Chapter - 2

Literature Review

Present review summarizes the available literatures on radiator performance improvements in two sections. The first section concentrates the experimental and theoretical investigations on heat transfer enhancement of radiator based on various fin surfaces and radiator coolants. The second section also includes the recent research on performance enhancement on radiator based on fin materials and different positions of radiator in vehicles. The second sections also include the recent numerical and experimental research on engine performance with engine assembly using radiator modifications.

A high efficiency engine is not only related to the performance of radiator but also related to better fuel economy and less emission rate [1-4]. Reducing the vehicle weight by optimizing design and size of a radiator is a capital feature [5-8]. Another option is to use alternative coolant with better thermophysical properties. Various investigators [9-36] reported the correlations for thermophysical properties i.e heat capacity, thermal conductivity and viscosity for various conventional fluids, nanofluids, hybrid nanofluids as radiator coolant.

2.1 Improvements based on radiator surfaces and coolants

2.1.1 Based on radiator fin surfaces

Addition of fins is one of the approaches to increase the heat transfer rate of radiator, provides greater heat transfer area and enhances the air convective heat transfer coefficient. Truong and Mancuso [37] analyzed on the performance of fins for various profile shapes and developed correlations for heat transfer and flow friction characteristics. Achaichia and Cowell [38] studied the heat transfer performance of multi-louvered fin and found that the louvered fin compact HEX provides better heat transfer performance than other types of HEX due to the louver array's flow directing properties which caused the increment in velocity of the working fluid relative to the elemental flat-plate surface. Kays and London [39] described various types of heat transfer phenomena with HEX design techniques for rectangular fins, pin fins, wavy fins, offset fins, perforated fins and louvered fins. Tinaut and Melgar [40] developed the correlations for heat transfer and flow friction characteristics of compact plate-type HEXs. Louvered fins are favourable for the air side of a radiator which increase the heat transfer coefficient and keep a low pressure drop on the air side, especially at high Reynolds number of the air. Webb [41] summarized two methods to increase the thermal performance of HEXs. The passive technique, which includes special surface geometries and fluid additives and the active technique, in which the external power is required. Cowell *et al*. [42] outlined some common constraints for the radiator design with compactness, low pressure drop, low weight and low cost. Wang and Chi [43] presented the airside performance of fin-and-tube HEXs with plain fin configurations and found that the heat transfer characteristics were strongly related to the fin pitch. Yan and Sheen [44] investigated the heat transfer and pressure drop characteristics of plate, wavy and louvered fin surfaces experimentally and found that at the same Reynolds number, louvered fin geometry shows larger values of f and j factors, compared with the plate fin surfaces. Saboya and Saboya [45] experimentally determined the average transfer coefficients for plate fin and elliptic tube exchangers and showed the performance advantage of the elliptical tube arrangements resulted from the higher fin efficiency. Kim and Bullard [46] studied experimentally the effect of louvered geometry on the air-side thermal and hydraulic performance for a multi-louvered HEX and concluded that the heat transfer coefficient increases exponentially with face air velocity and decreases with flow depth. Depending on the number of tube rows, Lyman *et al*. [47] conducted experiment in a number of large-scale louver models with varied fin pitch and louver angle over a range of Reynolds numbers. Zhang and Tafti [48] investigated the effect of the Reynolds number, fin pitch, louver thickness and louver angle on flow efficiency in multi-louvered fins and found that the flow efficiency is strongly dependent on geometrical parameters, especially at a low Reynolds number. Zhang [49] analyzed the theoretical performance and verification of simulation results to improve the efficiency of the radiator through pin fins which increased with reduction in pin-fin diameter. Wolf *et al*. [50] studied the heat transfer performance of a wavy fin and tube HEX by numerical and experimental methods. They presented some results of a three dimensional numerical analysis of heat transfer on the air side of a wavy fin and tube HEX and the numerical results were validated with the experimental results with a deviation within 8%. Oliet *et al*. [51] investigated the importance of coolant flow lay-out on the radiator global performance with numerical methods and the result showed that the air inlet temperature did not affect the overall heat transfer coefficient. Nuntaphan *et al*. [52] analysed the effect of inclination angle on the louver finned tube HEX in natural convection condition. Junqi *et al*. [53] investigated eleven cross-flow HEXs having wavy fin and flat tube experimentally and proposed correlations such as j factor and friction factor. Vetrovec [54] carried out the work on engine cooling system with heat load averaging capacity using passive heat load accumulator. Heat load accumulator is phase change material which stores heat generated during peak and dissipates stored heat during reduced heat load condition which leads to compact heat exchanger for same heat rejection with a reduction of load on cooling system. Salah *et al*. [55] discussed about hydraulic actuated cooling system, which can improve the temperature tracking and offer greater power density with compact in nature. Wen *et al*. [56] experimentally investigated the heat transfer performance of plate fin, wavy fin, compound fins and strongly suggested the use of the compound fin configuration for the heat exchangers. Wais [57] analysed that the fin shapes modified the heat transfer conditions by changing the distribution of fluid mass in the channel. Pelaez *et al*. [58] carried out 3D numerical simulations to compare both an air side and coolant side model of a plain fin and tube HEX and the influence of the Reynolds number, fin pitch, tube diameter, fin length and fin thickness were studied. Li and Wang [59] conducted an experimental study on the air side heat transfer and pressure drop characteristics of brazed aluminum HEXs, with multi-region louver fins and flat tubes and found that the heat transfer coefficient and pressure drop tend to decrease with increasing Reynolds numbers, and increase with the number of louvers. Leong *et al*. [60] investigated thermal performance of an automotive car radiator operated with copper nanofluid as a coolant.

Vaisi *et al*. [61] experimentally investigated air-side heat transfer and pressure drop characteristics of flow over louvered fins in compact HEXs. Any change in geometrical parameters impacts the flow characteristics and as a consequence effects the heat transfer. Shati *et al*. [62] presented the effect of surface roughness and emissivity on radiator heat output by experimentally and using computational fluid dynamics (CFD). Chavan *et al*. [63] explained and developed a circular shape radiator which is more efficient and leads to minimum power consumption to drive a fan and maximum utilization of air flow. Trivedi *et al*. [64] illustrated the modification in arrangement of tubes in radiator by studying the effect of pitch of tube by CFD analysis using CFX. Results showed that, the heat transfer rate is affected by tube pitch for optimum radiator performance. Gunnasegaran *et al*. [65] reported the fluid flow and heat transfer characteristics over louver angle fin compact heat exchangers through numerical simulations and found that the Nusselt number is higher for increased or decreased louver angle compared to uniform louver angle. Lee *et al*. [66] presented the numerical method to efficiently predict heat transfer phenomena of a louver fin radiator. Dwivedi and Rai [67] modelled on CATIA V5 for wavy fin radiator and the performance evaluation is done on pre-processing software ANSYS 14.0. Studies on radiator with various fin profiles are summarized in Table 2.1.

Table 2.1: Summary of experimental and numerical studies radiator fin surfaces.

Authors and Year	**Type of radiator fin surfaces**	**Findings**
Troung and Manuso (1980) [37]	Compact Plate-type Heat exchangers.	Developed correlations for heat transfer and flow friction characteristics.
Achaichia and Cowell, (1988) [38]	Multi-louvered fin compact heat exchanger	Better heat transfer performance due to the louver array's flow directing properties caused the increment in velocity of the working fluid.
Kays and London (1995) [39]	Compact Plate-Type Heat Exchangers	Described various types of heat transfer phenomena and HEX design techniques
Tinaut and Melgar, (1992) [40]	Louvered fin radiator	Developed the correlations for heat transfer and flow friction characteristics of compact plate-type HEXs.
Webb, (1995) [41]	Rectangular fin heat exchangers	Presented two methods to increase the thermal performance of HEXs

Cowell *et al*., (1995) [42]	Multi-louvered fin aluminum heat exchangers	Analysis higher fin density with applications to size, weight, and pumping power are particularly.
Wang and Chi, (2000) [43]	Plain fin configurations.	Airside performance and heat transfer characteristics were strongly related to the fin pitch.
Yan and Sheen, (2000) [44]	Wavy and louvered fin surfaces	At same Reynolds number, louvered fin geometry shows larger values of f and j factors, compared to plate fin surfaces.
Saboya and Saboya, (2001) [45]	Plate fin and elliptic tube exchangers	The elliptical tube arrange ments resulted the higher fin efficiency, heat transfer coefficients and performance .
Kim and Bullard, (2002) [46]	Louvered fin heat exchangers	Heat transfer coefficient increases exponentially with face air velocity and decreases with flow.
Lyman *et al*., (2002) [47]	Multi-louvered fins	Experiments done with varied fin pitch and louver angle over a range of Reynolds numbers.
Zhang and Tafti, (2003) [48]	Louver finned tube heat exchanger	Flow efficiency is strongly dependent on geometrical parameters, especially at a low Reynolds number.
Zhang, (2004) [49]	Pin fin heat exchanger	Performance evaluation is done on pre-processing software ANSYS 14.0 and radiator modelled on CATIA V5.
Igor Wolf *et al*., (2006) [50]	Wavy fin and flat tube heat exchanger	Design optimization of fin with CFD software fluent model and validated with the experimental results with a deviation of 8%.
Oliet *et al*., (2007) [51]	Rectangular fin heat exchangers	Carried out parametric studies for automotive radiators.
Nuntaphan *et al*., (2007) [52]	Louvered fin heat exchanger	With an inclination angle such as 30–45^o, increase of heat transfer performance in natural convection condition.
Junqi *et al*., (2007) [53]	Wavy fin radiator	Proposed correlations such as j factor and friction factor
Vetrovec, (2008) [54]	Rectangular fin heat exchanger	Work on engine cooling system with heat load averaging capacity using passive heat load accumulator
Salah *et al*., (2009) [55]	Hydraulic actuated cooling system	Analysis for hydraulic actuated cooling system.
Wen *et al.,* (2009) [56]	Heat exchanger	Experimentally studied the heat

	with compounded fins.	transfer performance with compound fin configuration.
Wais , (2010) [57]	Plain fin heat exchange	The fin shapes modified the heat transfer conditions by changing the distribution of fluid mass in the channel.
Pelaez *et al*., (2010) [58]	Plain fin and tube heat exchanger.	3D numerical simulations to compare performance with influence of the Reynolds number, fin pitch, tube diameter, and fin length.
Li and Wang, (2010) [59]	Louvered fins in compact heat exchangers	Heat transfer coefficient and pressure drop tend to decrease with increasing Reynolds numbers and with number of louvers.
Leong *et al*., (2010) [60]	Wavy fin radiator	Invested and proposed correlations for j factor and friction factor.
Vaisi *et al.,* (2011) [61]	Louver angle fin Compact Heat Exchangers	Heat transfer and pressure drop characteristics increases.
Shati *et al.,* (2011) [62]	Surface roughness of radiator	Surface roughness will increase both the surface area for heat transfer and the turbulent intensity which increase the mass transfer.
Chavan *et al*., (2011) [63]	Circular shape radiator	Developed a circular shape radiator which is more efficient and leads to minimum power consumption to drive a fan.
Trivedi *et al*. (2012) [64]	Rectangular fin heat exchangers	Effect of tube pitch for enhancement of radiator performance.
Gunnasegaran *et al*. (2012) [65]	louver angle fin heat Exchangers	Numerical simulations on fluid flow and heat transfer characteristics
Lee *et al*., (2014)[66]	Wavy fin radiator	Analysis for numerical method to efficiently predict heat transfer phenomena.
Dwivedi and Rai, (2015) [67]	Wavy fin radiator	Suction side of the wavy fin punched with Rectangular Winglet Pairs (RWPs) can increase Nusselt number by 1.2%–4.1%, and decrease friction factor by 2.7%–9.6% .

2.1.2 Improvements based on radiator coolants

To enhance the cooling rate, increasing the surface area by addition of fins is the earliest approach but this approach of increasing heat transfer already reached to their limit. Water and water mixed with anti-freezing agents such as ethylene glycol (EG) and PG (PG) are the traditional coolants for automotive radiator. Recently nanofluid have been proposed as coolant for automotive radiator However, the operation and long term stability are major challenges for nanofluid. Nanofluids were introduced by Choi [68-71] and showed that the liquids with nanoparticles are having enhanced thermal conductivity as compared to conventional fluids for vehicle thermal management. Researchers [73-74] reported CuO gave the best heat transfer effect and cooling capability of nanofluid with 3.0 vol.% of nanoparticle concentration was increased by 15%. CuO–EG/water (50:50) as coolant for radiator has higher heat transfer coefficients of nanofluids as improved the engine power, coolant pump speed. Chopkar *et al.* [74] measured the thermal conductivity of Al_2Cu and Ag_2Al nanoparticles dispersing about 0.2–1.5vol. % in water and showed that the degree of enhancement strongly depends on size, volume fraction and shape of the dispersed nanoparticles. Namburu *et al*. [75-76] discussed the viscous behaviour of 0% to 6.12% vol. concentration copper oxide nanofluids in ethylene glycol and water mixture and showed that the viscosity of nanofluids increases with increase in volume concentration of nanoparticles. Leong *et al*. [77] experimentally investigated the effective viscosities and thermal conductivities of Al_2O_3 water based nanofluids and detected that the alumina nanofluids have a nonlinear relation between their viscosity which decreases with increase in temperature. Mohammadi *et al*. [78] investigated that 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 [79-80] showed that maximum enhancement of thermal conductivity of 1.5 vol. % of Al_2O_3 nanoparticles at 50 °C and 3.5 vol.% of Al_2O_3 for Al_2O_3–EG at 80 °C, are 4.5% and 11.25% respectively. Zhong *et al*. [81] showed for coolants 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.

Researchers [82-83] analyzed for CuO–EG and CuO–EG/water (50:50) as coolant and found that an additional power of 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. Lv *et al*. [84] showed for Cu–oil as coolant, engine heat transfer coefficient and heat dissipating capacity enhancement of Cu–water nanofluid with 5.0 vol.% of nanoparticle concentration were respectively about 46% and 43.9% more than pure water. Vajjha *et al*. [85-86] analyzed that 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. At Reynolds number of 5500, the percentage increment of the average heat transfer coefficient over the base fluid for 3 vol.% Al_2O_3 and CuO nanofluid were 36.6% and 49.7% respectively.

Peyghambarzadeh *et al*. [87-88] showed that for Al_2O_3–water, Al_2O_3–EG and Al_2O_3–EG/water (5–20 vol.% of EG) coolants, the maximum enhancement of thermal conductivity and heat transfer of nanofluids was 3.0% and 45% respectively as compared to water. Vasheghani [89] analysed for coolants AlN–engine oil, α-Al_2O_3–engine oil,γ-Al_2O_3–engine oil, with 3.0 vol.% of nanoparticles and found that the thermal conductivity maximum enhancement of the AlN nanofluid was 75.23% followed by γ-Al_2O_3,α-Al_2O_3 and α-Al_2O_3 nanofluid with 37.49%, 31.47% and 26.10% respectively. Huminic and Huminic [90-91] showed that maximum enhancement of heat transfer coefficient of 82% when Reynolds number was 125 for Cu–EG coolants and the convective heat transfer coefficient for CuO–EG nanofluid was higher than pure EG. Researchers [92-93] showed maximum enhancement of thermal conductivity of with 0.5 vol.% of MWCNT nanoparticles and 0.4 vol.% are 12.7% and 49.6% respectively. Liu *et al*. [94] showed 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.* [95] reported that the overall heat transfer coefficient, heat transfer rate, heat transfer coefficient and Nusselt number of 0.4 vol.% CuO concentration are 14.79%, 14.72%, and 9.51%, respectively. Sarkar and Tarodiya [96] showed heat transfer rate improvement for SiC, Al_2O_3, TiO_2, CuO were 15.34%, 14.33%, 14.03% and 10.20% respectively, with 1.0 vol.% of nanoparticle concentration compared to pure base fluid. Raja [97] showed that the maximum enhancement of thermal conductivity of the Al_2O_3–water nanofluids was 3% and heat transfer enhancement 40–45% when compared to pure fluid with 1.0 vol.% of nanoparticles. Peyghambarzadeh *et al*. [98] showed heat transfer coefficient was enhanced up to 9% at 0.65 vol.% CuO,Fe_2O_3 nanoparticle concentration in comparison with water. Ali *et al*. [99] showed the enhancement of coolant heat transfer rate, heat transfer coefficient and Nusselt number are 14.79%, 14.72%, and 9.51%, respectively, using water based Al_2O_3 nanofluids. Elias *et al*. [100] showed the maximum enhancement of thermal conductivity of the nanofluids was

8.3% with 1.0 vol.% of Al_2O_3nanoparticles at 50 °C. Chougule and Sahu [101] investigated that the maximum enhancement of thermal conductivity of the CNT–water, Al_2O_3–water nanofluids were 76%, 18% respectively and 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 with 1.0 vol.% of nanoparticles at 80 °C. Nieh *et al*. [102] analysis that the thermal conductivity of Al_2O_3 and TiO_2 nanocoolant were similar and about 24–39% higher than EG/water at all nanoparticle concentrations. Maximum efficiency factor were 27.2%, 14.4% using TiO_2–EG/water, Al_2O_3–EG/water with 2.0 vol.% nanoparticle concentration. Heris *et al*. [103] showed for coolant 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. Hussein *et al*. [104-106] analysed that the heat transfer rate enhancement were 20% and 32% for TiO_2 and SiO2 nanofluids respectively. Samira *et al*. [107] showed the pressure drop and thermal performance of CuO/ethylene glycol (60%)–water (40%) nanofluid in car radiator. Hatami *et al*. [108] showed that 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. Baniamerian [109] analysed that the heat transfer coefficient decreases along the flow as the vapour 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. Researchers [110-111] experimentally analysis that for Al_2O_3–water, Al_2O_3–EG as coolant, the Nusselt number for two-phase approach was 10%–45% greater and closer to the experimental data than the single-phase approach. Many other [112-120] showed the some of the work on radiators performance with nanofluids and hybrid nanofluids. Studies on radiator performance with various coolants are summarized in Table 2.2.

Table 2.2: Summary of experimental and numerical studies radiator coolants.

Author and Year	Coolants for radiator	Findings
Choi, (1995-2001)[68-71]	nanofluids	Application of nanofluids for vehicle thermal management in enhancing thermal condu ctivity of coolants.
Tzeng *et al*., (2005) [72]	CuO–coolant	Due to high heat transfer coefficients of nanofluids engine power improved.
Zhang *et al*., (2007) [73]	CuO–EG/water (50:50)	2 and 4 vol. % were optimal points for highest increase of thermal conductivity.
Chopkar *et al*., (2007) [74]	Al_2Cu and Ag_2Al nanoparticles	Enhancement strongly depends on composition, size, volume fraction and shape (aspect ratio) of the dispersed nanoparticles.
Namburu *et al*., (2007) [75-76]	CuO-EG	Viscosity of nanofluids increases and exhibit Newtonian behaviour with increase in volume fraction.
Leong *et al*., (2008) [77]	Al_2O_3–water nanofluids	Nanofluids have a nonlinear relation with viscosity and the nano particle concentration(0.01–0.3 vol. %).
Mohammadi *et al*., (2009) [78]	γ- Al_2O_3–engine oil, CuO–engine oil,	Enhancement of thermal conductivity of γ- Al_2O_3, CuO–engine oil nanofluid are 5%, 8% respectively.
Kole and Dey, (2010) [79-80]	Al_2O_3–EG	Enhancement of thermal conductivity of 4.5% with 1.5 vol.% of Al_2O_3 nanoparticles at 50 °C.
Zhong *et al*., (2010) [81]	Al_2O_3–water, Al_2O_3–EG, Al_2O_3–EG/water	Enhancement of heat transfer coefficient of nanofluids is 6.52% with compared to pure water.
Leong *et al*., (2010) [82]	CuO–EG	Maximum heat transfer rate of nanofluids enhanced about 3.8% compared to pure EG.
Kole and Dey,(2010)	CuO–EG/water	Alumina nanoparticles (up to

[83]	(50:50)	0.4 vol.%) has transformed it into a non-Newtonian fluid.
Lv *et al*., (2010) [84	Cu–water,Cu–oil engine	Heat transfer coefficient and heat dissipating capacity enhancement of Cu–water nanofluid are 46% and 43.9% more than pure water.
Vajjha *et al*.,(2010,2014) [85-86]	Al_2O_3–EG/water (60:40),CuO–EG/water (60:40)	10 vol.% Al_2O_3 led to 94% enhancement of heat transfer coefficient compared to base fluid.
Peyghambarzadeh *et al*., (2011) [87-88]	Al_2O_3–water, Al_2O_3–EG, Al_2O_3–EG/water (5–20 vol.% of EG)	Enhancement of thermal conductivity was 3.0% with 1.0 vol.% of Al_2O_3 nanoparticles.
Vasheghani, (2012) [89]	AlN–engine oil, α-Al_2O_3–engine oil,γ-Al_2O_3–engine oil	Enhancement of the AlN nanofluid was 75.23% followed by γ- Al_2O_3 ,α- Al_2O_3 and α- Al_2O_3 nanofluid.
Huminic and Huminic, (2012-2013) [90-91]	Cu–EG, CuO–EG	Enhancement of heat transfer coefficient of 82% was obtained when Reynolds number was 125
Ettefaghi *et al*., (2013) [92]	MWCNT–engine oil Maximum	Enhancement of thermal conductivity of the nanofluids of 12.7% with 0.5 vol.% of MWCNT nanoparticles at 20 °C.
Teng and Yu, (2013) [93]	MWCNT–EG/water (50 vol.% of EG)	Enhancement of thermal conductivity of the MWCNT–EG/W nanofluids 49.6% compared to EG/W.
Liu *et al*., (2013) [94]	Nanodiamond–engine oil	Maximizing the engine power and torque up to 1.15% and 1.18% respectively;
Naraki *et al*.,(2013) [95]	CuO–water	Heat transfer coefficient enhancement of nanofluids about 8% at 0.4 vol.% CuO compared to pure water.
Sarkar and Tarodiya, (2013), [96]	nanofluids	Performance analysis of louvered fin tube automotive radiator using nanofluids as coolants
Raja *et al*., (2013) [97]	Al_2O_3–water	Maximum overall enhancem ent of heat transfer coefficient of the nanofluids of 25% with Peclet number of 3000 .
Peyghambarzadeh *et al*.,	CuO–water, Fe_2O_3–	Heat transfer coefficient was

(2013) [98]	water	enhanced up to 9% at 0.65 vol.% nanoparticle concentra tion in comparison with water.
Ali *et al*., (2014) [99]	Al_2O_3–water	Enhancement of coolant heat transfer rate, heat transfer coefficient and Nusselt number are14.79%, 14.72%, and 9.51%, respectively.
Elias *et al*., (2014) [100]	Al_2O_3–EG/water (50:50)	Enhancement of thermal conductivity of the Al_2O_3 nanofluids of 8.3% with 1.0 vol.% at 50 °C.
Chougule and Sahu, (2014) [101]	Al_2O_3–water, CNT–water	Maximum enhancements of heat transfer of the CNT–water nanofluids and Al_2O_3–water nanofluid were 90.76% and 52.03%.
Nieh *et al*., (2014) [[102]	Al_2O_3–EG/water (50 vol.% of EG), TiO_2–EG/water	Thermal conductivity of Al_2O_3 nanocoolant and TiO_2 nanocoolant 24–39% higher than EG/water.
Heris *et al*., (2014) [103]	CuO–EG/water (40:60)	Heat transfer enhancement of 0.8 vol.% of CuO–EG/water about 55% compared to the base fluid
Hussein *et al*., (2014) [104-106]	TiO_2–water,SiO2–water	Enhancement was 20% and 32% for TiO_2 and SiO2 nanofluids respectively
Samira *et al*., (2014) [107]	CuO/ethylene glycol (60%)–water (40%)	Pressure drop and thermal performance of nanofluid in car radiator
Hatami *et al*., (2014) [108]	CuO–water, Fe_2O_3–water, TiO_2–water, EG/water (50:50)	TiO_2–water nanofluid can enhance 10% of heat followed by Fe_2O_3–water and CuO–water nanofluid compared to EG/water.
Baniamerian *et.al*, (2014) [109]	Al_2O_3, Au, CuO, TiO_2–water/vapor	Heat transfer coefficient enhancement for Al_2O_3 was the highest followed by TiO_2, Au, and CuO nanofluids.
Delavari and Hashemabadi, (2014) [110]	Al_2O_3–water, Al_2O_3–EG	Nusselt number for two-phase approach was 10%–45% greater.
Ali and Azhar (2015) [111]	Water-MgO	Heat transfer enhancement of car radiator using aqua based magnesium oxide nanofluids
Mutuku, (2016) [116]	EG-CuO,Al_2O_3	Modelled the flow regime for the parameters on the velocity,

		temperature, and the local Nusselt number
Subedar and Ramani, (2016) [117]	Al_2O_3/ethylene glycol and water	Correlations for the thermal conductivity and viscosity.

2.1.3 Proposed coolant- From the summarized Table 2.2, the radiator performance with various coolants used for radiator applications are EG, water and nanofluids. Based on this survey, it is found that no work has been done on PG brine with varying concentrations as radiator coolant.

2.2 Improvements based on radiator fin materials and configurations

2.2.1 Radiator fin materials

Gallego and Klett [121] presented six different configurations of graphite foam HEXs and showed that the solid foam had the highest pressure drop while the finned configuration had the lowest pressure drop. Vafai [122] showed the simulation models for the calculation of thermal conductivity. There are two major models for the heat transfer of the graphite foam (porous medium). Thermal equilibrium model and the other is the non-thermal equilibrium model (two-equation model). In thermal equilibrium model where a local thermal equilibrium exists between fluid and solid phases, the effective thermal conductivity has been calculated to ensure the accuracy of the simulation model. Straatman and Thompson [123-124] analysed a new design concept similar to current radiators, but replaces aluminium fins with carbon foam channels. Due to the higher thermal conductivity and increasing surface area of carbon foam, the air side resistance and size of the radiator can be reduced. The most important issue is that there is a high pressure drop due to the large hydrodynamic loss associated with the cell windows connecting the pores. Fell *et al*. [125] analysed the simulation with graphite foam HEXs with improve performance of radiators. Garrity *et al*. [126] carried out an experimental comparison between a carbon foam heat exchanger and a multilouvered fin HEX and found that the carbon foam samples brought away more heat than the multilouvered fin with same volume of the HEXs. Leong *et al*. [127] found that the baffle foam presented the lowest pressure drop among four configurations of graphite foams at the same heat transfer rate. Studies on radiator performance with various fin materials are summarized in Table 2.3.

Table 2.3: Summary of experimental and numerical studies radiator fin materials.

Author and Year	**Radiator fin material**	**Findings**
Gallego and Klett., (2000) [121]	Six different configurations of graphite foam heat exchangers	Solid foam had the highest pressure drop while the finned configuration had lowest pressure drop.
Vafai, (2005) [122]	Graphite foam heat exchanger	Using simulation model thermal conductivity calculated.
Straatman and Thompson (2006-2007) [123]	Carbon foam fin	Reduction in the overall size of the radiator with increasing the surface area exposed to the air.
Gallego et al., (2007) [124]	Carbon foam fin	High pressure drop due to the large hydrodynamic loss associated with the cell windows connecting the pores.
Fell and Kazanis, (2007) [125]	Graphite foam heat exchangers	Analysis the simulation to improve performance of radiators.
Garrity *et al*., (2010) [126]	Carbon foam heat exchanger	Carbon foam samples brought away more heat than the multi louvered fin for same volume of heat exchangers.

2.2.2 Position of radiators

Heavy duty conventional radiators generally get placed in the front of the vehicle. A possible position for placing the radiator is the roof of driver compartment where the coolant flow direction and the air flow direction would be opposite. However, the engine radiator is normally a cross flow HEX in vehicles but based on the HEX design theory, generally a countercurrent flow HEX has better thermal performance than a cross flow HEX.

Thus, the option of placing a countercurrent flow HEX on the roof of the truck driver compartment might be a good idea to the engine radiator revolution. Khaled *et al*. [128] compared the in-rank configuration of the HEXs and the in-plane configuration HEXs and found that increase in the overall thermal performance by 4.4 % and 0.9 % of the pressure losses were eliminated. The position of HEXs in vehicles has to be rearranged to get a chance to dissipate the huge cooling power. Malvicino *et al.* [129] tried to use some parts of the vehicle body panels as HEXs to reduce the radiator size in the light duty vehicles and found that two roll bond HEXs installed on the engine hood and below the engine could dissipate 60 % of heat from the engine in all the test conditions. On the other hand, in [130] two levels of cooling systems (high temperature system (engine radiator) and low temperature system) were introduced to a car. The intercooler and condenser were cooled by liquid instead of air and the intercooler and condenser can be removed from the front of the vehicles to other suitable places and with two levels of cooling systems, the fuel consumption in the vehicle can be reduced by 4 %. Studies on radiator performance with different positions are summarized in Table 2.4.

Table 2.4: Summary of experimental and numerical studies radiator configuration.

Author , Year ,Ref	**Position of radiator**	**Findings**
Khaled, (2010) [128]	Heat exchangers are positioned differently, i.e.one is behind the other and parallel in the flow direction.	Increase the overall thermal performance by 4.4 % and 0.9 % of the pressure losses obtained.
Malvicino C., (2011) [129]	Flat exchanger at roof of driver compartment.	Better thermal management system.
Peuvrier and Wasaki, (2011) [130]	Two levels of cooling systems high tempe rature system (engine radiator) and low temperature system to the car.	Fuel consumption in the vehicle can be reduced by 4 %.Due the slim cooling package, the cooling fan power reduced and the fuel consumption reduced 3-5 %.

Also, various researchers [131-135] have published their review articles on air flow management, coolant flow circuit in vehicle's cooling system, engine cooling technologies for modern engines, energy consumption, management and recovery in automotive systems, the applications and challenges of nano-fluids as coolant in automobile radiator. References [136-153] presented the engine cooling performance i.e effect of electric field on heat transfer performance at low frontal air velocity, performance evaluation of radiator in diesel engine, nanofluid applications in future automobiles, exploitation of thermal properties of fluids embedded with nano structured materials and economic factors in radiator selection vehicle cost reduction through cooling system optimization. Researchers [154-157] analyzed the economic factor of vehicle cooling system for reducing fuel consumption, radiator selection, vehicle cost and size. Some researchers [158-168] have done optimization of size of vehicle and airflow simulation with the effect of changes in ambient, coolant radiator inlet temperatures, coolant flow rate on specific dissipation, the measurement of the distribution of the airflow through radiator and analyzed the air circuit for engine cooling systems and [169-178] have shown the numerical analysis, modelling of flow field and heat transfer on radiator performances.

2.3. Research Gap

The following research gaps have been found from literature review:

(i) No attempt has been made yet to search an alternative coolant apart from water and EG (conventional coolants) and related nanofluids.

(ii) Very little theoretical and experimental analysis have been done on radiator performance using PG brine and related nanofluids.

(iii) Very little work has been done using carbon and graphite foam as fin material on radiator performance apart from aluminium and copper.

(iv) Very little work has been done on radiator performance in alternative configuration and orientation for the position of radiator apart from cross flow.

(v) No experiment has been done on engine cooling system (engine with radiator) performance using PG brine and related nanofluids.