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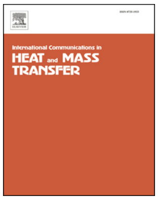

A review on the application of nanofluids in vehicle engine cooling system☆

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ABSTRACT

This paper reviewed the application of nanofluids in vehicle engine cooling system. So far, nanoparticles have been used in engine oil, transmission oil, and radiator coolant to enhance heat transfer removal from vehicle engine. The heat transfer performance of nanofluids has been reported to perform better compared to pure fluid. This review focused on the experimental and numerical studies by previous researchers and their suggested amount of nanoparticles for optimum performance in vehicle engine cooling system. Finally, the conclusions and important summaries were presented according to the data collected.

1. Introduction

The last few decades have witnessed vast research on the new types of heat transfer fluids, namely nanofluids. A nanofluid is a fluid which contains nanometer-sized solid particles. Nanofluids were introduced by Choi [1] and they have been proven to provide efficient heat transfer compared to conventional fluids. Detailed reviews on the physical and thermal properties of nanofluids have been reviewed by several authors [2–5]. Since its first introduction to actual engineering applications [6–9], a nanofluid has been successfully applied to enhance heat transfer in many applications such as electronic components [10–12], nuclear reactor [13–15], building heating and cooling systems [16–19], water boiling [20], and many more [21–26].

A nanofluid can be produced by dispersing a typical size of less than 100 nm of metallic or non-metallic nanoparticles or nanofibers in a base liquid. The presence of nanoparticles in the base fluids contributes better flow of mixing and higher thermal conductivity compared to pure fluid. A novel study by Masuda [27] revealed that the dispersion of γ-Al_2O_3 particles at 4.3 vol.% can increase the effective thermal conductivity of water by almost 30%. Since then, many studies have been carried out to investigate the enhancement of thermal conductivity for other potential nanoparticles. Eastman et al. [28] experimentally proved that 5 vol.% of nanocrystalline copper oxide particles suspended in water resulted in an improvement of thermal conductivity for almost 60% compared to pure water. For the purpose of measuring the performance of nanofluids with oxide nanoparticles, Lee and his co-workers [29] have conducted a transient hot-wire experimental technique to determine the thermal conductivity of Al_2O_3 and CuO nanofluids. Good agreements were obtained when compared with Hamilton and Crosser's thermal conductivity model. Using the same experimental set-up, Li et al. [30] measured the thermal conductivity of boron nitride/ethylene alcohol nanofluids. They concluded that thermal conductivity enhancement of nanofluids increased with the increment of nanoparticle volume fraction, aspect ratio of nanoparticles, the size of nanoparticles, and temperature of nanofluids. Ho et al. [31], Godson et al. [32], Duangthongsuk and Wongwises, [33], Lee et al. [34], Mahbubul et al. [35], Lelea and Laza [36], and Zakaria et al. [37] also found similar results indicating the enhancement of thermal conductivity of various nanofluids. However, surprisingly, a few researchers have found insignificant improvement of thermal conductivity as shown by Putnam et al. [38], Zhang et al. [39], Eapen et al. [40] and Timofeeva [41]. Recently, Wang et al. [42] have provided an excellent review on the effects of several parameters to determine the effective thermal conductivity of nanofluids.

Some literature has investigated the applicability of nanofluids in vehicle engine cooling system. With the purpose to increase the efficiency of heat removal from the engine, nanoparticles have been dispersed into conventional coolants (water, ethylene glycol, and glycerol) and their performance has been acknowledged by many researchers. However, there are some discrepancies in the reported findings, especially in the optimum amount of nanoparticles, percentage of improvement, novel type of nanoparticles, and others. Therefore, in the present paper, we attempt to thoroughly review the application of nanofluids in vehicle cooling system that has been published previously. To the best of authors' knowledge, there is no comprehensive literature on the subject.

2. Engine coolant and vehicle radiator system

Radiator system plays a vital role in preventing the vehicle engine from overheating due to friction. Conventionally, a car radiator pumps

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water as the heat transfer medium through the chambers within the engine block to absorb the heat and spread it away from other important parts. A radiator is designed with louvered fins so that additional heat transfer at the surface area can be created and interrupt the growth of a boundary layer formed along the surface.

In countries with extreme weather conditions, antifreeze is used as an additive to lower the freezing point or elevate the boiling point of a liquid. Since water has good properties as a coolant, the mixture of water as a base liquid with glycol family, especially ethylene glycol (EG) at various percentages depends on the weather conditions. The properties of pure EG and water, and water-based EG with various mixing ratios are shown in Table 1 and Table 2.

The last few decades have witnessed a rapid development of vehicle engine performance. Engine manufacturers have been competing with each other to meet customers' demands in producing high-efficiency engine at low cost. However, low thermal conductivity of engine coolant limits the cooling efficiency of a vehicle radiator, which makes it difficult in maintaining the compact size of the cooling system. In addition, increasing the cooling rate by traditional technologies (i.e. fins and microchannel) has already reached their limits. One of the innovative efforts to enhance heat transfer in an automotive car radiator is by using a new type of coolant which is called nanocoolant.

Nanocoolant, which consists of the dispersion of nanomaterials in a traditional coolant, has been considered in actual applications since early 2000s. Interestingly, the literature records show that automotive radiator was the pioneer complex system that used nanocoolant for cooling technology [43]. Choi and his co-workers [43] have experimentally measured the thermal conductivity of metallic and oxide, ethylene glycol-based nanofluids using a transient hot wire method. They claimed that the measured thermal conductivity was much higher than the predicted ones. Their finding is in agreement with the study by Maranville et al. [44] who measured the thermal conductivity of water and ethylene glycol/water-based metal oxide nanofluids using a transient planar source method. However, the problems of agglomeration and oxidation of metallic nanoparticles remain unsolved. A year later, by using differential scanning calorimetry, Goldenstein et al. [45] proved that the addition of nanoparticles to water leads to high thermal diffusivity of nanofluid. This excellent characteristic as a coolant can be applied to any system that needs a quick response to thermal changes, such as a vehicle radiator.

3. Experimental research on real vehicle engine

Experimental investigation on the performance of nanofluid in vehicle cooling system of an actual car engine was initiated by Tzeng et al. [46]. They investigated the performance of CuO, Al_2O_3 nanoparticles, and antifoam when added to transmission oil. The engine run at four different rotating speeds (400 rpm, 800 rpm, 1200 rpm, and 1600 rpm) and Mazda's four-wheel-drive (4WD) transmission system was used as the test vehicle. They found that among the tested nanoparticles and antifoam, CuO gave the best heat transfer effect and had the lowest heat transfer distribution for all rotating speeds.

Zhang et al. [47] tested the effect of the addition of nanographite in heavy-duty diesel engine coolant. They found that the cooling capability increased by 15% when 3 vol.% of nanographite was added to the coolant. The effect of nanofluid coolant in a truck engine has been studied by Saripella et al. [48]. 50/50 mixture of ethylene-glycol and water was used as the base fluid and 2 vol.% and 4 vol.% of CuO particles were added to investigate the effect on engine's temperature, pump's speed, and power. The authors inferred that the addition of nanographite contributed to the reduction of pump speed up to a factor of two to give the same amount of heat rejection without nanographite. This resulted in the reduction of power consumption of a truck engine.

Table 1
Properties of pure ethylene glycol and water.

	Ethylene glycol	Water
Density (g/cm^3)	1.1132	1.0
Molar mass (g/mol)	62.07	18.02
Freezing point (°C)	−12.9	0
Boiling points (°C)	197.3	100
Viscosity (Ns/m^2)	1.61×10^{-2}	1.002×10^{-3}
Thermal conductivity (Wm/K)	0.258	0.609

Table 2
Freezing and boiling points of water/EG vs. concentration of EG.

Percentage of EG in water	Freezing point (°C)	Boiling point (°C)
0	0	100
10	−4	102
20	−7	102
30	−15	104
40	−23	104
50	−34	107
60	−48	110
70	−51	116
80	−45	124
90	−29	140
100	−12	197

The most recent experimental investigation on an actual vehicle cooling system was conducted by Ali and his co-workers [49]. They attempted to investigate the characteristics of forced convection heat transfer in Toyota Yaris radiator filled with Al_2O_3–water nanofluid. They concluded that the heat transfer coefficient reached its optimum only when the volume fraction was 1%. Increasing the volume fraction would deteriorate the performance of the radiator cooling system.

3.1. Other experimental research on nanofluid for engine cooling

Other than the experimental studies on the actual car engine discussed above, many researchers have set up experimental test rig and performed experimental research which are similar to the condition of actual engine vehicles. Mohammadi et al. [50] studied the enhancement of thermal conductivity when γ-Al_2O_3 and CuO are dispersed in engine oil. They claimed that the addition of 2 vol.% γ-Al_2O_3 and CuO could increase the thermal conductivity up to 5% and 8% respectively. Kole [51] extended the study by varying the temperature and found the enhancement of thermal conductivity was 4.2% and 4.5% for the temperature at 30 °C and 50 °C respectively. However, their experiment was restricted to 1.5 vol.% of Al_2O_3 nanoparticles.

The thermal conductivity of 3 vol.% of aluminum components in the engine oil has been determined by Vasheghani [52]. The researcher reported that aluminum nitride behaves exceptionally with thermal conductivity enhancement of 75.23%, followed by γ-Al_2O_3 and α-Al_2O_3 with 31.47% and 26.1% respectively. Prior to that, Kole [53] found that the enhancement of thermal conductivity was 10.4% when 3.5 vol.% of Al_2O_3 nanoparticles was dispersed in the engine coolant.

Knowing that excessive volume fraction of nanoparticles tends to deteriorate the engine performance, Ettefaghi et al. [54] investigated the effect of the dispersion of precisely 0.5 vol.% multi-walled carbon nanotube in engine oil. As much as 22.7% of thermal conductivity enhancement was reported. With the same objective, Elias et al. [55] conducted an experimental research on the dispersion of 1 vol.% of Al_2O_3 nanoparticles in water and ethylene glycol-based coolant used in a car radiator. 8.3% of thermal conductivity enhancement was achieved in their study. More recently, Chougule and Sahu [56] studied the cooling performance of an automobile radiator using Al_2O_3–water and carbon nanotube–water nanofluid. They summarized that the thermal conductivity could be enhanced up to 38% with 0.6 vol.% of nanoparticles.

The dispersion of nanoparticles in a base fluid does not only contribute to the enhancement of thermal conductivity, but also due to a greater heat transfer area, superior convective heat transfer coefficient can be achieved, which will also lead to the enhancement of heat transfer. To

Table 3
A summary of experimental studies of nanofluid for vehicle system cooling.

Authors	Nanofluids	Findings
Tzeng et al. [46]	CuO, Al_2O_3, antifoam–transmission oil	CuO gave the best heat transfer effect and had the lowest heat transfer distribution for all rotating speeds.
Zhang et al. [47]	CuO–coolant	Cooling capability of nanofluid with 3.0 vol.% of nanoparticle concentration was increased by 15%.
Saripella et al. [48]	CuO–EG/water (50:50)	Higher heat transfer coefficients of nanofluids resulted in lower engine and coolant temperatures as well as improved the engine power, coolant pump speed, and power.
Ali et al. [49]	Al_2O_3–water	Heat transfer coefficient achieved its maximum at 1 vol.% of nanoparticle concentration. The maximum enhancement of coolant heat transfer rate, heat transfer coefficient, and Nusselt number was 14.79%, 14.72%, and 9.51%, respectively.
Mohammadi et al. [50]	γ-Al_2O_3–engine oil, CuO–engine oil,	The maximum enhancement of thermal conductivity of γ-Al_2O_3–engine oil nanofluid was 5%, whereas CuO–engine oil nanofluid was 8% with 2.0 vol.% of respective nanoparticle concentrations.
Kole and Dey [51]	Al_2O_3–EG	Maximum enhancement of thermal conductivity of 4.5% with 1.5 vol.% of Al_2O_3 nanoparticles was at 50 °C.
Vasheghani [52]	AlN–engine oil, α-Al_2O_3–engine oil, γ-Al_2O_3–engine oil	With an addition of 3.0 vol.% of nanoparticles, the thermal conductivity maximum enhancement of the AlN nanofluid was 75.23% followed by γ-Al_2O_3 (20 nm) nanofluid, α-Al_2O_3 (20 nm) nanofluid, and α-Al_2O_3 (100 nm) nanofluid with 37.49%, 31.47% and 26.10% respectively.
Kole and Dey [53]	Al_2O_3–EG	The maximum enhancement of thermal conductivity of the nanofluids was 11.25% with 3.5 vol.% of Al_2O_3 nanoparticles at 80 °C.
Ettefaghi et al. [54]	MWCNT–engine oil	Maximum enhancement of thermal conductivity of the nanofluids was 12.7% with 0.5 vol.% of MWCNT nanoparticles at 20 °C.
Elias et al. [55]	Al_2O_3–EG/water (50:50)	The maximum enhancement of thermal conductivity of the nanofluids was 8.3% with 1.0 vol.% of Al_2O_3 nanoparticles at 50 °C.
Chougule and Sahu [56]	Al_2O_3–water, CNT–water	The maximum enhancement of thermal conductivity of the CNT–water nanofluids was 76%, whereas Al_2O_3–water nanofluid was 18% with 1.0 vol.% of respective nanoparticles at 80 °C. With 1.0 vol.% of nanoparticles, the maximum enhancements of heat transfer of the CNT–water nanofluids and Al_2O_3–water nanofluid were 90.76% and 52.03%, respectively higher compared to water only.
Peyghambarzadeh et al. [57]	Al_2O_3–water	Maximum enhancement of thermal conductivity of nanofluids was 3.0% with 1.0 vol.% of Al_2O_3 nanoparticles. However, with 1.0 vol.% of nanoparticles, maximum enhancement of heat transfer of the nanofluids was 45% when compared to water only.
Peyghambarzadeh et al. [58]	Al_2O_3–water, Al_2O_3–EG, Al_2O_3–EG/water (5–20 vol.% of EG)	With 1.0 vol.% of nanoparticles, the maximum enhancement of heat transfer of the nanofluids was 40% when compared to pure fluid.
Chavan and Pise [59]	Al_2O_3–water	The maximum enhancement of thermal conductivity of the Al_2O_3–water nanofluids was 3% with 1.0 vol.% of nanoparticles. With the addition of 1.0 vol.% of nanoparticles, the maximum enhancement of heat transfer of the nanofluids was 40–45% when compared to pure fluid.
Raja et al. [60]	Al_2O_3–water	Maximum overall enhancement of heat transfer coefficient of the nanofluids was 25% with 2.0 vol.% of nanoparticles at Peclet number of 3000 and no load compared to pure water. NOx emission was reduced by 12.5% with 2.0 vol.% of nanoparticles compared to pure water.
Zhong et al. [61]	Al_2O_3–water, Al_2O_3–EG, Al_2O_3–EG/water	The maximum enhancement of heat transfer coefficient of nanofluids was 6.52% with 5.0 vol.% of nanoparticles compared to pure water.
Teng and Yu [62]	MWCNT–EG/water (50 vol.% of EG)	Maximum enhancement of thermal conductivity of the MWCNT–EG/W nanofluids was 49.6% with 0.4 vol.% of nanoparticles compared to EG/W. Maximum efficiency factor was 14.1% at low concentration of MWCNT nanoparticle.
Nieh et al. [63]	Al_2O_3–EG/water (50 vol.% of EG), TiO_2–EG/water (50 vol.% of EG)	The thermal conductivity of Al_2O_3 nanocoolant and TiO_2 nanocoolant was similar and about 24–39% higher than EG/water at all nanoparticle concentrations. Maximum efficiency factor was 27.2% using TiO_2–EG/water with 2.0 vol.% nanoparticle concentration whereas it is 14.4% using Al_2O_3–EG/water with 2.0 vol.% nanoparticle concentration compared to EG/W.
Leong et al. [64]	CuO–EG	An additional 12.13% is required to pump the power for the radiator using nanofluids with 2 vol.% compared to pure EG. Maximum heat transfer rate of nanofluids was enhanced about 3.8% compared to pure EG.
Sarkar and Tarodiya [65]	CuO, SiC, Al_2O_3, TiO_2–EG/water (80% water, 20% EG)	Maximum heat transfer rate improvement for SiC was 15.34%, whereas for Al_2O_3 was 14.33%, for TiO_2 was 14.03%, and for CuO was 10.20% with 1.0 vol.% of nanoparticle concentration compared to pure base fluid.
Heris et al. [66]	CuO–EG/water (40:60)	The heat transfer enhancement of 0.8 vol.% of CuO–EG/water was about 55% compared to the base fluid.
Kole and Dey [67]	CuO–EG/water (50:50)	Addition of a small amount of alumina nanoparticles (up to 0.4 vol.%) has transformed it into a non-Newtonian fluid.
Peyghambarzadeh et al. [68]	CuO–water, Fe_2O_3–water	Heat transfer coefficient was enhanced up to 9% at 0.65 vol.% nanoparticle concentration in comparison with water.
Liu et al. [69]	Nanodiamond–engine oil	Nanofluid increases the engine performance by maximizing the engine power and torque up to 1.15% and 1.18% respectively; while decreasing the fuel consumption relatively to 1.27% as compared to the engine oil.
Naraki et al. [70]	CuO–water	Overall heat transfer coefficient enhancement of nanofluids was about 8% at 0.4 vol.% CuO concentration compared to pure water.
Hussein et al. [71]	TiO_2–water, SiO_2–water	The heat transfer rate enhancement was 20% and 32% for TiO_2 and SiO_2 nanofluids respectively.
Hussein et al. [72]	SiO_2–water	The maximum enhancement of heat transfer nanofluid of 2.5 vol.% nanoparticle concentration was 46%.
Hussein et al. [73]	SiO_2–water, TiO_2–water	Maximum Nusselt number enhancements for TiO_2 and SiO_2 nanofluids were 11% and 22.5% respectively compared to pure water.
Ebrahimi et al. [75]	SiO_2–water	Maximum heat transfer enhancement of nanofluid was 9.3% with 0.4 vol.% of nanoparticle and the concentration was at 60 °C.

prove this, Peyghambarzadeh et al. [57,58], and Chavan and Pise [59] have considered to disperse 1 vol.% of Al_2O_3 nanoparticles in water and obtained a heat transfer enhancement of 45% when compared to water only. Interestingly, Chougule and Sahu [56] performed a similar experimental research and claimed that they obtained heat transfer enhancement as high as 52.03%.

Other studies by Raja et al. [60] and Zhong et al. [61] have examined the performance of alumina water at different ranges of nanoparticle volume fractions. Raja et al. [60] demonstrated that the maximum enhancement of heat transfer coefficient of 25% was obtained at 2 vol.%. However, Zhong et al. [61] achieved an enhancement of only 6.52% at 5 vol.% compared to water. Again, this indicates the deterioration of heat transfer at high volume fraction of nanoparticles.

Many experimental studies of nanocoolant with ethylene glycol as the base fluid have been conducted by many researchers. Teng and Yu [62] have investigated the performance of MWCNT nanocoolant and

Table 4
Summary of numerical studies on nanofluid for vehicle system cooling.

Authors	Nanofluids	Findings
Lv et al. [76]	Cu–water, Cu–oil engine	Heat transfer coefficient and heat dissipating capacity enhancement of Cu–water nanofluid with 5.0 vol.% of nanoparticle concentration were about 46% and 43.9% more than pure water.
Vajjha et al. [77]	Al_2O_3–EG/water (60:40), CuO–EG/water (60:40)	Addition of 10 vol.% Al_2O_3 led to 94% enhancement of heat transfer coefficient, whereas 6 vol.% CuO achieved 89% enhancement compared to base fluid.
Huminic and Huminic [78]	Cu–EG	A maximum enhancement of heat transfer coefficient of 82% was obtained when Reynolds number was 125.
Vajjha et al. [79]	Al_2O_3–EG/water (60:40), CuO–EG/water (60:40)	At Reynolds number of 5500, the percentage increment of the average heat transfer coefficient over the base fluid for 3 vol.% Al_2O_3 nanofluid was 36.6% and for a 3 vol.% CuO nanofluid was 49.7%.
Huminic and Huminic [80]	CuO–EG	The convective heat transfer coefficient for nanofluid was higher than pure EG. In all Reynolds number and nanoparticle concentrations, the heat transfer coefficient for flattened tubes was more than elliptic and circular tubes.
Abbasi and Baniamerian [81]	Al_2O_3, Au, CuO, TiO_2–water/vapor	Heat transfer coefficient decreases along the flow as the vapor quality increases. In two-phase flow, the heat transfer coefficient enhancement for Al_2O_3 was the highest followed by TiO_2, Au, and CuO nanofluids.
Hatami et al. [82]	CuO–water, Fe_2O_3–water, TiO_2–water, EG/water (50:50)	TiO_2–water nanofluid can enhance 10% of heat recovery without any pressure drop followed by Fe_2O_3–water and CuO–water nanofluid compared to EG/water.
Delavari and Hashemabadi [83]	Al_2O_3–water, Al_2O_3–EG	Nusselt number for two-phase approach was 10%–45% greater and closer to the experimental data than the single-phase approach.

found an efficiency factor (heat exchange capacity / pumping power) of 14.1%. In their study, the ratio of nanofluid and ethylene glycol was 50/50 and was limited to low volume fraction of nanoparticles. They also found that high concentration of nanocoolant could not achieve better performance due to the uneven distribution of nanoparticles. In another study, Nieh et al. [63] found that the efficiency factor for 0.2 vol.% of TiO_2 nanofluid in ethylene glycol with 50/50 ratio was 27.2%.

Other experimental research studies on the performance of vehicle cooling system can be seen elsewhere [64–78]. A summary of experimental research is shown in Table 3.

4. Numerical studies on nanofluid application for vehicle engine cooling

Recent advanced developments in computer and computational schemes have attracted the interest of many researchers in computational physics. Unlike conventional experimental approach, computational or numerical predictions allow more comprehensive research to be conducted at low cost. Numerical studies on nanofluids have become the alternative approach to demonstrate their superior performance to traditional heat transfer fluids.

In 2010, Lv et al. [76] had predicted the improvement of heat transfer in internal combustion engine by the application of 5 vol.% of Cu nanoparticles. Using Star-CD commercial software, they found that the enhancement of heat transfer coefficient was 46% compared to pure fluid.

In another study by Vajjha et al. [77], they conducted numerical prediction using Fluent software on the fluid dynamics and heat transfer performance of Al_2O_3 and CuO nanofluids in the flat tubes of a radiator. Their results demonstrated that at Reynolds number of 2000, the addition of 10 vol.% Al_2O_3 led to 94% enhancement of heat transfer coefficient, whereas 6 vol.% CuO achieved 89% enhancement compared to pure water.

The use of nanofluids in flattened tube was studied by Huminic and Huminic [78] using ANSYS CFX numerical tool. The thermal performance of a nanofluid containing 4 vol.% CuO was compared to ethylene glycol. The results indicated that the maximum enhancement of heat transfer coefficient was 82% when Reynolds number of flow was set at 125.

Recently, Vajjha et al. [79] computationally compared the performance of oxide nanoparticles dispersed in ethylene glycol and water mixture in the flat tubes of an automotive radiator. They found that the percentage increment of the average heat transfer coefficient over the base fluid for 3 vol.% Al_2O_3 nanofluid was 36.6% and for 3 vol.% CuO nanofluid was 49.7%.

A summary of other computational research [80–83] on nanofluid performance for vehicle cooling system is described in Table 4.

5. Conclusion

This paper presented an inclusive review on the application of nanofluids for cooling engine vehicles. A vast number of available references showed that nanofluids have a great application prospect in the development of modern engines. For engine cooling system, nanoparticles can be dispersed in the engine oil to enhance the thermal conductivity of the liquid. In addition, the presence of nanoparticles in engine oil will also improve the performance of lubricants and reduce friction. However, the optimum amount of nanoparticles in engine oil still remains unknown. Another method for cooling the engine system is by dispersing nanoparticles in a conventional coolant radiator. Heat transfer coefficient can be improved up to 50% compared to the original coolant; however, the problem of pressure drop limits the efficiency factor of the cooling system. For this case, most researchers agree that the optimum performance of cooling system can be achieved at low volume fraction of nanoparticles (<1%). At the same time, there are still some problems and challenges regarding the mechanisms of heat transfer enhancement and the actual applications on engine vehicle. Current research on nanofluids for engine cooling system is still at its initial stage and needs further development.

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