (94%), maximum viscosity increase for MWCNT (83%) and maximum thermal conductivity improvements were reported for SWCNT (53.7%).

3.2. Types of nanoparticles

In this section, studies are classified based on the commonly used nanoparticles. Although some researchers used ZnO and SiC, the most used nanoparticles are TiO_2, Al_2O_3, GNP, CNT, Cu/ CuO, and hybrid nanoparticles for this application of nan-coolants. Following these studies are discussed based on outcomes.

3.2.1. Al_2O_3

Al_2O_3 can be introduced as the most used nanoparticles in this application which its details are presented in Table 2. Among the reviewed papers which used Al_2O_3 as the alone nanoparticle, the highest heat transfer coefficient reported 78.67% improvements, and the heat transfer efficiency enhanced up to 45%.

3.2.2. Cu/CuO

Table 3 confirms that Cu/CuO nanoparticles addition to coolant-based fluid have a negligible effect on heat transfer compared to before discussed nanoparticles.

3.2.3. G/GO

Table 4 shows the main effects reported by using Graphene nanoplatelets (GNP) in nano-coolants. Thermal conductivity improvements, low-pressure drop, and pumping power, heat transfer improvements are the most reported effects by GNP. Maximum heat transfer coefficient and Nusselt number improvements were 104% and 21%, respectively.

3.2.4. SiO_2

Based on Table 5, SiO_2 improved the radiator effectiveness up to 56% for 30 nm nanoparticles, and maximum heat transfer improvements reported 56% for low concentrations with 21 nm nanoparticles diameter.

3.2.5. TiO_2

Based on Table 6, TiO_2 improved the radiator effectiveness up to 47% for 44 nm nanoparticles, and maximum heat transfer improvements reported 37% for low concentrations with 21 nm nanoparticles diameter.

3.2.6. CNT

Table 7 reveals that maximum average heat transfer coefficient enhancement by CNTs can be 196.3% and maximum increase in nanofluid thermal conductivity Figure 3 to 4. Effect of temperature and nanoparticles on thermal conductivity shows almost 53.7%.

3.2.7. Hybrid nanoparticles

Among the reviewed studies, CuO, TiO_2, Al_2O_3 are the most used nanoparticles in hybrid or comparative shapes with other nanoparticles presented in Table 12. For example, 75% of Al_2O_3 and 25% CeO_2 nanoparticle mixture reported a considerable impact in convective heat transfer coefficient concerning mass flow rate. The maximum enhancement of Nusselt number was 31.8 and 24.21% for Co_3O_4- Al_2O_3 and Al_2O_3 -TiO_2 hybrid nanoparticles, respectively. Also, it was observed that EG-TiO_2 with platelet shapes had better cooling performance than Al_2O_3 and CuO. Many correlations are presented for the thermal conductivity and viscosity of hybrid nanoparticles. Many factors affect the viscosity of hybrid nanofluids, such as temperature, particles concentrations, pH value, particle size, morphology, etc. Obtained values for the rheological properties of nanofluids determine the efficiency of nanofluids in this application.

Table 2 Studies classified Al_2O_3 nanoparticles and their application in nan-coolants.

Nanoparticle	Base fluid	Particle size	Vol. Conc.	Application	Conclusion	Reference
Al_2O_3	Water	50-200nm	0-0.2%	Automobile radiator	Heat transfer rate improved of 44.29%	(Chaurasia et al., 2019)
Al_2O_3	Water	21-37nm	0-2%	Engine	78.67% of improvement in the heat transfer coefficient	(Moghaieb et al., 2017)
Al_2O_3	Water	20nm	0.1-1%	Automobile radiator	45% efficacy enhancement in Heat transfer by low concentration of nanoparticles.	(Peyghambarzadeh et al., 2011)
Al_2O_3	EG	40nm	0.08,0.5, & 1.0 %	Car radiator	Thermal performance and heat transfer rate enhancements are 14 and 9 %, respectively.	(Goudarzi et al., 2017)
Al_2O_3	EG	-	0.5-1 %	Heat exchanger	Increased friction factor and heat transfer with 49.7% HT coefficient & lessened pumping power.	(Salimi et al., 2015)
Al_2O_3	EG-Water (1:1)	20nm	0.2-0.8%	Car radiator	Increased heat transfer of 30% with nanoparticles in fluid	(Subhedar et al., 2018)
Al_2O_3	EG-Water (1:1)	40-50nm	1.43%	Radiator cooling system	Improved heat transfer performance of the radiator is proved	(Choi et al., 2020)
Al_2O_3	EG-Water	0.2, 0.4, 0.6, 0.8, 1, &1.2%	20nm	Car radiator	40% improvement in Heat transfer with respect to the base fluid.	(Peyghambarzadeh et al., 2011)
Al_2O_3	EG-Water (50:50)	13nm	0.5%	Car radiator	The cooling performance of the system was enhanced to 17.46%	(Mert et al., 2020)
Al_2O_3	Glycerin	12.825nm	0.05, 0.1&0.15 vol. %	Automotive cooling system	62% of heat transfer coefficient enhancement and an increase in effectiveness	(Sundari et al.)
Al_2O_3	EG-Water	0-1%	13nm	Car radiator	Enhanced thermal conductivity, density, and viscosity to be 8.30, 2.91 & 150 %, respectively.	(Elias et al., 2014)

Table 3 Studies classified for Cu/CuO nanoparticles and their application in nan-coolants.

Nanoparticle	Base fluid	Particle size	Vol. Conc.	Application	Conclusion	Reference
CuO	Water	20nm	0-2.5%	Radiator	Temperature reduced up to 13.6% on the exhaust valve seat and up to 4.1% on the exhaust valve spindletration and increased thermal performance.	(Sahoo, 2020)
CuO	Water	60nm	0.04-0.4%		Increased heat transfer up to 8%.	
Cu	EG	-	0-02%	Automotive radiator, flat tubes, and fins	3.8% of heat transfer enhancement was achieved with the addition of 2% Cu particles.	

Table 4 Studies classified G/GO nanoparticles and their application in nan-coolants.

Nanoparticle	Base fluid	Particle size	Vol. Conc.	Application	Conclusion	Reference
Graphene nanoribbons	Water	20-30 nm	0.01, 0.02%	Radiator	Overall heat transfer coefficient enhancement was 24.8%, increased concentration increased effectiveness.	(Kilinc et al., 2019)
Graphene oxide	Water+ EG	-	3, 4, 5%	Heat transfer application	Increased thermal conductivity by 47%	(Izadkhah et al., 2019)
Graphene oxide/graphene nanoribbons	Water	-	0.01, 0.02%	Vehicle radiator	5.41 and 26.08% overall heat transfer coefficient increments and heat transfer.	(Kılınç et al., 2019)
Graphene oxide	DI Water/EG (60:40)	<100 nm	0.01-0.10%	-	Thermal conductivity increased with concentrations and temperature; viscosity decreased with temperature increase	(Ijam et al., 2015)
Graphene oxide	EG-Water (1:1)	<100 nm	0.02, 0.03, 0.04%	Radiator test rig	GO improved the radiator performance, effectiveness with moderate stability	(Ponangi et al., 2018)
Graphene nanoplatelets	Water-EG (70:30)	<100 nm	0.1,0.2,0.3,0.4,0.5%	Automobile radiator	Overall, HTC is 104%, increased thermal conductivity with nanofluid	(Selvam et al., 2017)
Graphene M-5 Graphene M-15	Water	5µm 15µm	0.01	-	Thermal conductivity and stability is high for oxidized Graphene, with an increased rate of viscosity	(Park et al., 2014)
Graphene	Water	1.4-2.3nm	0.005,0.01,0.015,0.02,0.025%	Heat transfer	6, 5, 10.3 % enhancements for heat transfer coefficient, viscosity, and thermal conductivity	(Akhavan-Zanjani et al., 2014)
Graphene nanoplatelets	Distilled water	2nm,	0.025,0.05,0.075,0.1%wt	Heat transfer	Increased thermal conductivity up to 27.67% and the thermal performance factor of 15-1.9 for different surface areas.	(Mehrali et al., 2015)
Graphene	Water	1-5nm	0.05,0.1,0.15%	Heat transfer	47.12% increment in viscosity with inverse reaction on temperature.	(Ahammed et al., 2016)
Graphene oxide	Water-EG (1:1)	-	0.02,0.03,0.04%	Radiator	Improved effectiveness up to 56.45% w.r.t different flow rates, temperature, and concentrations	(Bharadwaj et al., 2018)

Table 5 Studies classified for SiO_2 nanoparticles and their application in nan-coolants.

Nanoparticle	Base fluid	Particle size	Vol. Conc.	Application	Conclusion	Reference
SiO_2	Water					(Akbarzade et al., 2014)
SiO_2	Water	20nm	0.04, 0.08, 0.12 vol.%	Aluminium Tube Radiator	The improvement of HTR and Nu number was observed with 36.92% and 45.53%, respectively.	(Shah et al., 2020)
SiO_2	Water	D=50–166 nm	5wt %	Radiator with spiral microchannel	the heat transfer capability improved when the mass fraction of nanoparticles increased.	(Yan et al., 2018)
SiO_2	Water	D=30nm	1, 1.5, 2.0 and 2.5 vol%	Automotive cooling system	SiO_2 nanofluid showed higher heat transfer enhancement and 56% in Nu number.	(Hussein et al., 2014)
SiO_2	W+EG (50:50)	15nm	0.1 &0.15%	Radiator	Increasing the mass flow rate and volume concentration improved HT Coefficient	(Senthilkumar et al., 2020)
SiC	W+EG (60:40)	30nm	0.1,0.2,0.3,0.4,0.5 vol %	Car engine	overall effectiveness and thermal conductivity enhancement is 1.6 and 53.81% respectively.	(Li et al., 2016)

Table 6 Studies classified for TiO_2 nanoparticles and their application in nan-coolants.

Nanoparticle	Base fluid	Particle size	Vol. Conc.	Application	Conclusion	Reference
TiO_2	Water	44nm	0.1,0.2,0.3 %	Car radiator	47% of enhancement in the effectiveness with nanoparticles and volume conc. proportional to HT coefficient	(Ahmed et al., 2018)
TiO_2	Water	21nm	0.2,1,2 & 3%	-	7.4% enhancement of thermal conductivity w.r.t water and volume fraction	(Turgut et al., 2009)
TiO_2	EG	<100nm	0.025%, 0.05%, & 0.075%	Heat exchanger	Increased thermophysical properties and heat transfer characteristics performance with an increase in volume concentration	(Permanasari et al., 2019)
TiO_2	Water	-	1, 2, 3 & 4%	Car Radiator	HT efficacy increased by 20% with the low concentration compared with water	(Hussein et al., 2017)
TiO_2	EG-Water	21nm	0.1, 0.3 & 0.5%	Automobile radiator	HT rate increased 37% with low concentration	(Devireddy et al.,, 2016)
TiO_2	water	18nm	0.5-5 wt%	Automobile cooling system	3% and more than 10% of thermal conductivity and HT improvement respectively observed with minimum wt%.	(Chen et al., 2017)

Table 7 Studies classified for CNT nanoparticles and their application in nan-coolants.

Nanoparticle	Base fluid	Particle size	Vol. conc	Application	Conclusion	Reference
Al_2O_3, CNT, Graphene	Water	-	1-3%	Radiator	18.45% of enhancement for heat transfer rate with an increased pressure drop. No effect with an increase in volume concentration and increased thermal performance.	(Sahoo, 2020)
Al_2O_3, CuO, ZnO	EG+Water (60:40)					
Al_2O_3, CuO				Automotive radiator, float tubes and fins		

Table 8 Studies classified for hybrid nanoparticles and their application in nan-coolants.

Nanoparticle	Base fluid	Particle size	Vol. Conc.	Application	Conclusion	Reference
FCNT SCNT	Water	20-30 nm	0.15, 0.45, 0.60, 1%	Automobile radiator	FCNT increased heat transfer performance compared to SCNT, and increased particle concentration increased thermal conductivity and radiator performance.	(Chougule & Sahu, 2013)
MWCNT	Water/EG	20–30 nm out dia, 5–10 nm Inner dia, l= 30µm	0.02, 0.1 wt%	Engine cooling system	Proved higher thermal conductivity. Corrosion test for different metals is less with CNT. This resulted in higher heat absorption and performance in the small radiator.	(Rashmi et al., 2014)
CNT	EG+ Water (40:60)	-	0.02%	Car Radiator	30% of performance enhancement with comparison to water/EG.	(Ramaraju et al.,2014)
MWCNT	Water	-	0.05-0.16 wt%	Automobile radiator	The observed decrease in heat transfer rate with an increment in particle concentration, a slight increase in thermal conductivity compared with water.	(Oliveira et al., 2017)
MWCNT	Water	20-40 nm dia and 25µm length	0.025, 0.05 and 0.1 wt%	Automotive	CNT's improved thermal conductivity, heat transfer, and overall heat transfer coefficient.	(Srinivas et al., 2016)
MWCNT	Water+ EG (50:50)	20-30nm	0.1, 0.25, 0.5%	Engine system in car	Enhanced heat transfer coefficient by 196 %, with an increase in volume concentration the heat transfer coefficient, also increased	(M'hamed et al., 2016)
MWCNT	Water	50-80nm out dia,5-15nm in dia,10-20µm length	0.1, 0.3 and 0.5%	Engine coolant system	Increased mechanical efficiency from 7% to 24% for different concentrations	(Muruganandam & et al., 2020)
MWCNT	Water +EG (1:1)	20-30nm	0.1, 0.2,0.4 wt.%	Radiator cooling system.	Heat transfer capacity was not higher for higher concentrations, and heat exchange improvement was 12.8% and 4.9 % pumping power.	(Teng et al., 2013)

4. Applications of Nanofluids

Graphene-based nanofluids have many applications like heat transfer, anti-infection therapy, energy harvesting systems, cosmetics, defect sensors, and biomedical. Graphene plays a crucial role in heat transfer applications because of its thermal conductivity. In an automobile, the combustion of fuel in the presence of air produces power. In automotive engines, heat management highly influences the engine's output and its overall performance. Fuel expenditure, comfort range, engine performance, the engine's life, vehicles dependability, and waste emission are hugely influenced by thermal management. Most of the energy in the fuel (around 75%) is converted into heat, but only 25% of the total energy produced is converted into practical work. If this unutilized heat is not removed from the engine, it results in overheating of components and thus leading to their damage. By using a liquid cooling system, heat is carried away by a coolant circulated in the engine. After heat extraction, the coolant is pumped into tubes in the radiator, where the air is forced over these tubes. As the air flows through the radiator, the heat is transferred from the coolant to the air. The development of advanced nanofluids, which have better conduction and convection thermal properties, has presented a new opportunity to design a high-energy efficient, light-weight automobile radiator.

For effective cooling of engines, primary research and many investments have been done, application of GE nanofluid has been studied for this purpose by many research groups. Associated GNPs discrete in EG-water mixture, as a cooling agent flowing inside an engine radiator. Excellent cooling properties were found when CNDG/DI water + EG-based nanofluids are used, showing excellent heat transfer and Nusselt number for all ranges of temperature and mass application. The elevated improvement in thermal conductivity of GNP/water+EG nanofluid is achieved with rising temperature and GNPs loading. Singh et al. assessed the application of high thermal conductivity nanofluids for automobile cooling and reported that it could reduce the frontal area of the radiator by up to 10% and fuel-saving is up to 5% due to the reduction in aerodynamic drag.

Leong et al. (2010) applied ethylene glycol-based copper nanofluids in an automotive cooling system. Relevant input data, nanofluid properties, and empirical correlations were obtained from the literature. It was observed that overall heat transfer coefficient and heat transfer rate in engine cooling system increased with the usage of nanofluids (with ethylene glycol the base fluid) compared to ethylene glycol (i.e., base fluid) alone.

Kulkarni et al. (2008) studied the performance of a diesel electrical generator with an aluminium oxide nanofluid coolant. They dispersed the aluminium oxide in 50:50 inhibited Ethylene glycol and water mixture and concluded that the heat exchanger efficiency increases with increasing particle concentration because of nanofluids' higher heat transfer coefficients. Nanofluids used in the cooling applications indicated an improvement in the performance of cooling devices leading to their size reduction. Hence, there exists a potential application of nanofluid for automobile cooling.

Besides that, nanofluids show promising results in removing the heat from an automobile's engine more efficiently than readily available coolants. The benefits of an enhanced cooling system led to full utilization of engine capacity without overheating the engine that can cause the engine to be blown. This also helps in improving fuel economy as the conversion of energy is fully optimized by the engine (Gdhaidh, 2016).

5. Conclusion

Graphene-based nanoparticles are mostly advantageous over the other nanoparticles because of their high stability, high thermal conductivity, low rate of erosion and corrosion, and higher carrier mobility. The water-based Graphene nanofluid is made for the different weights in the concentration of Graphene particles, and then the conductivity of the particles is measured. The different measured conductivity of Graphene nanofluids with their temperature is then illustrated in the above table. The conductivity of the nanofluids or particles increases with temperature, and it is applicable for all variations of weight concentration of Graphene nanofluids. If the nanofluids' weight concentration increases, the nanofluids' thermal conductivity also increase at a specified temperature. The thermal conductivity of the graphene-based nanofluid is consistently higher than the Di-ionized water. At its topmost concentration, the thermal conductivity inflation is equivalent to 17% of water-conducting at 25°C, while the identical enhancement at 45 ˚C is about 29% of thermal conductivity.

When the concentration of the nanofluid increases due to a higher temperature, the conduction electron, or we can say the free electrons which are available in the atoms, like the metal atoms which are mainly responsible for thermal conductivity, gets enhanced because the distance between the atoms in a fixed proportion of graphene nanofluids decreases. Therefore, when the concentration of the nanofluids is raised, the familiar surface areas between the atoms of the nanoparticles and the liquid base are intensified. This phenomenon results in the enhancement of the thermal conductivity of the particles. Therefore, it can be concluded that the Graphene-based nanofluids are very useful and are better when compared to the other nanofluids because of their advancement in morphological, transport properties, and industrial applications. From the above study, it has been found that the research on Graphene-based nanofluids is mainly based on thermal aspects like thermal conductivity and heat transfer enhancement. Nanofluids possess a superior heat transfer characteristic which enables them to be merged with readily available lubricants or cooling fluids to improve the heat absorption capacity.

This application plays an essential role in the automotive field as current researchers focus on elevating the performance of an automobile engine that releases minimum heat from the engine. However, nanofluids do demonstrate some disadvantages that can question their application in automobile engines.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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References

Ahammed, N., Asirvatham, L. G., & Wongwises, S. (2016). Effect of volume concentration and temperature on viscosity and surface tension of Graphene–water nanofluid for heat transfer applications. Journal of Thermal Analysis and Calorimetry, 123(2), 1399-1409.

Ahmed, S. A., Ozkaymak, M., Sözen, A., Menlik, T., & Fahed, A. (2018). Improving car radiator performance by using TiO_2-water nanofluid. Engineering science and technology, an international journal, 21(5), 996-1005.

Akbarzade, S., Sedighi, K., & Farhadi, M. (2014). Experimental investigation of force convection heat transfer in a car radiator filled with SiO2-water nanofluid. International Journal of Engineering, 27(2), 333-340.

Akhavan-Zanjani, H., Saffar-Avval, M., Mansourkiaei, M., Ahadi, M., & Sharif, F. (2014). Turbulent convective heat transfer and pressure drop of Graphene–water nanofluid flowing inside a horizontal circular tube. Journal of dispersion science and technology, 35(9), 1230-1240.

Azad, A. K. (2016). MHD combined convection in a channel with cavity using nanofluids.

Bharadwaj, B. R., Mogeraya, K. S., Manjunath, D., Ponangi, B. R., Prasad, K. R., & Krishna, V. (2018). CFD analysis of heat transfer performance of Graphene based hybrid nanofluid in radiators. Paper presented at the IOP Conference Series: Materials Science and Engineering.

Cengel, Y. A., & Ghajar, A. (2011). Heat and mass transfer (a practical approach, SI version). In: McGraw-Hill Education.

Chaurasia, P., Kumar, A., Yadav, A., Rai, P. K., Kumar, V., & Prasad, L. (2019). Heat transfer augmentation in automobile radiator using Al 2 O 3–water based nanofluid. SN Applied Sciences, 1(3), 257.

Chen, J., & Jia, J. (2017). Experimental study of TiO_2 nanofluid coolant for automobile cooling applications. Materials Research Innovations, 21(3), 177-181.

Choi, T. J., Kim, S. H., Jang, S. P., Yang, D. J., & Byeon, Y. M. (2020). Heat transfer enhancement of a radiator with mass-producing nanofluids (EG/water-based Al_2O_3 nanofluids) for cooling a 100 kW high power system. Applied Thermal Engineering, 180, 115780.

Chougule, S. S., & Sahu, S. (2013). Experimental investigation of heat transfer augmentation in automobile radiator with CNT/water nanofluid. Paper presented at the International Conference on Micro/Nanoscale Heat Transfer.

Chougule, S. S., & Sahu, S. K. (2016). Comparative study on heat transfer enhancement of low volume concentration of Al_2O_3–water and carbon nanotube–water nanofluids in transition regime using helical screw tape inserts. Experimental Heat Transfer, 29(1), 17-36.

Devireddy, S., Mekala, C. S. R., & Veeredhi, V. R. (2016). Improving the cooling performance of automobile radiator with ethylene glycol water based TiO_2 nanofluids. International Communications in Heat and Mass Transfer, 78, 121-126.

Dhaiban, H. T. (2016). Numerical Study of Heat Transfer Enhancement in Heat Exchanger Using AL_2O_3 Nanofluids. Journal of Engineering, 22(4).

Elias, M. M., Mahbubul, I. M., Saidur, R., Sohel, M. R., Shahrul, I. M., Khaleduzzaman, S. S., & Sadeghipour, S. (2014). Experimental investigation on the thermo-physical properties of Al_2O_3 nanoparticles suspended in car radiator coolant. International Communications in Heat and Mass Transfer, 54, 48-53.

Ganvir, R. B., Walke, P. V., & Kriplani, V. M. (2017). Heat transfer characteristics in nanofluid—a review. Renewable and Sustainable Energy Reviews, 75, 451-460.

Ghanbarpour, M., Bitaraf Haghigi, E., & Khodabandeh, R. (2014). Thermal properties and rheological behavior of water based Al_2O_3 nanofluid as a heat transfer fluid. Experimental Thermal and Fluid Science, 53, 227-235.

Goudarzi, K., & Jamali, H. (2017). Heat transfer enhancement of Al_2O_3-EG nanofluid in a car radiator with wire coil inserts. Applied Thermal Engineering, 118, 510-517.

Hussein, A. M., Bakar, R., & Kadirgama, K. (2014). Study of forced convection nanofluid heat transfer in the automotive cooling system. Case Studies in Thermal Engineering, 2, 50-61.

Hussein, A. M., Dawood, H., Bakara, R., & Kadirgamaa, K. (2017). Numerical study on turbulent forced convective heat transfer using nanofluids TiO_2 in an automotive cooling system. Case Studies in Thermal Engineering, 9, 72-78.

Ijam, A., Saidur, R., Ganesan, P., & Golsheikh, A. M. (2015). Stability, thermo-physical properties, and electrical conductivity of Graphene oxide-deionized water/ethylene glycol based nanofluid. International Journal of Heat and Mass Transfer, 87, 92-103.

Izadkhah, M.-S., Erfan-Niya, H., & Heris, S. Z. (2019). Influence of graphene oxide nanosheets on the stability and thermal conductivity of nanofluids. Journal of Thermal Analysis and Calorimetry, 135(1), 581-595.

Kılınç, F., Buyruk, E., & Karabulut, K. (2019). Experimental investigation of cooling performance with Graphene based nanofluids in a vehicle radiator. Heat and Mass Transfer, 1-10.

Kulkarni, D. P., Vajjha, R. S., Das, D. K., & Oliva, D. (2008). Application of aluminum oxide nanofluids in diesel electric generator as jacket water coolant. Applied Thermal Engineering, 28(14-15), 1774-1781.

Leong, K. Y., Saidur, R., Kazi, S. N., & Mamun, A. H. (2010). Performance investigation of an automotive car radiator operated with nanofluid-based coolants (nanofluid as a coolant in a radiator). Applied Thermal Engineering, 30(17-18), 2685-2692.

Li, X., Zou, C., & Qi, A. (2016). Experimental study on the thermo-physical properties of car engine coolant (water/ethylene glycol mixture type) based SiC nanofluids. International Communications in Heat and Mass Transfer, 77, 159-164.

Mehrali, M., Sadeghinezhad, E., Rosen, M. A., Latibari, S. T., Mehrali, M., Metselaar, H. S. C., & Kazi, S. N. (2015). Effect of specific surface area on convective heat transfer of graphene nanoplatelet aqueous nanofluids. Experimental Thermal and Fluid Science, 68, 100-108.

Mert, S., Yaşar, H., Durmaz, U., Topuz, A., Yeter, A., & Engin, T. (2020). An experimental study on cooling performance of a car radiator using Al_2O_3-ethylene glycol/water nanofluid. Thermal Science(00), 179-179.

M'hamed, B., Sidik, N. A. C., Akhbar, M. F. A., Mamat, R., & Najafi, G. (2016). Experimental study on thermal performance of MWCNT nanocoolant in Perodua Kelisa 1000cc radiator system. International Communications in Heat and Mass Transfer, 76, 156-161.

Mintsa, H. A., Roy, G., Nguyen, C. T., & Doucet, D. (2009). New temperature dependent thermal conductivity data for water-based nanofluids. International Journal of Thermal Sciences, 48(2), 363-371.

Moghaieb, H. S., Abdel-Hamid, H., Shedid, M. H., & Helali, A. (2017). Engine cooling using Al_2O_3/water nanofluids. Applied Thermal Engineering, 115, 152-159.

Murshed, S. M. S., Leong, K. C., & Yang, C. (2005). Enhanced thermal conductivity of TiO_2—water based nanofluids. International Journal of thermal sciences, 44(4), 367-373.

Muruganandam, M., & Kumar, P. M. (2020). Experimental analysis on internal combustion engine using MWCNT/water nanofluid as a coolant. Materials Today: Proceedings, 21, 248-252.

Naraki, M., Peyghambarzadeh, S. M., Hashemabadi, S. H., & Vermahmoudi, Y. (2013). Parametric study of overall heat transfer coefficient of CuO/water nanofluids in a car radiator. International Journal of Thermal Sciences, 66, 82-90.

Nguyen, C. T., Roy, G., Gauthier, C., & Galanis, N. (2007). Heat transfer enhancement using Al_2O_3–water nanofluid for an electronic liquid cooling system. Applied Thermal Engineering, 27(8-9), 1501-1506.

Oliveira, G. A., Contreras, E. M. C., & Bandarra Filho, E. P. (2017). Experimental study on the heat transfer of MWCNT/water nanofluid flowing in a car radiator. Applied Thermal Engineering, 111, 1450-1456.

Pamies, R., Avilés, M. D., Arias-Pardilla, J., Espinosa, T., Carrión, F. J., Sanes, J., & Bermúdez, M. D. (2018). Antiwear performance of ionic liquid+ graphene dispersions with anomalous viscosity-temperature behavior. Tribology International, 122, 200-209.

Pang, C., Jung, J. Y., Lee, J. W., & Kang, Y. T. (2012). Thermal conductivity measurement of methanol-based nanofluids with Al_2O_3 and SiO_2 nanoparticles. International Journal of Heat and Mass Transfer, 55(21-22), 5597-5602.

Park, S. S., & Kim, N. J. (2014). Influence of the oxidation treatment and the average particle diameter of Graphene for thermal conductivity enhancement. Journal of Industrial and Engineering Chemistry, 20(4), 1911-1915.

Patel, H. E., Sundararajan, T., & Das, S. K. (2010). An experimental investigation into the thermal conductivity enhancement in oxide and metallic nanofluids. Journal of Nanoparticle Research, 12(3), 1015-1031.

Peng, H., & Ling, X. (2008). Optimal design approach for the plate-fin heat exchangers using neural networks cooperated with genetic algorithms. Applied thermal engineering, 28(5-6), 642-650.

Permanasari, A. A., Kuncara, B. S., Puspitasari, P., Sukarni, S., Ginta, T. L., & Irdianto, W. (2019). Convective heat transfer characteristics of TiO_2-EG nanofluid as coolant fluid in heat exchanger. Paper presented at the AIP Conference Proceedings.

Peyghambarzadeh, S., Hashemabadi, S., Hoseini, S., & Jamnani, M. S. (2011). Experimental study of heat transfer enhancement using water/ethylene glycol based nanofluids as a new coolant for car radiators. International Communications in Heat and Mass Transfer, 38(9), 1283-1290.

Peyghambarzadeh, S., Hashemabadi, S., Jamnani, M. S., & Hoseini, S. (2011). Improving the cooling performance of automobile radiator with Al_2O_3/water nanofluid. Applied Thermal Engineering, 31(10), 1833-1838.

Ponangi, B. R., Sumanth, S., Krishna, V., Seetharam, T., & Seetharamu, K. (2018). Heat transfer analysis of radiator using graphene oxide nanofluids. Paper presented at the IOP Conference Series: Materials Science and Engineering.

Pourpasha, H., Heris, S. Z., Mahian, O., & Wongwises, S. (2020). The effect of multi-wall carbon nanotubes/turbine meter oil nanofluid concentration on the thermophysical properties of lubricants. Powder Technology, 367, 133-142.

Ramaraju, R. V., Kota, M., Manap, H. B., & Veeredhi, V. R. (2014). Enhancement of Heat Transfer Coefficient in an Automobile Radiator Using Multi Walled Carbon Nano Tubes (MWCNTS). Paper presented at the ASME International Mechanical Engineering Congress and Exposition.

Rashmi, W., Ismail, A., Khalid, M., Anuar, A., & Yusaf, T. (2014). Investigating corrosion effects and heat transfer enhancement in smaller size radiators using CNT-nanofluids. Journal of materials science, 49(13), 4544-4551.

Sahoo, R. R. (2020). Thermo-hydraulic characteristics of radiator with various shape nanoparticle-based ternary hybrid nanofluid. Powder Technology.

Salimi, M., Peyghambarzadeh, S. M., Hashemabadi, S. H., & Chabi, A. (2015). Experimental investigation of convective heat transfer of Al_2O_3/water nanofluid through the micro heat exchanger. Modares Mechanical Engineering, 15(2), 270-280.

Sanukrishna, S. S., & Prakash, M. J. (2018). Experimental studies on thermal and rheological behaviour of TiO_2-PAG nanolubricant for refrigeration system. International Journal of Refrigeration, 86, 356-372.

Selvam, C., Raja, R. S., Lal, D. M., & Harish, S. (2017). Overall heat transfer coefficient improvement of an automobile radiator with Graphene based suspensions. International Journal of Heat and Mass Transfer, 115, 580-588.

Senthilkumar, G., Pavan Kumar, P., & Sai Gowtham, R. (2020). Performance of radiator by using SiO_2 nano fluids. International Journal of Ambient Energy, 41(9), 1038-1040.

Shah, T. R., Ali, H. M., & Janjua, M. M. (2020). On Aqua-Based Silica (SiO_2–Water) Nanocoolant: Convective Thermal Potential and Experimental Precision Evaluation in Aluminum Tube Radiator. Nanomaterials, 10(9), 1736.

Sharma, K., Sarm, P., Azmi, W., Mamat, R., & Kadirgama, K. (2012). Correlations to predict friction and forced convection heat transfer coefficients of water based nanofluids for turbulent flow in a tube. International Journal of Microscale and Nanoscale Thermal and Fluid Transport Phenomena, 3(4), 283.

Sridhara, V., & Satapathy, L. N. (2011). Al 2 O 3-based nanofluids: a review. Nanoscale research letters, 6(1), 1-16.

Srinivas, V., Moorthy, C. V., Dedeepya, V., Manikanta, P., & Satish, V. (2016). Nanofluids with CNTs for automotive applications. Heat and Mass Transfer, 52(4), 701-712.

Subhedar, D. G., Ramani, B. M., & Gupta, A. (2018). Experimental investigation of heat transfer potential of Al_2O_3/Water-Mono Ethylene Glycol nanofluids as a car radiator coolant. Case Studies in Thermal Engineering, 11, 26-34.

Sundari, K. G., Asirvatham, L. G., Ninolin, E., & Surekha, B. Feasibility Of Glycerin/Al_2O_3 Nanofluid For Automotive Cooling Applications. Journal of Thermal Engineering, 6(4), 619-632.

Teng, T.-P., & Yu, C.-C. (2013). Heat dissipation performance of MWCNTs nano-coolant for vehicle. Experimental Thermal and Fluid Science, 49, 22-30.

Teng, T.-P., Hung, Y.-H., Teng, T.-C., Mo, H.-E., & Hsu, H.-G. (2010). The effect of alumina/water nanofluid particle size on thermal conductivity. Applied Thermal Engineering, 30(14-15), 2213-2218. doi:10.1016/j.applthermaleng.2010.05.036

Turgut, A., Tavman, I., Chirtoc, M., Schuchmann, H. P., Sauter, C., & Tavman, S. (2009). Thermal conductivity and viscosity measurements of water-based TiO_2 nanofluids. International Journal of Thermophysics, 30(4), 1213-1226.

Turgut, A., Tavman, I., Chirtoc, M., Schuchmann, H., Sauter, C., & Tavman, S. (2009). Thermal conductivity and viscosity measurements of water-based TiO_2 nanofluids. International Journal of Thermophysics, 30(4), 1213-1226.

Yan, S., Zhang, H., Wang, F., Ma, R., Wu, Y., & Tian, R. (2018). Analysis of thermophysical characteristic of SiO_2/water nanofluid and heat transfer enhancement with field synergy principle. Journal of Renewable and Sustainable Energy, 10(6), 063704.

Zeinali Heris, S., Nasr Esfahany, M., & Etemad, S. G. (2007). Experimental investigation of convective heat transfer of Al_2O_3/water nanofluid in circular tube. International Journal of Heat and Fluid Flow, 28(2), 203-210.