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Advancement of nanofluids in automotive applications during the last few years—a comprehensive review

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Abstract
The present paper focuses on a review recalling the main contributions of studies that involve nanofluids on automotive industry. The novelty of the paper consists on the concise synthesis presented, that highlights new tested nanofluids in several applications in automotive. The review includes critics on the efficiency, the impact on material and the environmental issues when nanofluids are used as fuel. Three main sections are presented, which deploy the use of nanofluids as coolant in a car radiator, addition in the fuel or engine oil and finally the last section reviews the assessment of the wear effects of nanofluids on materials used in a car coolant system and in the car engine. The current review emphasized some major findings and critics: (1) The contradictory conclusions denoted about the effect of volume concentration on pumping power loss and the Nusselt number in a car radiator system. (2) Remarkable discrepancies in the determination of the optimal nanoparticles volume concentration and the precise heat transfer enhancement. (3) The viscosity of a nanolubricant needs a deep analysis to determine the optimal value that ensures the best lubricant film between components in a car engine. (4) Some mechanical problems should be analyzed when using nanofluids in fuel.

Keywords Nanofluids · Coolant · Car radiator · Nanofuel · Wear effects

Introduction

Nanotechnology concerns the use of devices and systems that exhibit new characteristics and properties related to matter with dimensions between 1 and 100 nm. Many fields and endeavor take benefits from the evolution of nanotechnologies, including electromechanical engineering, material science, physics, biology, chemistry, electronics, and computer science. The use of nanomaterials highlights several innovated industrial applications belonging to these fields with very high performance and high resistance to unpleasant surrounding environments, such as the rise or fall of temperatures. Looking to the applications in heat transfer field for example, studies carried out over the last few years have shown that the addition of nanoparticles in a fluid such as particles of copper oxide (CuO), copper (Cu), aluminum oxide (Al_2O_3), or carbon nanotubes in water for example could improve the heat transfer characteristics. In fact, nanoparticles added in fluid significantly modify the thermal conductivity, which leads to a remarkable improvement in convective transfers when these nanofluids are used, which is proved in the work of Choi et al. [1] who found in the beginning of this field that the effective thermal conductivity of the water–Al_2O_3 mixture increases by 20% for a volume concentration between 1 and 5% of Al_2O_3. In fact, Brownian agitation, linked to the nanometric size of the particles, minimizes the sedimentation problems encountered with larger particles. Therefore, the suspension of these nanoparticles in a fluid leads to interesting thermal characteristics compared

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to traditional fluids and undeniable advantages in improving heat transfer, Eastman et al. [2]. Thermal conductivity of nanofluids can be significantly higher than that of pure liquids. This high thermal conductivity indeed designates nanofluids as potential replacement of conventional fluids used in heat exchangers for example in order to improve their performance, Keblinski et al. [3]. Moreover, the addition of nanoparticles in a liquid increases its viscosity and therefore the pressure drops, Yang et al. [4]. However, the lack of stability over time of certain nanofluids can lead to agglomeration of the nanoparticles and a change in their thermal conductivity, Daungthongsuk et al. [5]. Remind that in particle suspension in fluids, different types of interactions between the particles themselves but also between the particles and the fluid govern the behavior of a suspension. Note that, these microscopic interactions have a very important macroscopic incidences such as the relative motion of particles compared to the liquid, which not only supports the diffusion of the particles in a suspension but also causes the regrouping, the arrangement of particles in aggregates even sedimentation and phase separation. The particles are also subjected to the action of gravity and buoyancy. Indeed, if the density or dimensions of particles increase, the sedimentation effect became faster. However, decreasing the scale to nano, nanofluids prevent the phenomenon of sedimentation since the thermal agitation can compensate the action of gravity. In fact, under a critical size of solid particles, the Brownian motion compensates the sedimentation. Conventionally, these nanoparticles have sizes, which do not exceed 50 nm, and their volume concentration φ does not exceed 10%. However, two families of nanofluids can be distinguished: those intended for thermal applications, for which φ remains less than 10% and those intended to present a magneto or electroactive behavior where φ can reach up to 30%. Mainly three groups of volume concentrations can be found in the literature: 0.1 to 1% for highly diluted nanofluids, up to 10% for diluted ones and > 10% for weakly diluted nanofluids. The nanoparticles commonly used consist of metallic or non-metallic materials and carbon nanotubes. In Fig. 1, Julien Chevalier [6] plotted the main families of nanofluids usually studied. Through this figure, the author emphasized the composition, size and volume concentration of common nanofluids. The base liquids generally used in the preparation of nanofluids are those of common use in heat transfer applications such as water, ethylene glycol and engine oil. Table 1 groups together a non-exhaustive list of combinations of nanoparticles and base fluids prepared by various research groups. Almost, by analyzing the references [1–114] cited in the present review, one or more combinations were used. Each row of the table gives the types of base fluids which were used with the nanoparticle cited in this row.

Several nanoparticles made from metallic/intermetallic elements such as Cu [7], Ni [8] or ceramic compounds such as MoS2 [9], Fe2O3 [10], Fe3O4 [11], CeO2 [12] and ZnO [13] are reported in the literature. A deep incite in this literature, several other base liquids are tested which can be selected from mixture of water and EG (W/EG), polyethylene glycol, diethylene glycol (DEG), vegetable oil [14], paraffin [15], coconut oil [16], engine oil [17], pump oil [18], gear oil [19] and kerosene [20]. The studied nanofluids as it is presented in the literature are made through a suspension using three phases drawn in Fig. 2; solid phase (nanoparticles), solid/ liquid interface and finally the liquid phase (base fluid).

To manufacture these nanofluids, a special attention in nanoparticles production is needed at the aim to obtain the nanometric sizes and to avoid the agglomeration or to plug the circuit. Nanoparticle manufacturing processes are numerous, they can be classified into two categories as listed in Yu et al. [22]. The first category is related to physical processes, such as mechanical grinding or inert-gas condensation technique. However, the second category concerns the chemical processes, such as laser pyrolysis, chemical precipitation, thermal spraying and chemical vapor deposition. There are two main methods to manufacture a nanofluid:

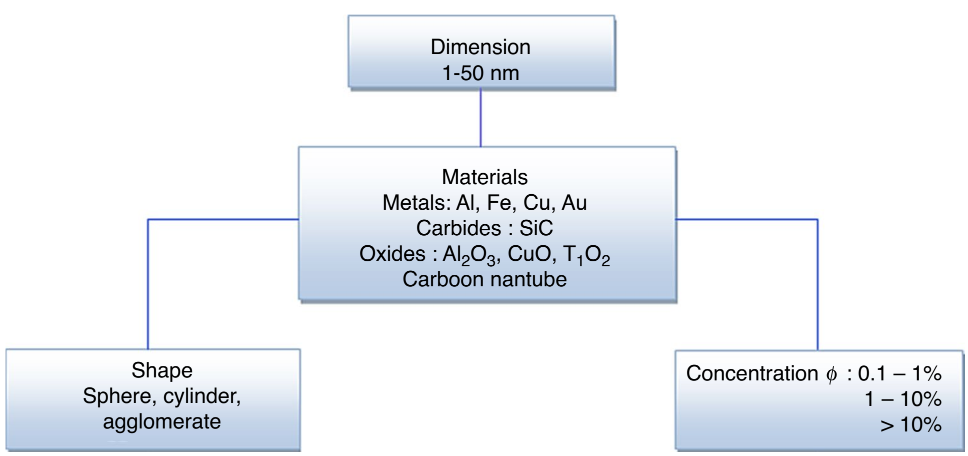


Fig. 1 Principal families of studied nanofluids [6]

Table 1 Nanoparticle/fluid combination

	Acetone	Water	Ethylene glycol	Oil	Toluene	Decene	Ethanol	Paraffin	Coconut oil	Vegetable oil	Kero-sene
Ag		√		√							
AIN							√				
Au		√			√						
$Al_{70}Cu_{30}$			√								
Al_2O_3		√	√	√				√	√	√	
C(diamond)		√									
C (Graphite)		√		√							
C (NTC)		√		√		√					
C (Fullerene)				√	√						
Cu	√	√	√	√							
CuO		√	√						√		
Fe			√								
SiC		√									
SiO_2		√	√							√	
TiO_2		√	√							√	
WO_3			√								
ZrO_2		√									
Ni		√	√								
MoS_2		√		√						√	
Fe_2O_3		√	√							√	
Fe_3O_4		√						√			√
CeO_2		√									
ZnO			√								

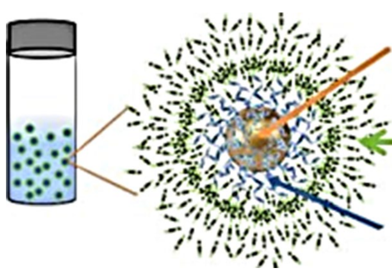


Fig. 2 Nanofluids suspension phases [21]

The one-step method consists in producing the nanoparticles in the fluid. This procedure is not widely used, but it helps to prevent agglomeration and oxidation of nanoparticles. An example of process consists on the solidification of the nanoparticles, which are initially introduced into the base fluid as gas phase [23]. The main drawback of this technique is that it is not appropriate for mass production [22].

The two-step method consists of first producing the nanoparticles and then dispersing them in the base fluid. To allow good dispersion, strong mechanical action using a rotary or ultrasonic agitator is often necessary in order to break up agglomerates. In addition, to avoid the agglomeration due to the attraction forces between the particles, we use forces of electrostatic repulsion by charging the surface of the particles through a pH adjustment. We can also use steric repulsive forces using molecules adsorbed or grafted on the surface. The main drawback of this technique is that there are a bad dispersion of the nanoparticles inside the fluid because of the clusters formed by nanoparticles during the preparation [22]. Despite this drawback, the two-step method is the most widely used method for the preparation of nanofluids, especially those based on nanotube carbon particles [24]. It has economic advantages and allows nanofluids to be prepared in large quantities due to the expanded industrial production of nanoparticles.

Figure 3 presents the annual evolution of the published papers related to the use of nanofluids in automotive systems. It is to be mentioned that although the number is still limited, there has been notable growth over the past five years.

The mastery of the manufacture of nanofluids reveals a wide range of applications in different areas. The main objective of the present paper is to report a literature review on the main studies that investigated the use of nanofluids in

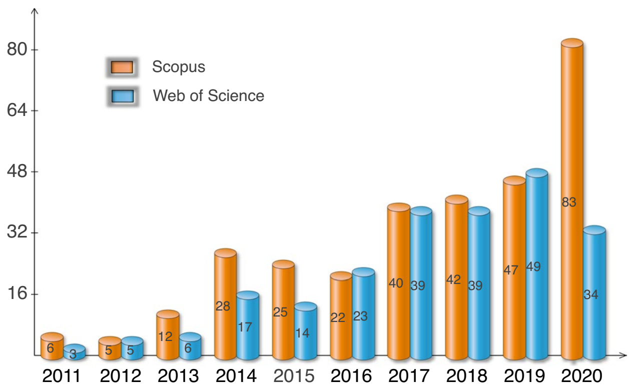


Fig. 3 Number of research articles published per year in the last 10 years, obtained from a search using the keywords (Nanofluid automobile) or (Nanofluid automotive) or (Nanofluid radiator) in Article Title, Abstract, Keywords for Scopus and in Topic for Web of Science

applications related to automotive during the recent years. The paper contains three main sections; the first deploys the use of nanofluids in a car radiator. The second reviews the main contribution on the addition of nanoparticles in the fuel or engine oil. Finally, the last section reviews the assessment of the wear effects of nanofluids on materials used in a car coolant system and in the car engine.

The potential of nanofluids in applications related to automotive systems

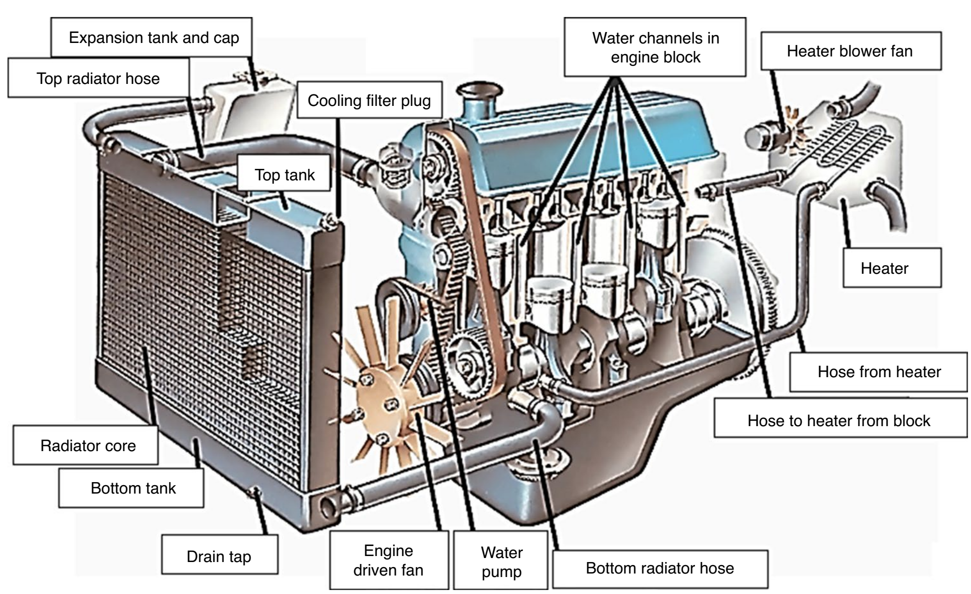
The evolution of technology in automobile industry and the growth of its customers' needs, force the auto industry to look for innovative solutions that push up the performance of their vehicle in terms of engine reliability and fuel consumption with the main vision to remain competitive. In fact, to achieve highest performances, vehicle engines need coolants, lubricants and transmission fluids with high thermal conductivity. However, using conventional synthetic high-temperature heat transfer fluids limits the capability of vehicle's components such as radiators, engines, gearboxes, heating, ventilation and air-conditioning systems. For coolant for examples, cars usually use ethylene glycol and water mixture as engine coolant, which have a poor heat transfer rates due to their lower thermal conductivity. This is the fact that gives the opportunity to scientists to test new fluids with high thermal conductivity such as nanofluids.

The use of nanofluids in car radiator

Car engines are often cooled by circulating a liquid called engine coolant through the engine block, where it is heated, then through a radiator where it loses heat to the atmosphere, and then returned to the engine. It is common to employ a water pump to force the engine coolant to circulate and an axial fan to force air through the radiator like it is represented in Fig. 4. The use of fluids with high thermal conductivity in a car radiator, such as nanofluids, allows the car engine to resist overheating due to friction between the different components, which increases the engine performances especially for sports cars that need more horsepower also for cars used in places with extreme weather conditions.

Choi et al. [25] have introduced nanocoolant, applied in automotive since 2001, by dispersing metallic and oxide nanoparticles in ethylene glycol-based fluids. Authors claimed through experimental investigations that there is a remarkable enhancement of the thermal conductivity compared to conventional coolants, which is in total agreement with the discussions presented in the work of Maranville

Fig. 4 Car coolant system [37]



et al. [26] who used the same nanoparticles dispersed in water and ethylene glycol/water. Goldstein et al. [27] demonstrated that nanofluids enhance the thermal diffusivity of the radiator coolant. However, using a classic method of dispersion, a limitation of agglomeration and oxidation caused by metallic nanoparticles is denoted during these years. This problem is solved during the recent years by the evolution of methods used in manufacturing and dispersion of nanoparticles.

Singh et al. [28] proved that the use of nanofluids with high thermal conductivity gives the possibility to automotive engineers to reduce 10% the frontal area of the car radiator which improve the aero-dynamism of the vehicle by reducing the air resistance which lead to a reduction in the fuel consumption. Delavari et al. [29] demonstrated that the use of nanofluids in a car radiator can lead to a gain of power needed for pumping. In fact, for a given heat transfer rate, the required base fluid flow rate is much higher than that denoted for nanofluids, which also reduce the fuel consumption. This is in complete agreement with the work of Peyghambarzadeh et al. [30] who proved that the overall heat transfer coefficient of the car radiator could be enhanced if the concentration of nanoparticles is increased especially for Fe_2O_3/water nanofluid, which enhances the car engine performance and decreases the fuel consumption. A 45% enhancement in the heat transfer efficiency of the car radiator was recorded in the work of Peyghambarzadeh et al. [31, 32] especially for low concentrations of Al_2O_3/water, Al_2O_3/EG in comparison with pure water, which is in contradiction with the author conclusions in their investigations on the use of Fe_2O_3/water nanofluid [30], which mark a question about the effect of nanoparticles concentrations and their types. Muhammad Ali et al. [33] proved the same conclusion with ZnO–water nanofluid. An enhancement up to 46% for 0.2% concentration of ZnO nanoparticles was recorded. A lowest enhancement percentage was recorded in the work of Naraki et al. [34] proving that the use of CuO/water nanofluid enhances the overall heat transfer coefficient up to 8% for a concentration of 0.4 vol%. Similarly in the work presented by Leong et al. [35], the use of Cu nanoparticles dispersed in EG leads to the enhancement of the heat transfer by 3.8%. Vajjha et al. [36] proved that the friction factor and the convective heat transfer coefficient increase when the particle volumetric concentration of the Al_2O_3/EG, CuO/EG nanofluids increases. One can confirm that the highest concentrations of nanoparticles enhance the thermal efficiency of the car radiator. However, due to the increase of friction coefficient, several studies should be performed to investigate the negative effects of nanoparticles on the material wear and on the pumping power.

Analyzing the literature during the last few years, several types of nanoparticles have been dispersed in conventional coolant such as ethylene glycol, water and glycerol with the main purpose to test their performance in heat removal from a car engine. A summary of numerical and experimental studies on nanocoolant [38–52] is discussed in Table 2. It is remarked from this table that the thermal efficiency of nanofluids in a car radiator almost is the main purpose of investigations reported in this literature review. The most used nanoparticles in these investigations are the aluminum oxide (Al_2O_3), dispersed in water or ethylene glycol base fluids or a mixture between these two fluids with different percentages. The main factor analyzed is the effect of nanoparticles volume concentration. Some other factors are analyzed such as Reynolds number, the viscosity and the inlet temperature. The main common conclusions reveal the increasing effect on the thermal performance when all these parameters rise. Some contradictory conclusions about the effect of volume concentration on pumping power loss and the Nusselt number are denoted in this literature review, which need a deep analysis at the aim to found the best nanocoolant that can be safe used in a car radiator.

Details of experimental studies are reported in Table 3, which describe the experimental setup, the main setting parameters of experiments such as the type of nanofluids, flow rate, temperature range, nanoparticle size and dispersion method and concentrations. Analyzing the experimental setups figured in Table 3, authors usually preferred to study nanocoolant using prototypes of car radiators plugged to a water pump (usually not specified if it is a car water pump working in the same real condition or not) that circulates nanofluids in a closed circuit equipped with a heater (as replacement of the heat generated by the car engine). The use of heaters instead of car engines differs considerably from actual working conditions, especially under extremely hot weather conditions. Ahmed et al. [45] and Palaniappan et al. [56] are the only authors who used a real car coolant circuit of a FIAT DOBLO 1.3 MJTD and HINO WO6D model (six-cylinder diesel engine). Analyzing the experimental results, presented in this literature review, it has been proved that nanoparticles concentrations, Reynolds number, and inlet temperature have an increasing effect on the thermal performances of the car radiator. The main drawback in these experimental studies is the absence of standardization of the experimental method and instrumentation, which lead to some lack of transparency in the determination of a precise enhancement percentage of the radiator performance under different type of nanofluids. However, the use of a real car coolant system that integrates a real car engine working in the real condition certainly leads to better results, where researchers can analyze with precision the performance of nanofluids and their effects on the working life of all engine components. The main idea is to collaborate with car manufacturer to test the best nanofluids on car prototypes used to validate the new car production series. In such tests, car manufacturers run these prototypes under extreme

Table 2 Nanofluid applied on radiators

Type of nanofluid	Particles concentration	Specification of the radiator	Finding	References
Graphene nanoplatelets/water-ethylene glycol (GnP/H2O-EG)	0.1—0.5 vol%	Flat tube with louvered fin. -Elliptically cross-sectioned vertical aluminum tubes	Enhancement of the convective heat transfer coefficient especially when the temperature rises, considering specific flow characteristics (concentration 0.5 vol% and mass flow rate 100 g/s)	Selvam et al. [38]
		With induced draft axial fan to cool the nanofluid	The rise in pressure drop is predominant with respect to mass flow rate than that of nanoplatelets loading	
Titanium dioxide TiO_2–DW/EG	0.05 and 0.3 vol%	Toyota Corolla 2006 model radiator with 2 L capacity at idle condition	The thermal performance of the radiator was increased by 24.21% using aluminum oxide at a volume fraction of 0.3%	Said et al. [39]
Aluminum oxide Al_2O_3–DW/EG			The values of Performance Evaluation Criterion (PEC) of the radiator lie in the range of 1.03–1.31, which indicates significant flow enhancement	
f-MWCNT nanofluid	0.1 vol%	33 flat vertical aluminum tubes having flat cross-sectional area and louvered fin The distances between the tubes are filled with thin aluminum fins An axial force fan is used	Due to the high thermal conductivity of MWCNT, Reynolds number and Nusselt number increase with the increase in nanofluid flow rate. MWCNT nanofluid enhances the heat transfer of 45% compared to DI water	Jadar et al. [40]–[41]
Al_2O_3/EG	0.08, 0.5 and 1 vol%	Peugeot 405 radiator. With a fan with C78/22/4SO model and with specifications PH:1, HZ:50. V: 220	The thermal performance of the car radiator is enhanced up to 5% if we simultaneously use the coils inserts with the nanofluid compared to the use of coils inserts alone	Goudarzi et al. [42]
Al_2O_3/SiC_{UM}, Al_2O_3/SiC_M in DW and EG [43]	0.4, 0.8 vol% [43]	Radiator with axial fan	Hybrid nanoparticles with reduced size increase the heat transfer in the automotive system more than single type nanoparticles. Improvement of the overall thermal performance about 28.34% at 0.8% of concentration [43]. The thermal conductivity enhancement was found to be 53.81% for 0.5 vol.% nanofluid at 50 °C [44]	Ramalingam et al. [43]
SiC/DW-EG [44]	up to 0.5 vol.% [44]	With horizontal pipes encircled by material panels made of galvanized metallic, copper or aluminum		Li et al. [44]
TiO2/water	0.1, 0.2 and 0.3 vol%	Model FIAT DOBLO 1300 cc. MJTD forced draft fan and a cross flow heat exchanger	The efficiency of the car radiator can increases by 47% using 0.2% concentration of TiO2-water nanofluid compared to pure water coolant and compared to other concentrations such 0.1 and 0.3%	Ahmed et al. [45]

Table 2 (continued)

Type of nanofluid	Particles concentration	Specification of the radiator	Finding	References
TiO_2 /Ag, TiO_2/Cu and pure TiO_2 in DW and EG	0.3, 0.5, 1 and 2 vol%	Aluminum radiator with flat tubes and corrugated louver fin	The heat transfer performance of the car radiator depends on the type and concentration of nanoparticles. The optimal choice is as follows: 0.3%Ag-doped > 0.1% Ag-doped > Pure TiO_2 > 0.1% Cu-doped	Soylu et al. [46]
TiO_2/EG	0.1, 0.3 and 0.5 vol%	Radiator with 3 rows of 104 tubes diameter 5 mm and length of 0.3 m	The heat transfer performance of the car radiator can be improved by increasing the fluid circulation rate, while the fluid inlet temperature has a little effect	Sandhya et al. [47]
TiO_2/Water			Using nanofluids with low concentrations for car cooling can improve the heat transfer rate up to 37% in comparison with base fluid	
CuO, TiO_2, Al_2O_3 Fe_3O_4 (Brick, Cylindrical, Platelet and Spherical shapes) in water or EG	0, 0.2, 0.4 and 0.6 vol%	Radiator with a flat tube model for a numerical simulation	The best cooling performance for a car radiator is assessed in the case of TiO_2/EG nanofluid with platelet shape and larger volume fraction of nanoparticles	Hatami et al. [48]
Al_2O_3/Water-Mono Ethylene Glycol	0.2–0.8 vol%	Radiator with 36 vertical tubes with flat fins 24″ Axial flow fan is used	Naonofluids with lowest concentration 0.2% enhance the heat transfer rate about 30%. The frontal area of the car radiator can be reduced if a nanofluid is used as coolant, which will make lighter cooling system, produce less drag and reduce the fuel consumption	Subhedar et al. [49]
Graphene and silver in H_2O/EG	0.01, 0.05 and 0.1 vol%	Radiator with nozzle plate Centrifugal fan is used	The silver nanofluids enhances the heat transfer rate up to 4.4%, while the graphene nanoparticles decreases the thermo-hydraulic performance compared to base fluids	Contreras et al. [50]
Co_3O_4/$(CH_2OH)_2$-H_2O Al_2O_3/$(CH_2OH)_2$-H_2O	0.02, 0.05, 0.1, and 0.2 vol%	Vehicle radiator (FIAT-128) with staggered rectangular tube (aluminum material) Suction axial fan is used	The Co_3O_4-based nanofuid exhibits high thermal performance than Al_2O_3. The performance index reaches highest values in cases of lower concentration ratio and a higher Reynolds number	A.M Elsaid [51]

Table 2 (continued)

Type of nanofluid	Particles concentration	Specification of the radiator	Finding	References
Al_2O_3/water	0–2 vol% [52, 53]	Wavy fin radiator with Staggered tubes arrangement [53]	The convective heat transfer coefficient is inversely proportional with bulk temperature and directly proportional with the flow velocity. The cylinder head of the engine should be made of cast iron, which suits with c-Al2O3 water nanofluid reactions [52]	Moghaieb et al. [52]
	1, 3 and 5 vol% [54]	Radiator with serpentine tubes [54]	The spherical nanofluids are more efficient as a car radiator coolant than brick and platelet nanofluids [53]	Kumar et al. [53]
			High nanoparticles concentration leads to a higher heat transfer coefficient at the expense of negligible pressure drop. L–H serpentine tube used for a car radiator has an important impact on the heat transfer performance compared to conventional ones [54]	Awais et al. [54]
$Al_2O_3+CeO_2$ /water	0.2, 0.4, 0.6%, 0.8 and 1 vol%	-Radiator with 40 flat tubes and 2 mm gap between fins	The rise of mass flow rate pushes up the convective heat transfer coefficient. Which is directly proportional to the volume fraction of nanoparticles	Sathish et al. [55]
Fly ash /(EG-water)	0.2 – 2 vol%	-Radiator of a heavy vehicle HINO WO6D model	The rise of nanoparticles concentration increases the heat transfer coefficient and the pumping power	Palaniappan et al. [56]
Al_2O_3 (CNT, Graphene) /Water	1–3 vol %	Staggered way circular tubes configuration based on a wavy fin radiator	For ternary hybrid nanofluids, the particle shape has a great effect on the efficiency of nanofluid to enhance the thermo-hydraulic performance of the car coolant system. The cylindrical (CNT) nanoparticles are more efficient	R.R Sahoo [57]
Carbone quantum dots (CQDs) /CRC	100, 200, 500, and 1000 ppm	Car radiator (characteristics not specified)	For 200-ppm nanoparticles concentration, an enhancement of the thermal conductivity and convection heat transfer by 5.7% and 16.2% respectively is recorded compared to the base fluid. CQDs have better efficiency for low volume concentrations (less than 500 ppm) because of their small sizes	Ettefaghi et al. [58]

Table 3 Experimental setups

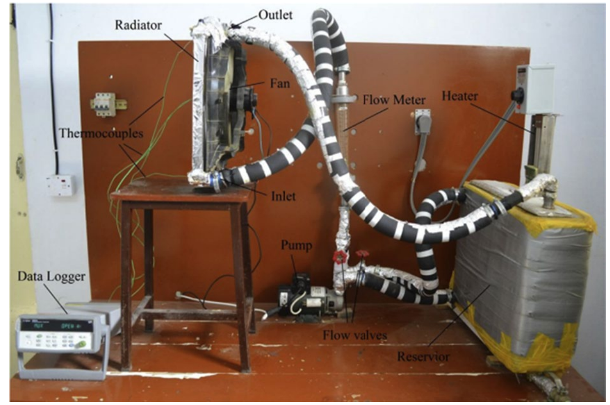
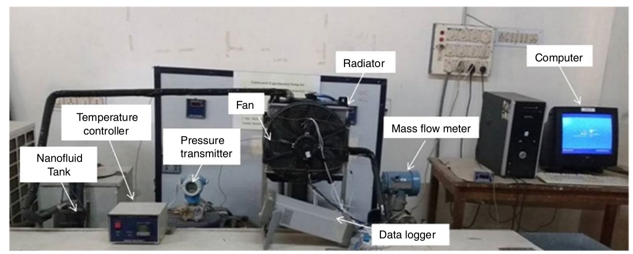
Experimental parameters	Experimental setup	References
Nanofluid type: ZnO/water Concentrations: 0.01, 0.08, 0.2 and 0.3 vol% Nanoparticle size: 20 nm (5.606 g/cm^3) Suspension by lowering the pH of distilled water, as the particles are homogenous to acidic solution for 2 h (using two step method) Flow rate of 7, 8, 9, 10, 11 LPM Inlet temperature: 45 °C, 50 °C and 55 °C Reynolds number range: 17,500 – 27,600		Muhammad Ali et al. [33]
Nanofluid type: Graphene nanoplatelets/ WG-EG (GnP/H2O-EG) Concentrations: 0.1—0.5 vol% Nanoparticles size: GnP = 5–10 nm Mass flow rate: from 10 g/s to 100 g/s Inlet temperature: 35 °C, 45 °C The ambient air velocity: 3 m/s Reynolds number range: 25 – 300 Base Fluid: Sodium deoxycholate (0.75 vol%) + De-ionized water (70 vol%) + ethylene glycol (30vol%) Suspension using intensive ultrasonic vibration for 2 h using a Probe Sonicator (QSonica, USA, Power Rating: 700 W, Frequency: 20 kHz)		Selvam et al. [38]

Table 3 (continued)

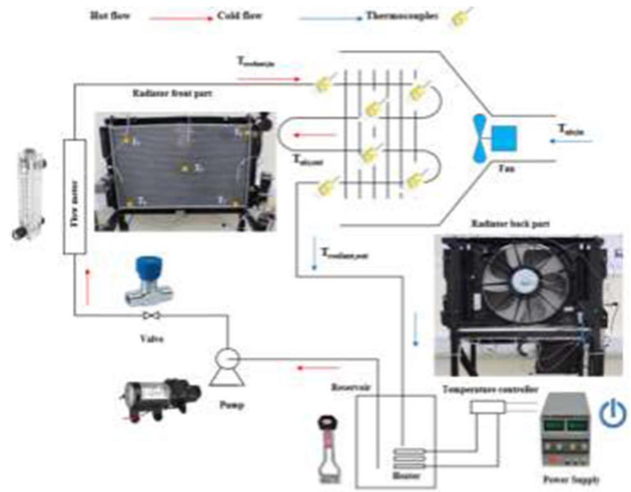
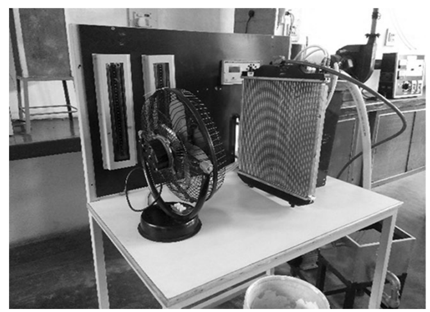
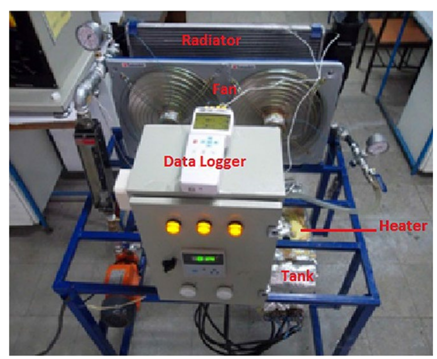
Experimental parameters	Experimental setup	References
Nanofluid type: TiO_2–DW/EG, Al_2O_3–DW/EG Concentrations: 0.05 and 0.3 vol% Nanoparticles size: $TiO_2 = 5$ nm, $Al_2O_3 = 10$ nm Mass flow rate: 4 L min^{-1} Temperature range: 20 °C–70 °C Base Fluid: Mixture DW-EG Suspension using a magnetic stirrer for 30 min and sonication by ultrasonic processor (UP400S, 400 W maximum power, 24 kHz frequency) for about 2 h Reynolds number range: 400 – 3000		Said et al. [39]
Nanofluid type: f-MWCNT/ DI water Concentrations: 0.1 vol% Nanoparticle size: outer diameter: 20 nm, inner diameter: 16 nm, length: 20 µm Suspension using an ultrasonic bath sonicator for 3 h Flow rate in the range of 0.5 LPM to 3 LPM Inlet temperature: 45 °C		Jadar et al. [40]–[41]
Nanofluid type: Al_2O_3/EG Concentrations: 0.08, 0.5 and 1 vol% Nanoparticle size: 40 nm Base fluid: EG + small quantity of sodium dodecylbenzene sulfonate (SDBS) as dispersant Mixture using ultrasonic vibration (UP-400S model) Wire coil inserts having pitch ratios of 2 is used Three flow rate of 11, 12.25 and 13.50 lit/min Temperature: 80 °C 18,500 < Re < 22,700	 	Goudarzi et al. [42]

Table 3 (continued)

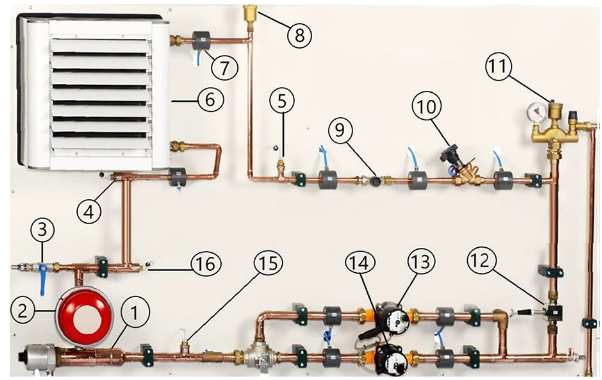
Experimental parameters	Experimental setup	References
Nanofluid type: Al_2O_3/SiC_{UM}, Al_2O3/SiC_M in DW and EG at 60:40, 50:50, 60:40, 50:50 Concentrations: 0.4, 0.8 vol% Nanoparticle size: 20 nm Stirred for 60 min using a magnetic stirrer followed by sonication for 4 h (Using the two-step method) Flow rate: 0–3.5 LPM Experiment temperatures: 0 °C – 65 °C		Ramalingam et al. [43]
Nanofluid type: TiO_2/water Concentrations: 0.1, 0.2 and 0.3 vol% Nanoparticles size: 30—60 nm Flow rates of 0.097 m^3/h and 0.68 m^3/h Temperatures range: 20 °C – 80 °C Using a vehicle engine system (Model FIAT DOBLO 1300 cc. MJTD) Reynolds number: 430 – 1400		Ahmed et al. [45]

Table 3 (continued)

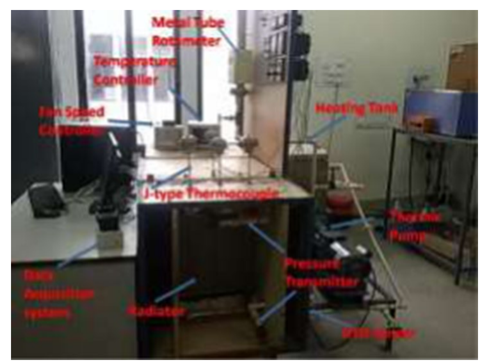
Experimental parameters	Experimental setup	References
Nanofluid type: TiO_2 /Ag, TiO_2/Cu and pure TiO_2 in DW and EG Concentrations: 0.3, 0.5, 1 and 2 vol% Fluid Velocity: 0.193 – 0.218 – 0.240 – 0.265 – 0.285 (m/s) Re Number Range: 337 – 830 Heating Power: 8600 W Flow rate: 3 m^3/h Temperature range: 40–60 °C Reynolds number Re: 337 – 830 Nanofluid type: TiO_2/EG-Water (40:60)		Soylu et al. [46]
Concentrations: 0.1, 0.3 and 0.5 vol% Nanoparticles size: 21 nm Dispersion by keeping in a sonicator continuously for about 8 h Flow rates: 2, 3, 4 and 5 l/min Air velocity: 2, 3 and 4 m/s Temperature range: 39 °C—95 °C Reynolds number Re: 4000 – 16,000		Sandhya et al. [47]
Nanofluid type: Al_2O_3/Water-Mono Ethylene Glycol (50:50) Concentrations: 0.2–0.8 vol% Nanoparticles size: 20 nm Dispersion under ultrasonic agitation Flow rates: 4–9 LPM Air velocity: 1–2.5 m/s Coolant Inlet temperature: 68 – 85 °C		Subhedar et al. [49]

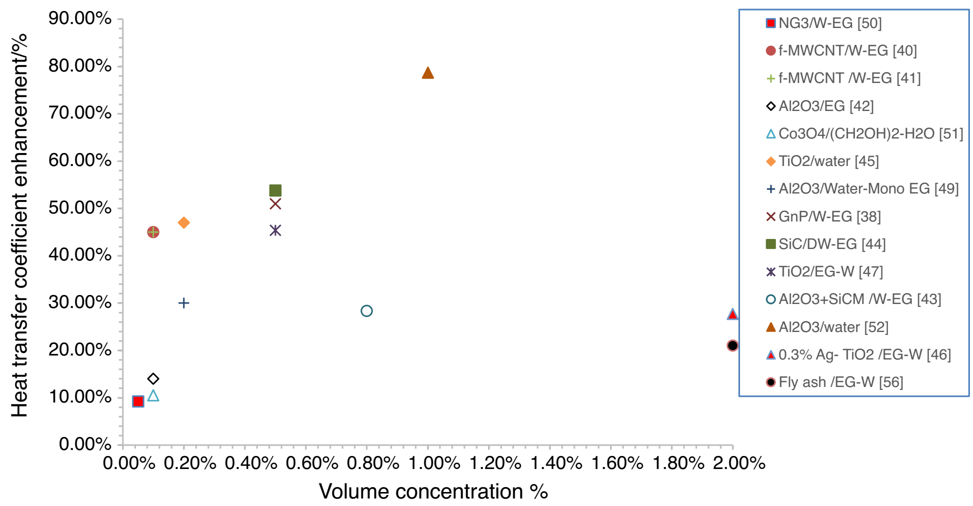
Table 3 (continued)

Experimental parameters	Experimental setup	References
Nanofluid type: Graphene and silver in H_2O/EG Concentrations: 0.01, 0.05 and 0.1 vol% Nanoparticles size: Silver 10–100 nm Two-step high pressure homogenization method Flow rate: up to 12 L/min Temperature range: 25–55 °C Air inlet temperature conditions at 25 °C Air velocity: 2.1 m/s		Contreras et al. [50]
Nanofluid type: $Co_3O_4/(CH_2OH)_2$-H_2O $Al_2O_3/(CH_2OH)_2$-H_2O Base fluid with three ratios of EG/water 0:100%, 10:90%, and 20:80% Concentrations: 0.02, 0.05, 0.1, and 0.2 vol% Nanoparticles size: Al_2O_3: 11 -25 nm, Co_3O_4: 8 nm to 21 nm Air velocity: 0.6 m/s Temperature range: 50–90 °C Flow rate: 0.05–0.2 kg/s Reynolds number Re: 12,500—50,000		A.M Elsaid [51]

Table 3 (continued)

Experimental parameters	Experimental setup	References
Nanofluid type: Fly ash /(EG-water) Base fluid: water (60%), ethylene glycol (40%) Concentrations: 0.2 – 2 vol% Nanoparticles size: 50 nm manufactured using Spex-8000 ball milling Nanoparticles composition: alumina (21.96%), ferric oxide, (6.48%), titanium oxide (1.03%), magnesium oxide, (2.12%), silica (47.08%), calcium oxide (16.03%), sodium, oxide (1.28%), sulfur trioxide (2.13%) and potassium oxide (0.93%) Ultrasonic vibration for mixture (2-step method) Flow rate: adjusted to coolant Reynolds number 4000		Palaniappan et al. [56]
Nanofluid type: Carbone quantum dots (CQDs) /CRC Concentrations: 100, 200, 500, and 1000 ppm Nanoparticles size: 1.5 nm (Synthesized using microwave method) Suspension stabilized using merely the bath ultrasonic at the frequency of 37 kHz for 5 min Flow rate: 1.15–6 L/min Reynolds: 2457, 3249, 4031 and 4782		Ettefaghi et al. [58]

Fig. 5 Effect of nanofluid type and concentration on heat transfer enhancement



conditions to see the performance of each component of the car.

Effect of the volume concentration

Most of analyzed results summarized in Table 2 showed that nanocoolant could enhance the thermal performances of the car radiator with different degrees of efficiency considering the type of nanoparticles, concentrations, type of base fluid, temperature, etc. Many factors can affect the heat transfer coefficient, a key parameter analyzed by many researchers cited in [38–52]. In fact, Fig. 5 plots the best performance of nanofluids tested in these studies, the figure indicates the maximum of heat transfer enhancement measured for the optimal volume concentration. The best performance is recorded in the work of Moghaieb et al. [52] about 78.67% achieved at 1% volume concentration of c-Al_2O_3 nanoparticles suspended in pure water at a bulk temperature of 80 °C and flow velocity of 2 m/s. The main drawback of the use of Al_2O_3/Water in a car radiator is the type of materials of the car engine components, in fact authors precise that this type of nanofluid should be used to cool engine components made of cast iron. Much other type of nanofluids tested in [38, 40, 41, 44, 45, 47] and [54] can enhance the heat transfer in a car radiator between 45 and 55%. Selvam et al. [38] measured 51% enhancement for the highest volume concentration 0.5 vol % (of graphene nanoplatelets dispersed in water-ethylene glycol mixture) and the maximum mass flow rate (100 g/s) at 45 °C inlet temperature. A maximum pressure drop of 4.88 kPa at 35 °C for the same concentration and flow rate. In Jadar et al. [40, 41], the heat transfer enhancement reached 45% for 0.1 vol% of f-MWCNT dispersed in Water-EG mixture at 45 °C. Li et al. [44] recorded 53.81% for 0.5 vol% of silicon carbide (SiC) suspended in water/

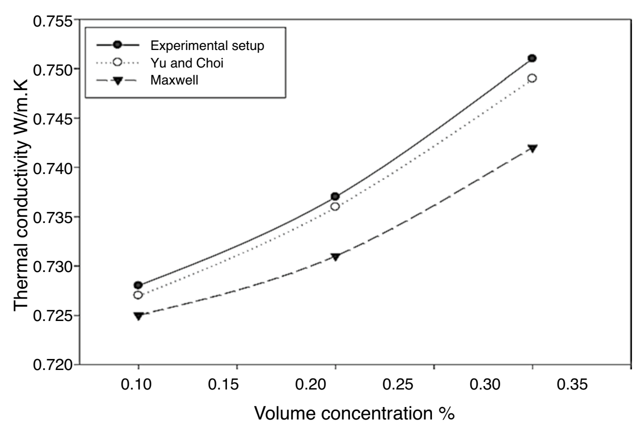


Fig. 6 Thermal conductivity of TiO2 nanofluid at different volume fraction [45]

ethylene glycol mixture at 50 °C. TiO_2-water nanocoolant is tested in the work of Ahmed et al. [45] where the heat performance enhancement reached 47% for a volume concentration 0.2%. The thermal conductivity measured increases remarkably, if the volume concentration increases from 0 to 0.35 vol% as it is denoted from Fig. 6. However, 0.5% TiO_2 dispersed in 40% EG and 60% water at 45 °C enhances the heat transfer about 45.4% [47]. Awais et al. [54] measured 50% for 5% volume concentration of Al2O3 dispersed in pure water circulated in a uniform serpentine tube at 5L/min, which makes highest volume concentration of Al_2O_3 more than 1 vol% dispersed in water-based fluids not the optimal choice to obtain the best thermal performance in a car radiator as it is confirmed in the result of Moghaieb et al. [52]. Going back to Fig. 5, lower volume concentrations between 0.4 and 1% are the best choice to enhance the performance of the car coolant system. However, some discrepancies in the determination of the optimal nanoparticles volume

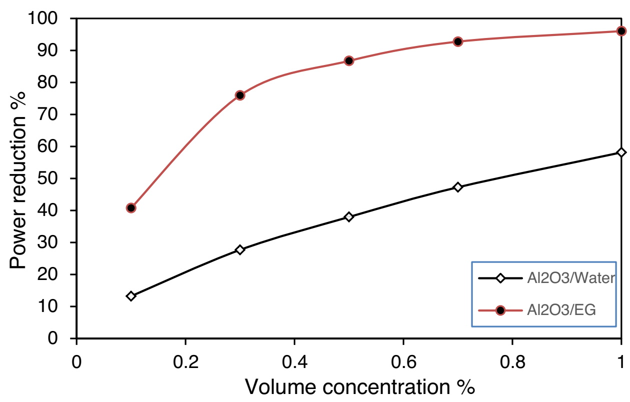


Fig. 7 Effect of volume concentration on pumping power reduction

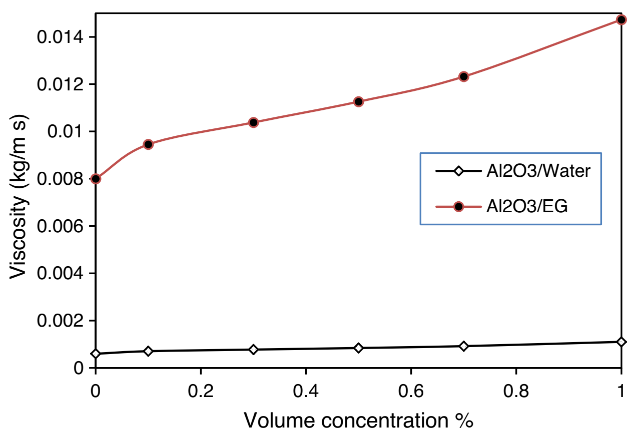


Fig. 8 Effect of volume concentration on viscosity

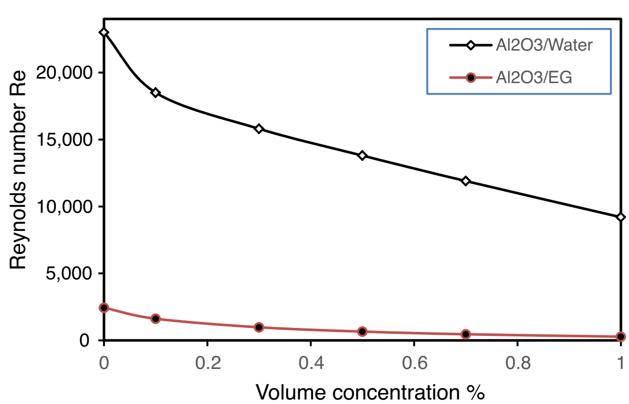


Fig. 9 Effect of volume concentration on Reynolds number

concentration and the precise heat transfer enhancement are remarked through this literature review. The range of volume concentration above 2% is not enough investigated which need more intention in further studies at the aim to optimize the amount of nanoparticles dispersed in base coolants.

Figures 7–9 are plotted using experimental data presented in the work of Delavari et al. [29] who tested the use of Al_2O_3 nanoparticles in water and ethylene glycol base fluids. Figure 7 plots the evolution of pumping power reduction in function of different volume concentrations. The increase in Al_2O_3 volume concentration up to 1% reduces the power needed to circulate the fluid in the coolant system. In fact, the required nanofluid flow rate is much smaller than that needed for base fluids, which is explained by the increase in viscosity when the nanoparticle concentration increases as it is remarked in Fig. 8. Kole et al. [59] proved through several experimental results that viscosity is a key factor that influences both the convective heat transfer and the pumping power. The pressure drop denoted in several experimental results found in the literature [60–63] trigs the need to increase the pumping power in a car radiator. In addition, dispersing nanoparticles in fluids increases the friction factor with the material of the coolant circuit [64–66], which limits the radiator performance. Therefore, a deep incite on the interaction between nanoparticles and materials of the coolant circuit is needed through more careful numerical and experimental investigations. The principal aim of these studies should be the determination of the optimum nanocoolant and the best pipes's surface skin. For best results, such studies need experimental setups that use a real coolant system with a real car engine.

Figure 9 plots the decreasing effect of nanoparticles volume concentration on Reynolds number Re, which is a result of the rise of viscosity when the nanoparticles volume concentration rises.

Effect of Reynolds number

It is proved in several research papers such as [67–72] that the Reynolds number is a key parameter that influences the heat transfer coefficient of nanofluids. Authors preferred the turbulent flow regime at the aim to avoid sedimentation and agglomeration of nanoparticles, which improve the performance of a nanocoolant circuit. Chavan et al. [67] proved that the increase in turbulence improves considerably the heat transfer of both conventional fluids and nanofluids. Ali et al. [68] denoted a remarkable increase in the heat transfer coefficient by increasing the Reynolds number from 20,000 to 40,000, which proves the advantage of turbulence in enhancement of nanofluids performances. Karimi et al. [69] used the laminar flow regime (Re: 350–1060) in vertical and horizontal radiators, they confirmed that Reynolds number push up the Nusselt number and pressure drop in a nanocoolant circuit. Akash et al. [70] used also the laminar flow regime (Re: 300–1300), they linked the increasing effect of

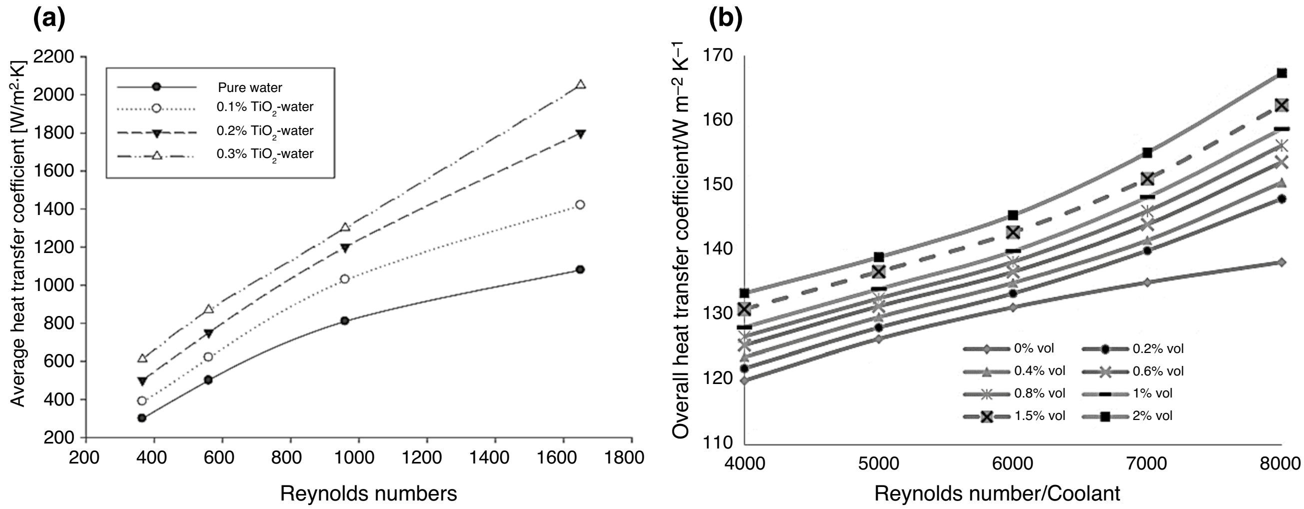


Fig. 10 **a** Average of heat transfer coefficient as a function of Reynolds numbers [45], **b** overall of heat transfer coefficient as a function of Reynolds numbers on fly ash nanofluid [56]

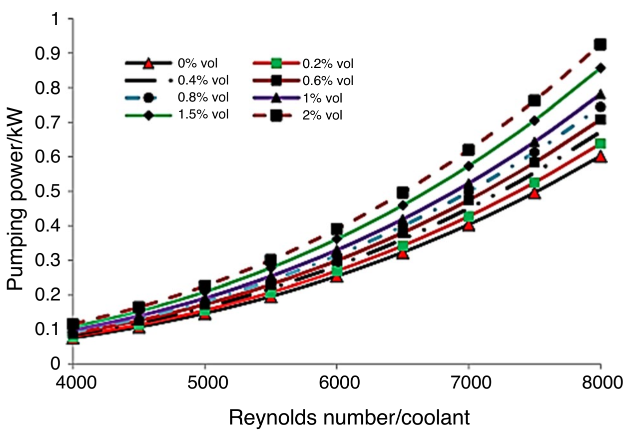


Fig. 11 Influence of the Reynolds number (fly ash coolant) on pumping power of radiator [56]

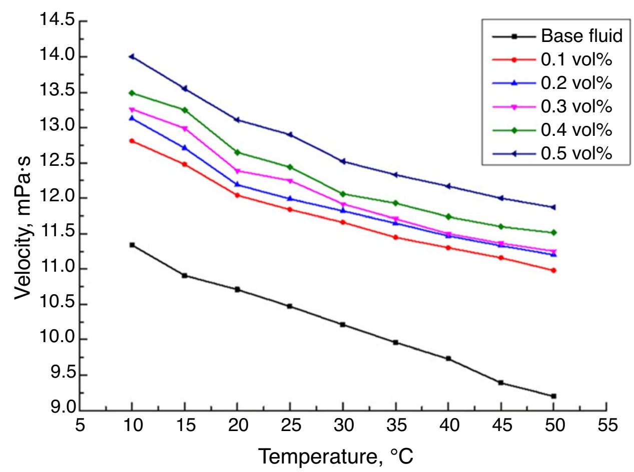


Fig. 12 Effect of temperature on viscosity of SiC nanofluid [44]

Reynolds number with the type of nanoparticiles dispersed in base fluids. In fact, authors confirmed that the overall heat transfer coefficient could be slightly increased with Reynolds number for copper and MWCNT nanofluids. However, the values of heat transfer coefficient do not change in the case of aluminum nanofluids, which makes some contradictions with the results of many other researchers such as Kumar et al. [71] who tested Al_2O_3/water nanofluid. In fact, in this work, authors confirmed that the increase in the flow rate increases considerably the heat transfer rate, which is in correlation with the Reynolds number. Toh et al. [72] showed in their work that volumetric concentration and Reynolds number enhance the Nusselt number. The best enhancement percentage is calculated for 0.5 vol.% of GnP and a Reynolds number equal 2000.

Figures 10 and 11 plot samples of results found in the literature [45, 56] that clearly show the positive effect of Reynolds number on heat transfer coefficient and the pumping power needed in a car radiator.

The main downside denoted in this literature is that the effect of Reynolds number on the heat transfer enhancement has different percentages from an investigation to another, which makes difficult to determine the best choice between any two nanofluids and to find which one exhibits more heat transfer characteristics.

Effect of the inlet temperature

The inlet temperature has an influence on the thermal performance of a car radiator, but it is less important

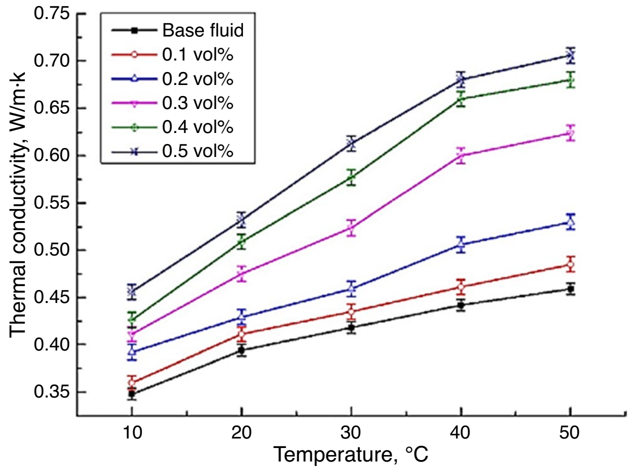


Fig. 13 Thermal conductivity of the nanofluid at different temperatures [44]

compared to the effect of nanoparticles volume concentration and Reynolds number. In fact, if the inlet temperature increases, the viscosity of nanofluid decreases, which is clear in Fig. 12 plotted in the work of Li et al. [44] also proved in the review of Zhao et al. [73]. The decrease in viscosity helps the Brownian motion and the interaction between nanoparticles. Several investigations proved that the rise of temperature enhances the thermal conductivity of the nanofluid, but at certain limit, the rise of inlet temperature decreases the thermal performance of the radiator. Sharma et al. [74]. proved that the increase in inlet temperature of Al/water nanofluids enhances the thermal conductivity of the car radiator. However, the temperature can affect the friction factor, and at a certain value, the performance of the radiator will decrease, which is in complete agreement with the work of Sumanth et al. [75] who investigated the use of carboxyl graphene nanoplatelets/EG-water nanocoolant. However, in the work of Muhamed Ali et al. [33] and Ali et al. [68], authors remarked that the inlet temperature weakly influences the heat transfer rate in the case of ZnO/water and MgO/water. Samira et al. [62] noted that the increase in inlet temperature helps to reduce the pressure drop in a CuO/water coolant circuit which improves the radiator performance. Using the same nanofluid Naraki et al. [34] proved that the overall heat transfer coefficient decreases when the inlet temperature increases from 50 to 80 °C. However, the results of Li et al. [44] plotted in Fig. 13 in the case of SiC/EG-water nanocoolant proved that by increasing the temperature from 10 to 50 °C, the thermal conductivity increases remarkably. In the work of Tijani et al. [76], a numerical simulation studying the distribution of heat transfer across the surface of a radiator with flat tubes and louvered fins is presented. In this investigation, authors plotted the temperature profile, which proved that the heat is transferred via conduction and convection to the walls of the flat tube and to the fins.

Analyzing such literature review, it can be noticed that it is difficult to confirm one conclusion about the effect of temperature on the thermal conductivity of nanofluids, which is due to a variable influence of temperature on the thermophysical properties of nanofluids.

From the cost point of view, almost it can be noted that the manufacturing and maintenance of the radiator cost approximately 20 percent from the whole cost of the car engine. Through the use of nanofluids in the radiator, the performance of this key subsystem is remarkably increased. However, the design of this system can be improved to be smaller or integrating less components needed for cooling or circulating the nanocoolant. In fact, reducing the size or simplifying the design of the radiator can decrease the manufacturing and also the maintenance cost of the cooling system equipment. Compared to classic coolant, it is not costly to adjust the pH and add surfactant for the nanofluids to increase the heat transfer performance of the car radiator.

The use of nanofluids in transmission oil and fuel

Nanofluids used in transmission

During the last few years, many researchers have introduced the suspension of nanoparticles in oil-based fluids. Several type of nanoparticles and oils have been tested looking for the best thermal conductivity and dynamic viscosity, which leads to a high thermal efficiency needed in lubricant applications such as car engine oil and gearbox oils.

About ten years ago, Mohammadi et al. [77] investigated the suspension of Al_2O_3 and CuO in engine oil. They concluded that the thermal conductivity increased with the increase in concentration. The maximum enhancement calculated is 5% for alumina and 8% for copper oxide at 2% volume concentration. Similar conclusion has been remarked in the work of Vasheghani et al. [78] who tested the suspension of alumina and aluminum nitride in engine oil. Authors denoted that aluminum nitride engine oil nanofluid has the maximum thermal conductivity (75.23% enhancement at 3%) especially for the smaller size of nanoparticles. The main downside in this result is the high volume concentration of nanoparticles that can lead to some problems of performance in the engine components. Ettefaghi et al. [79] used MWCNTs-engine oil nanofluid, which enhanced the thermal conductivity about 27% at 0.5 vol%. Adding the zinc oxide with MWCNTs, Dinesh et al. [80] remarked an enhancement of the friction coefficient, wear resistance added to the enhancement of the thermophysical proprieties such as the flash point, viscosity and thermal conductivity. However, it is proved in the work of Rehman et al. [81] that single carbon nanotubes (SWCNTs) dispersed in engine oil gives higher skin friction and Nusselt number compared to multiwalled carbon nanotubes (MWCNTs) which is due to higher thermal conductivity and density. In addition, it is reported in these researches that nanoparticles enhance the performance of lubricant, which decreases the friction between the engine components and leads to a reduction in wear and material damage that increase the car engine performance and durability. Recently, many papers [82–95] have investigated the suspension of MWCNT, Al_2O_3, Fe_2O_3, MgO, ZnO, Cr_2AlC, MoS_2-WS_2, Ni-MoS_2 in engine and gearbox oils. The main contributions of these papers are reported in Table 4. Overall, authors agreed that the thermal conductivity of nanolubricant is enhanced when the temperature and volume concentration of nanoparticles increase. Promising results have been remarked in the suspension of alumina and carbon nanotube with lower volume concentration. Especially in the reduction in friction coefficient, and the prevention of wear and damage of mechanical components.

Analyzing this literature review, one can note that it remains difficult to define until now the optimal value of nanoparticles volume concentration that should be dispersed in engine and gearbox oils. In fact, the heat transfer enhancement reached good values under low and high volume concentrations, which is related to the type and size of nanoparticles. The major factor that can help in further research is that nanolubricant should have an optimal value of viscosity that ensure the best lubricant film between components at the aim to reduce friction, which prevent the material wear, and damage. Noting that for a best performance of the car engine in higher temperature and during cold starts, a reduction in viscosity of lubricant is needed. Certainly, a deep investigation is needed to determine the best volume concentration of nanoparticles. In fact, researchers need to determine the best range of viscosity (which is positively influenced by the increase in volume concentration as seen in Fig. 14) for the best engine performances.

Nanofluids used in fuel

Nanofluids are not widely tested in fuel addition compared to their application in the car radiator or in engine and gear oils. However, the addition of metal-based nanofluids in fuel attracted the intention of many researchers. The main purpose in their investigations is the reduction in fuel consumption and gases' emissions. The main new researches [96–101] performed during the last few years are reported in the last section of Table 4. Some tests on the addition of nanoparticles in biofuels (mustard oil methyl ester [97], AC BDD [98], Jatropha biodiesel [99], orange peel oil biodiesel [100], honge oil methyl ester [101]) have been reported also in this table. The main conclusions denoted from these researches and some previous ones such as [102–107] are that nano-added particles reduce the engine outflows generated by biodiesel such as NOx, SO_2, CO, CO, HCs and smoke emissions. Many nanoparticles promote more oxygen, which help the combustion process in the engine.

For instance, during the combustion process of diesel fuel, more hydrogen can be produced by dispersing aluminum nanoparticles that help the decomposition of water. Aluminum nanofluids mixed with diesel fuel could enhance the combustion heat and reduce smoke and nitrous oxide from the engine emissions. Related to some type of nanoparticles, some researchers remarked a dramatic drop in NOx and SO_2 emissions, and a remarkable increase in CO emission and smoke opacity such as the work of Sarvestani et al. [96] who tested Fe_3O_4 nanoparticles. A new detailed review on the effects of nano-additives on toxicity and exhaust emissions is presented in the work of Norhafana et al. [108].

Note that, some mechanical problems should be analyzed when using nanofluids in fuel. In fact, some mechanical defects can happen in the injection system (injectors, pump, and pipes) for example which usually have a high maintenance cost. Corrosion problems should be also analyzed certainly in the case of use of water-based additives, a major problem causing a material wear and damage leading to more mechanical defects with highest maintenance cost.

Furthermore, regarding the nanofluids capability in reducing the fuel consumption and the combustion efficiency, the cost will be considerably reduced. Certainly, less emission rate, less NO_x production and less fuel consumption are key parameters that can be considered in the application of nanofuels. Capable fluids have promising attractions regarding above-mentioned considerations.

Wear effects of nanofluids on materials of the car coolant system

The present section reports the main contributions of few researches found in the literature about how nanofluids react with the radiator material, or with all the other components of the cooling system of the car engine such as the pump, the pipes, the engine block and the cylinder head. In fact, few studies are related to the eventual reactions between nanofluids and radiator's materials. The procedure used on these tests is based on the calculation of the mass loss under different impact angles and fluid velocity. Celata et al. [109] investigated the effects of nanofluids

Table 4 Nanofluid applied on car engine as fuel or coolant

Type of Nanofluid	Particles concentration	Applied on	Finding	References
MWCNT-MgO /Engine oil	0.0625, 0.125, 0.25, 0.5, 0.75 and 1 vol%	Engine oil	The increase in the temperature from 25 to 50 °C push down the dynamic viscosity of the hybrid nanofluid by 75%. However it increases with an increase in the solid volume fraction	Alirezaie et al. [82]
ZnO-MWCNT/10W40 engine oil	0.05 – 1 vol% [83]	Engine oil	This lubricant based on hybrid nanofluids is shear-thinning non-Newtonian fluid. When the solid volume fraction increases, the power law index drops slightly [83]	Esfe et al. [83]
	0.05—0.8 Vol % [84]		The thermal conductivity is enhanced if the temperature and nanoparticle concentration increase [84]	Wu et al. [84]
Al_2O_3-MWCNT/10W40 engine oil [85]	0.05, 0.1, 0.25, 0.5 and 1 vol.% [85]	Engine oil	Adding Al_2O_3-MWCNT in engine oil enhanced 30.35% the thermal conductivity. This positive effect is amplified under higher temperatures [85]	Tian et al. [85]
Al_2O_3-Fe_2O_3/10W40 engine oil [86]	0.25, 0.5, 1, 2, and 4 vol% [86]		33% is the largest improvement of the thermal conductivity recorded at a mass fraction of 4 vol% [86]	Sulgani et al. [86]
Cr_2AlC/5 W-30 engine oil	0.5 vol%	Engine oil	An enhancement by 3 times denoted in anti-wear properties and oil film strength (OFS) of the base oil. Cr_2AlC added to engine oil reduces considerably the friction coefficient	Davis et al. [87]
ZnO/SAE 50 engine oil	0.125—1.5 vol%	Engine oil	The thermal conductivity is enhanced if the temperature and nanoparticle concentration increase	Yang et al. [88]
MWCNT-ZnO/5W50 engine oil [89]	Up to 1 vol%	Engine oil	For lubrication goals, MWCNT-ZnO added to engine oil gives better engine performances especially in higher temperature and during the cold start because of the reduction in viscosity [89]	Esfe et al. [89] [90]
MWCNT-ZrO_2/5W50 engine oil [90]			MWCNT-ZrO_2 (at 0.05 vol %) offer 20% decrease in viscosity compared to MWCNT-ZnO and with base oil [90]	
MoS_2/20W40 engine oil [91]	0.2, 0.1, 0.5 and 0.025 vol% [91]	Engine oil	Dispersing MoS_2 nanoparticles in engine oil reduces remarkably the friction coefficient by 15.3% (at 0.025 vol%) and improve the anti-wear properties [91]	Devan et al. [91]
MoS_2-WS_2 inorganic fullerenes/Engine oil [92]	0.1–2 vol% [92]		Reduction in fuel consumption and a general improvement of the emission abatement compared to base engine oil [92]	Sgroi et al. [92]
Al_2O_3/gear oil	0.5—2 vol%	Gear oil	Spherical alumina nanoparticles are more efficient for gear lubrication at high speed in term of reduction in temperature and friction coefficient at the contact between gears	Huang et al. [93]
			The increase in nanoparticle concentration decrease the friction coefficient and the temperature at the contact zone, increases film tangential stiffness. However, concentration has a less effect on normal stiffness and film thickness	

Table 4 (continued)

Type of Nanofluid	Particles concentration	Applied on	Finding	References
Ni-MoS_2/Gear oil	0.5 vol%	Gear oil	The interaction between Ni and MoS_2 nanosheets in the gear oil improves the thermophysical behavior which leads to a better tribo-chemical film in the contact zone between gears which reduces remarkably the friction in this zone that improve the life cycle of the gearbox	Rajendhran et al. [94]
CuO/API GL-5 gear lubricant sol	0.1, 0.3 and 0.5 vol%	Gear lubricant sol	The uniform distribution of CuO nanoparticles improves the thermos-stability of the gear lubricant up to 0.3 mass%. and apparition of agglomeration above 0.3 mass% which reduces the thermos-stability	Maheswaran et al. [95]
Fe_3O_4 in diesel fuel	0.4, 0.8 vol.%	Diesel fuel	The optimal fuel consumption is denoted for 0.4 vol% nanoparticules concentration in diesel fuel. However, a dramatic drop in NOx and SO_2 emissions, and a remarkable increase in CO emission and smoke opacity is denoted	Sarvestani et al. [96]
TiO2/mustard oil methyl ester	100 and 200 ppm	Biodiesel fuel	TiO_2 nanoparticles added to biodiesel (mustard oil methyl ester) reduces various emissions and can be an alternative fuel	Yuvarajan et al. [97]
TiO2/biodiesel (AC BDD)	50, 100, 150 and 200 mg/l	Biodiesel fuel	It is denoted that considering a TiO_2 dope of 150 mg/l, 82.37% engine load and an injection timing of 22.5°CA btdc. The brake specific fuel consumption (BSFC) is improved by 18.42%, the brake thermal efficiency (BTE) by 3.25%, 7% for ignition delay (ID), 38% hydrocarbon (HC) and 20% in smoke emissions A slightly increase in NOx emissions is remarked in comparison with diesel	Saxena et al. [98]
Al_2O_3 CNTs, TiO_2/Jatropha biodiesel	25, 50, and 100 ppm	Biodiesel fuel	The suspension of Al_2O_3 in Jatropha biodiesel enhance 6.5% the thermal efficiency The suspension CNTs in Jatropha biodiesel decrease 35% the CO emission and 52% NOx emissions TiO_2 reduces 22% HC and 50% smoke emissions	Gad et al. [99]
TiO_2/orange peel oil biodiesel	50 and 100 ppm	Biodiesel fuel	Using the OOME-T100 a remarkable reduction of smoke, NOx, CO and HC emissions is denoted and an increase in the BTE of the engine compared to 50-ppm suspension and pure orange peel oil biodiesel	Kumar et al. [100]
Al_2O_3/honge oil methyl ester and diesel fuel	20, 40, and 60 ppm	Biodiesel fuel	Al_2O_3 nanoparticles added to biodiesel enhance the engine performance, combustion and reduce CO, HCs, and smoke emissions. 40-ppm suspension give the best results	Soudagar et al. [101]

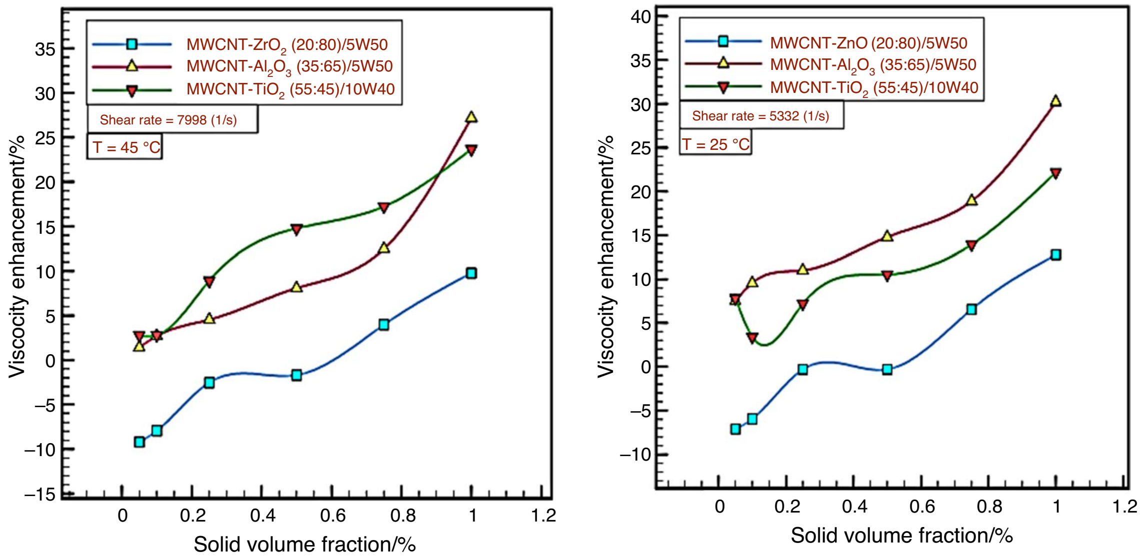
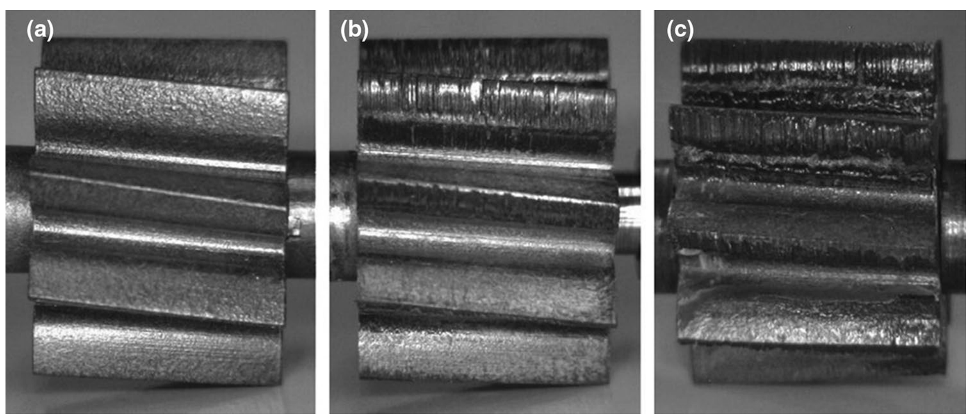


Fig. 14 Viscosity enhancement in function of nanoparticles volume concentration [89]

Fig. 15 Abrasion of the PTFE gear: new gear (**a**), using TiO2 (**b**) and using Al_2O_3 (**c**) [109]



flow on metal (copper, stainless steel, aluminum) surfaces. The action of several nanoparticles such as Al_2O_3, SiC, TiO_2 and ZrO_2 has been analyzed. Authors remarked that stainless steel has the best resistance to nanofluids flow; however, the aluminum is the weakest material especially in the case of Al_2O_3 nanoparticles addition. From the observation of the effects of the nanoparticles on pump gears, it is denoted that Al_2O_3 nanoparticles caused the most serious damage as it is presented in Fig. 15, while TiO_2 nanoparticles remain the less effect.

Bubbico et al. [110] proved through experimental investigations using the same materials and the same nanoparticles that the material damage is caused by chemical corrosion rather than by mechanical erosion, which can be solved by maintaining the pH of suspension within the passivation range, at this time aluminum material can resist to the nanofluid flow reactions. Aktaruzzaman [111] has taken a measurement of the normalized Ra roughness

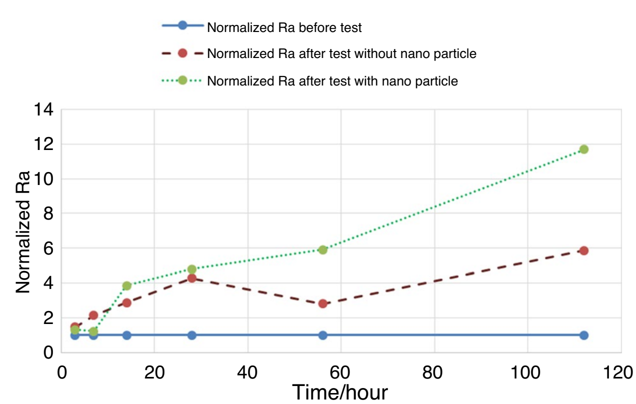


Fig. 16 Effect of Al_2O_3/water nanofluid on surface roughness for 3003-T3 aluminum [111]

for 3003-T3 aluminum after a several hours of treatment with Al_2O_3/distilled water nanofluid (2 vol% and 10.7 m/s

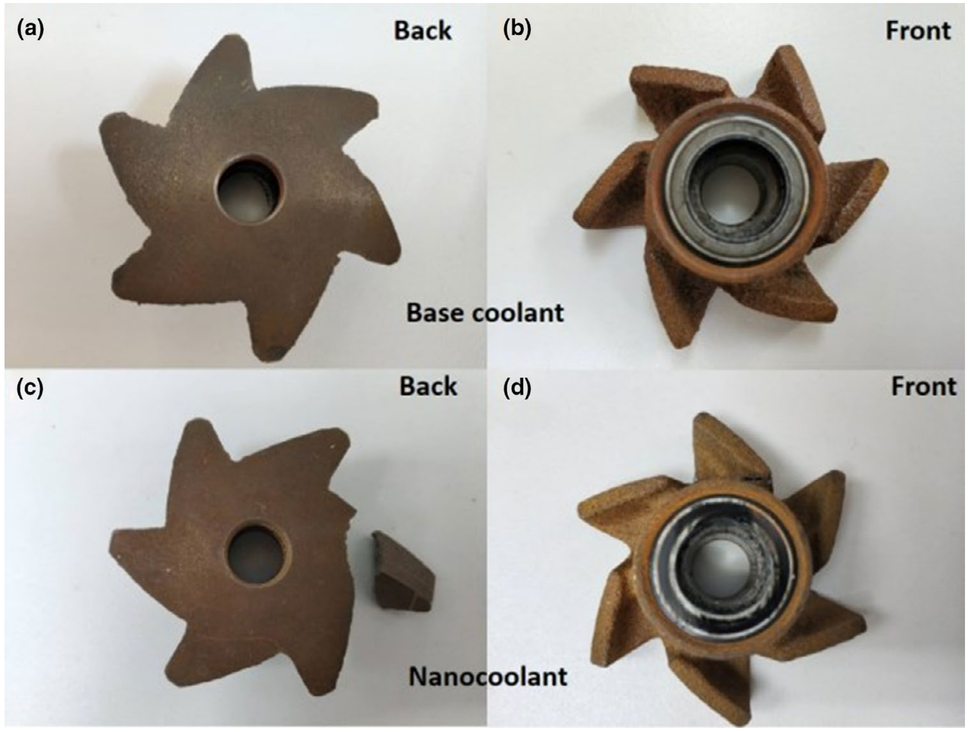


Fig. 17 Views of impeller for base coolant (**a**), (**b**) and nanocoolant (**c**), (**d**). [114]

jet speed). The result plotted in Fig. 16 marks a decrease in the surface state caused by the action of nanofluid flow. In fact, the normalized roughness is increased by 50% compared to the action of flow without alumina nanoparticles. A.M Mohammed [112] proved that the suspension of Cu in a distilled water decreases the cavitation phenomenon. Properties of nanomaterials and their effects on the erosion–corrosion behavior due to the cavitation phenomenon cause pipe wall erosion. Gandham et al. [113] conducted a study of corrosion resistance in automotive coolant system, measured in terms of mass loss of materials. Based on this study, authors recommended the use of oxidized MWCNTs in automotive systems, while silver and Al_2O_3 nanoparticles produce a higher wear rate than the base fluid. Xian et al. [114] studied the erosion–corrosion of an aluminum impeller of a water pump subjected by nanofluid (GnP/Water-EG) flow. It was observed that nanocoolant favors the erosion–corrosion, which increases the wear of the impeller as denoted in Fig. 17. However, no remarkable difference in the corrosion effect is found between base coolant and nanocoolant.

It is very important in these types of investigations to analyze a wide range of nanocoolant by varying the volume concentrations, the flow rate, temperature, etc., at the aim to understand which type of nanocoolant causes higher wear rate. It is necessary to analyze the wear of all the coolant system components, certainly those having the highest maintenance cost. The initiation of further researches to assess wear and damage of materials in the engine bloc and cylinder heads is very important, which is needed for better mastery of the technology of nanocoolant and which type leads to the best thermal performances without damaging the principal components of a coolant system such as the pump, the radiator, the engine bloc, the cylinders.

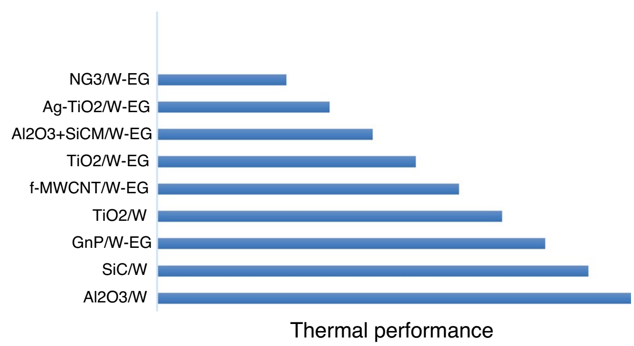


Fig. 18 Classification of nanocoolant in term of thermal performance

Discussions

Analyzing the previous sections, it is clear that nanofluids applied as coolant in a car radiator demonstrated better efficiency due to their higher thermal conductivity compared to conventional coolants. Nanocoolant pushed up the performance of the radiator at higher level and opened

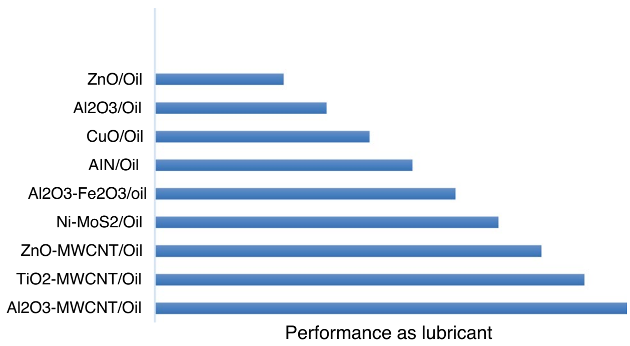


Fig. 19 Classification of nanofluids tested in car engine and transmission

the possibility in future to improve the design of radiators to be smaller and lighter by integrating less components needed for cooling or circulating the nanocoolant, which will decrease the manufacturing and maintenance costs of this car subsystem and leading to better fuel consuption and gase's emissions. Analyzing carefully the different studies presented in Sect. 2.1, a classification of nanocoolant is drawn in Fig. 18 in terms of order of thermal performance. This classification is based on different comparisons presented in [25–76].

In the application of nanofluid in a car radiator, common findings can be highlighted as follows:

- The thermal performance of the car radiator increases when the nanoparticle volume concentration, Reynolds number, the viscosity, and the inlet temperature increase. Commonly, the overall heat transfer coefficient of the car radiator is enhanced at higher nanoparticles concentrations.
- The use of nanofluids with high thermal conductivity gives the possibility to automotive engineers to reduce the exchange area of the car radiator which leads to the reduction in the fuel consumption by improving the aerodynamic effects of the car. By using nanocoolants, the design of the radiator can be improved to be smaller, lighter and integrating less components needed for cooling fluids, which will reduce the manufacturing and maintenance costs of this car subsystem.

Some limitations noted can be cited as follows:

- The use of classic method of dispersion can cause a problem of agglomeration and oxidation induced by metallic nanoparticles. However, the turbulent flow regime is preferred to avoid sedimentation and agglomeration of nanoparticles and thus enhances the performances
- The use of nanofluids as coolant causes more pressure drop, which is explained by the increase in viscosity which requires more pumping power and limits the radiator performances.
- Some contradictory conclusions especially about the effect of nanofluids volume fraction on pumping power loss and the Nusselt number are encountered, which requires further investigation at the aim to find the best nanocoolant that can be safe used in a car radiator.

Figure 19 plots a classification of several nanofluids tested as lubricant in a car engine or a car transmission system. This classification is based on the different studies presented in [77–95]. It is remarked that hybrid nanofluid gives better performance to these system by reducing friction and improving the heat transfer coefficient. Generally, the viscosity nanolubricants should have an optimal value which guaranties the best lubricant film between components in order to reduce friction, which prevents the material wear and helps the lubricant flow.

The tests of nanoparticles suspension in fuels remain few, as said previously in Sect. 2.2.2. However, one can note that TiO2 nanoparticle added in biofuel seems to be the best in terms of toxic gases emissions and in terms of engine performance enhancement. Nevertheless, some mechanical problems should be analyzed when using nanofluids in fuel. In fact, some mechanical defects can happen in the injection system (injectors, pump, and pipes) for example, which usually have a high maintenance cost.

During the last few months, some findings have been published about new nanofluid fuel. Ao et al. [115] mixed kerosene and nano-aluminum (n-Al) particles coated with polydopamine (PDA) at the aim to improve the stability of combustion. Promising results have been presented proving that n-Al/kerosene coated with PDA is the better choice in terms of combustion stability compared to uncoated n-AL/kerosene and other PDA-coated nanofluids. In similar investigation, Gao et al. [116] studied the combustion of n-Al/CuO kerosene fuels coated with PDA. Suozhu et al. [117] noted an enhancement of combustion in engines operated with methanol mixed with CeO_2 nanoparticles. The NOx and smoke emissions decreased by 70.9% and 90.3%, respectively, compared with the diesel mode. In fact, the environmental impact of the combustion of nanoparticles mixed in fuel is a key parameter that needs further development in this field.

Conclusions

The present paper reported a literature review on the use of nanofluids in applications related to automotive during the recent years. Applications of several nanofluids in car radiator, engine, transmission systems and fuel mixture are comprehensively reviewed in the different sections. As novelty, the paper highlighted new tested nanofluids with critics of their efficiency, their wear effects on components of the car engine, their environmental impact in terms of gases emissions when nanoparticles are added to fuels. Based on deep analysis of vast number of available references, a classification of nanofluids within their efficiency to enhance the performance of these subsystems is drawn. For engine cooling system, nanofluids can be used (1) as coolant in the car radiator. Due to the high thermal conductivity of nanoparticles, the heat transfer coefficient in the system can be enhanced with variable percentage in function of the type and the volume concentration. The main drawback is that nanocoolants cause more pressure drop, which is explained by the increase in viscosity which requires more pumping power and limits the radiator performance, which pushed the majority of researchers to use low nanoparticle volume concentrations. Some discrepancies in the determination of the optimal value of volume fraction and the precise heat transfer enhancement is remarked through this literature review. In addition, the use of classic methods of dispersion causes a limitation of agglomeration and oxidation impelled by metallic nanoparticles. (2) Dispersed in engine or gearboxes oils, several nanoparticles lead to a reduction in friction coefficient and prevent wear and damage of the mechanical components. Hybrid nanolubricant such as Al_2O_3-MWCNT/oil presented the best performances as coolant. It is to be noted that, further detailed studies are required to determine the optimal values of viscosity that guaranties the best lubricant film between components. Finally, nanoparticles mixed with fuel such as diesel, biodiesel and kerosene could enhance the combustion heat, reduce smoke and NOx from the engine emissions which improve the environmental impact of fuels. Current research on nanofuels is still at its initial steps and needs further development.

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