NANOCOOLANTS FOR ENGINE COOLING SYSTEM

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ABSTRACT

The automobile industry is constantly looking for increasing engine efficiency while complying with stringent emission norms. One such aspect studied in great detail is the effect of engine coolant temperature on fuel efficiency and emissions. It has been shown that coolant is responsible for maintaining the engine at optimum operating temperatures in addition to warming up the engine at start. In view of this, nanofluids have been proposed as potential replacement for conventional coolants based on their extra-ordinary lab-scale performance, however studies reported in literature are inadequate to predict the effect of nanofluids in automobiles. We have developed a process for large scale production of stable nanofluids using high energy milling. Using this top down approach, we have converted commercial engine coolants into nanocoolants. This study presents a comparison between commercial coolants and nanocoolants with respect to break specific fuel consumption (bsfc), log mean temperature difference (LMTD) of the heat exchanger (radiator) circuit, amount of NOx (ppm) and O_2 (% vol.) in the exhaust gas. This study is performed on a three cylinder, direct injection, 38.5 bhp diesel engine test rig equipped with a hydraulic dynamometer. Addition of nanoparticles exhibits an enhancement of about 2-3% in LMTD, while brake specific fuel consumption and extent of oxygen in the exhaust gas decreases when nanocoolant is used.

NOMENCLATURE

bsfc	[g/kWhr]	*Brake specific fuel consumption*
C_p	[J/kg-K]	Specific heat
IS	[-]	Indian Standard
k	[W/mK]	Thermal conductivity
LMTD	[^{0}C]	Log mean temperature difference
NOx	[-]	Nitrous oxides
PSD	[-]	Particle size distribution
T	[K]	Temperature
U	[W/m^{2}K]	Overall heat transfer coefficient

Special characters

μ	[Pa-s]	Dynamic viscosity
ρ	[Kg/m^3]	Density
Δ	[-]	Change

Subscripts

bc	Base coolant
nc	Nanocoolant

INTRODUCTION

Automobile engine design has been largely governed by ever increasing demand for reducing fuel consumption while meeting stringent emission norms. This has led to advancements in all aspects of engine design right from fuel injection system, catalytic converters, exhaust gas recirculation, combustion chamber design, better ignition timing to fuel additives, lubricants, batteries and many more. However, one area that has been neglected to some extent is the engine cooling system (ECS). This is evident from the fact that present day ECS still comprise of a mechanically driven coolant pump, expansion-element thermostat and coolant sensor based regulators to maintain the engine at optimum operating temperatures. It is rather strange; how ECS development has been anchored on cost rather than innovation. Since last two decades, researchers from the engine fraternity had been reporting the effect of coolant temperature, electric coolant pumps and electronic valves for regulating coolant flow; on fuel consumption, emissions and cold start. In one such study, Couëtoux et al. [1] reported a reduction of 3 to 5% in fuel consumption when coolant temperature at engine outlet was increased from 85^{0}C to 115^{0}C using an electronically controlled cooling system. However, they were not sure whether the advantage was due to the use of lower power electric pump or better engine response to higher working temperatures. Krause et al. [2] showed fuel consumption savings of upto 3% and 10-15% reduction in hydrocarbon emissions by replacing the conventional wax-element thermostat with their unique electronic thermostat. The authors pointed out that higher temperature of components associated with the combustion chamber, results in better combustion process around cylinder walls as well as reduced thermal and frictional losses especially at lower part-load range. This ensures that the engine remains at comparatively higher temperatures at part load thus avoiding sudden temperature rise when full load is applied, resulting in lower thermal fatigue. They also mentioned the possibility of using specially engineered coolants to exploit the advantage of running the engine at higher operating temperatures. Chanfreau et al. [3] used an electric water pump (600W) for a 3.8 L SI engine (180 bhp) to maintain lower flow rates in the cooling circuit for a given power condition and achieved higher coolant temperature at engine outlet (90-110^{0}C). Electric pumps are battery driven thus reducing auxiliary power requirement of the engine which results in increased fuel efficiency as compared to mechanically driven pumps (rated 2-3 kW) especially at part load conditions. The authors also argued that this replacement gave a 15% to17% reduction in CO and unburnt hydrocarbons respectively. Ap et al [4] replaced the belt driven pump (~1 kW) with an electric pump (30-80W) in conjunction with an advanced cooling system (REROM) and obtained higher coolant temperatures (5^0C-14^0C higher), thus reporting reduced fuel consumption.

The brief discussion above on previous work pertaining to engine thermal management system in a way, describes the characteristics of an efficient ECS. An appropriate ECS can help reduce thermal and frictional losses by maintaining the engine at comparatively higher temperatures without compromising on its structural safety and stability. In view of this, researchers had proposed use of lower coolant flow rates, electronic thermostats; pressure regulated thermostats and many more. However, the heart of the ECS- the coolant, had been seldom looked upon as a prospective solution. Coolant technology has come a long way from using only distilled water to mixtures of distilled water and antifreeze. However, it seems that advancements in coolant technology had been largely aimed at raising the boiling point and lowering the freezing point of the coolant; at the same time restricted by meeting stringent corrosion norms. Thus, coolants used earlier; and in use at present, suffer from poor thermal properties- especially thermal conductivity. Poor thermal conductivity requires higher flow rates to ensure uniform temperatures of critical areas in the engine head, eventually increasing the pumping power requirement. Stephen U. S. Choi [5] identified this gap in coolant technology and came up with the novel concept of nanofluids. Nanofluids are dispersion of nano sized (<100 nm) particles in a liquid. Dispersion of metal/metal-oxide nanoparticles in base-fluids augments the thermo-physical properties of these fluids, especially thermal conductivity [6, 7, 8]. Choi [9] also demonstrated that this enhancement in thermal conductivity could actually amount to higher heat transfer coefficient for nanofluids as compared to base-fluids. The author used Dittus-Boelter correlation for Nusselt number under the assumption that all thermo-physical properties for nanofluids remain same as that of base-fluid except thermal conductivity and showed that ratio of heat transfer coefficient of nanofluid to that of base-fluid is proportional to $2/3^{rd}$ the power of ratio of their thermal conductivities. Since then, plethora of research has been done to assess the effect of particle concentration and particle type on heat transfer coefficient of nanofluids especially under forced convection regime [10, 11, 12]. Almost a decade after Choi et al. [13] mentioned the potential benefits of nanofluids in automobile engine cooling in terms of miniaturized heat exchangers and lower pumping power due to enhanced thermal conductivity; this application of nanofluids has received a lot of attention by researchers all round the world. Peyghambarzadeh et al. [14] experimentally demonstrated that adding Al_2O_3 nanoparticles (20 nm) in small proportions (1% vol.) resulted in 45% enhancement in heat transfer efficiency of an automobile radiator as compared to water. In a similar study Chougule et al. [15] reported an increment of 52.03% in heat transfer performance for Al_2O_3-water nanofluid with the same concentration; for the radiator inlet temperature of 90^0C. Heris et al. [16] used CuO nanoparticles (60 nm) in 1:1 mixture of ethylene glycol-water with a concentration of 0.8% by volume and showed that Nusslet number increased by 55% for an automobile radiator as compared to the base-fluid. Bhogare et al. [17] performed similar experiments with Al_2O_3-EG/Water nanofluid and reported an enhancement of 40% in heat transfer for a fixed air Reynolds number of 84391 and coolant mass flow rate of 0.05 kg/s. Overall heat transfer on air side was also found to be 36% higher while 40% increase in effectiveness of radiator was also reported.

All the above mentioned experiments [14-17] to study the heat transfer performance of nanofluids in an automobile radiator have been largely carried out in an experimental setup as shown in Fig 1. The setup consisted of a storage tank with heating elements, a temperature control circuit, a pump, an automobile radiator, radiator fan, flow meter, thermocouples and other instrumentation. Various types of nanofluids were tried with volume concentrations ranging from 0-1% and coolant flow rates from 2-8 LPM across the radiator. The nanofluid was heated with a set of electrical heaters connected in conjunction with a temperature controller to maintain constant coolant inlet temperature to the radiator. Parametric studies with varying inlet temperatures (35^0C -95^0C) were also performed.

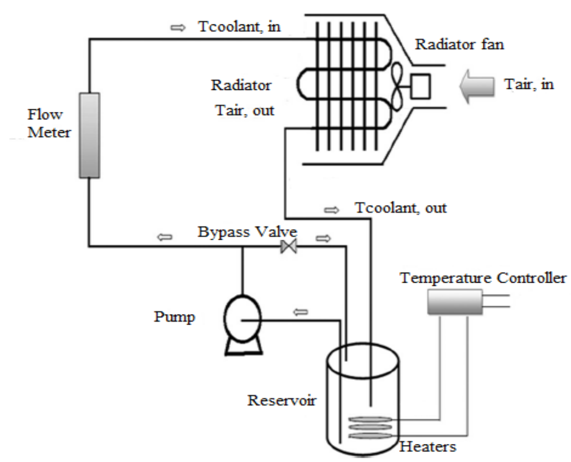

Figure 1 Schematic of experimental setup [15]

The aim behind these experiments was to assess the performance of nanofluids as heat transfer fluids in an automobile radiator as compared to conventional fluids. However, these experiments were based on several assumptions as far as the source of heat transfer to the coolant is concerned. In an automobile engine the rate of heat release is a strong function of crank angle [18] and hence time, making it a transient heat input boundary condition as opposed to one with constant heat flux (Fig. 1). Also, heat transfer to the coolant takes place across the walls of the engine in convection-conduction-convection mode which is not the case with the above experiments. Moreover, coolant flow rates in the engine are governed by engine speed because of the mechanical coupling of the coolant pump with the engine crankshaft. Thus, coolant flow rates are never of the order of 2-8 LPM across the radiator circuit. The coolant is allowed to pass through strategically engineered passages all throughout the engine right from the engine block, where it exchanges heat with the lubrication oil; to the engine head, where it extracts surplus heat generated during the combustion process.

Thus, experiments performed on setup as shown in Fig. 1 are unable to capture the complete physics of automobile engine cooling. This suggests that study of heat transfer performance of automobile engine coolant shall not be carried out in isolation with the engine. M. Raja et al. [19] were among the very few researchers who used an actual single cylinder diesel engine to study the heat transfer characteristics of Al_2O_3–water nanofluid. However, they replaced the radiator and radiator fan with a shell and tube heat exchanger where the hot nanofluid was allowed to flow through the tubes while cold water formed the shell fluid. The authors claimed maximum enhancement of 25% in overall heat transfer coefficient for the nanofluid (with 2% vol. nanoparticles) as compared to distilled water at a Peclet Number of 3000 at no load conditions, 28.4% at part load conditions and 29% at full load conditions. NOx emissions were shown to reduce by 12.5% at full load and about 3-4% at no load and part load conditions. Although the authors used an actual engine as opposed the temperature baths or heaters, replacing the radiator with the shell and tube heat exchangers makes the experiment impractical as opposed to an actual vehicle. Identifying the gap in literature, the present paper discusses the comparison of a commercial coolant and its nano counterpart as applied to an actual three cylinder diesel engine equipped with a radiator, radiator fan and mechanically driven coolant pump.

NANOCOOLANT- SYNTHESIS AND PROPERTIES

Nanocoolant (1% vol.) was produced using top down approach as mentioned in detail by Chiney et al. [20]. This is a single step method for production of nanocoolant where Alumina (A16-SG grade) was milled down in planetary ball mill. In this wet milling process commercial coolants are used as base fluids and zirconia beads as a grinding media. While the milling was in progress the new surface of alumina was created as larger alumina is milled down, this new surface is stabilized by systematic addition of surfactant–sodium citrate. This surfactant was chosen by applying molecular modelling approach as explained by Chiney et al. [21]. The final median particle size in nanocoolant was found to be around 80–95 nm. Nanocoolant thus produced was characterized for stability and thermo-physical properties.

Table 1 Thermo-physical properties of base fluid and nanocoolant

Properties	Commercial coolant	Nanocoolant (1 vol %)	%Change
ρ	1056	1169	+10.7%
μ	0.00279	0.00541	+93.90%
C_p	3454.11	3359.06	-2.75%
k	0.4107	0.4226	+2.89%

Stability was ascertained by comparing the initial particle size distribution (PSD) in a freshly made sample with that of the same sample after a year. It was found that the PSD varies only within 1% thus proving that the suspension is highly stable. Among the thermo-physical properties of nanocoolant, density was measured using first principles, viscosity using Brookfield viscometer (Model: LVDV -1, spindle S18), specific heat and thermal conductivity using mixture rule [22]. Table 1 summarizes these properties

EXPERIMENTAL WORK

Experiments were performed on a three cylinder direct injection 38.5 bhp (28.72 kW) diesel engine (Kirloskar Oil Engines Ltd.) test rig equipped with a hydraulic dynamometer (SAJ Test Plants Pvt. Ltd.). The engine is cooled with conventional cooling system comprising of a mechanically driven coolant pump, radiator and a radiator fan. The cold coolant from the radiator outlet is pumped to the engine block of each cylinder through the lower cooling line (LCL). After absorbing heat from the block, the coolant flows through the engine head of each cylinder before returning to the radiator inlet via the upper cooling line (UCL). Two K-Type thermocouples were installed in the LCL and UCL to measure temperatures of the coolant at inlet and outlet to the engine, respectively. The radiator used here is a fin-tube type crossflow heat exchanger where the coolant rejects its heat to the forced draft of air provided by the radiator fan. Measurement of air temperatures at inlet and outlet across the radiator is facilitated by installing three thermocouples at different locations throughout the core of the radiator on each side. The schematic of the experimental setup is shown in Fig 2. Engine RPM, torque, inlet and outlet temperatures of coolant, exhaust gas temperature and time elapsed for flow of every 50ml of fuel are measured using instrumentation already installed with the test rig (SAJ Test Plants Pvt. Ltd.) while air temperatures are being measured using a data acquisition system (Agilent-34672A2). The experimental conditions (engine RPM, torque and throttle) were maintained as per Indian Standard –Method of test for Internal Combustion Engines (IS 10000: Part 8-1980), Section 2-Performance test for variable speed engine.

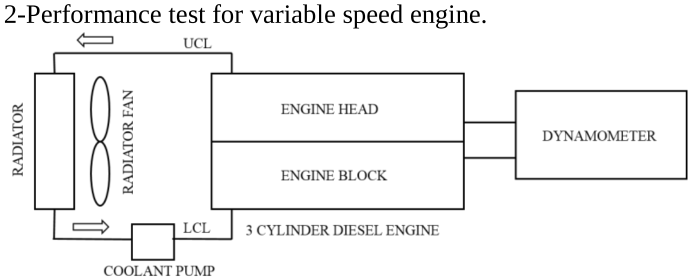

Figure 2 Schematic of experimental setup used in current study

RESULTS AND DISCUSSION

This study is aimed at comparing the performance of an automobile engine subjected to two different cooling liquids. Thus, results of the experiments are not only compiled in terms of parameters affecting heat transfer only but other variables affected by change of coolant in an automobile engine were also monitored. Experiments were carried out at engine RPM's ranging from 1200-1800 with results recorded at every 100 RPM.

Nanofluids, due to their enhanced thermo-physical properties, have been shown to enhance the overall heat transfer coefficient (U) across the automobile radiator. However, current study shows a reduction in U for nanofluid as compared to base fluid. The simplified expression to calculate U for the radiator, based on the coolant, can be expressed as

$$U_{nc} = U_{bc} * (C_{p,nc}/C_{p,bc}) *(\Delta T_{nc}/\Delta T_{bc}) *(LMTD_{bc}/LMTD_{nc}) .... (1)$$

The above equation is valid under the assumption that both the coolants have same mass flow rate and other experimental conditions also remain same except the cooling liquid. Thus, evaluation of U is merely reduced to determination of temperatures from the experiment. Figure 3 shows the variation of LMTD with engine RPM for base coolant as well as nanocoolant.

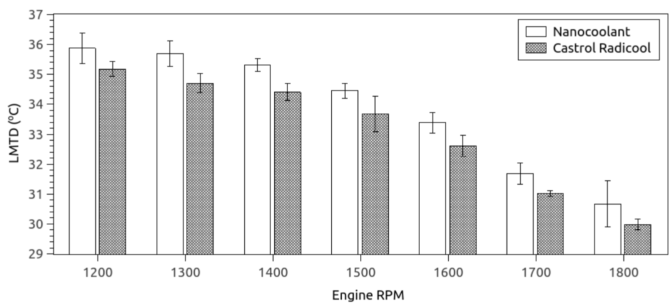

Figure 3 LMTD v/s Engine RPM for base coolant and nanocoolant

LMTD for nanocoolant is found to increase by a maximum of 2.62% for 1400 RPM and 2.37% based on an average across all engine speeds, as compared to the base coolant. However, U for nanocoolant is shown to reduce by a minimum of 3.8% for 1600 RPM and 2.8% on an average as compared to the base coolant. This reduction in overall heat transfer coefficient suggests that, for the current design of the engine cooling system (designed for the base coolant) the nanocoolant performs poorly, thus transferring less heat to the air. This implies that nanocoolant reduces the heat loss from the engine.

Considering the complex flow passage of the coolant in the engine it becomes necessary to monitor the effect of this small amount of extra heat stored in the nanocoolant as compared to base coolant on other relevant parameters like fuel consumption and emissions. Figure 4 shows the variation of bsfc with engine speed for base coolant as well as nanocoolant.

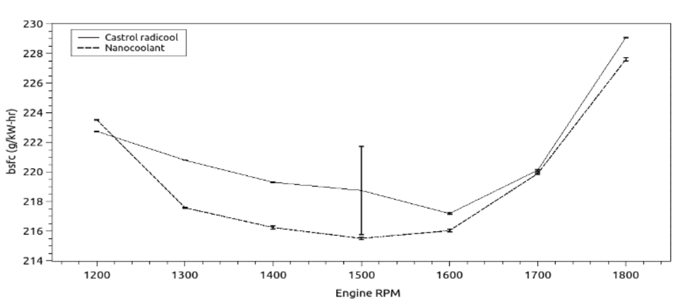

Figure 4 Bsfc v/s Engine RPM for base coolant and nanocoolant

Break specific fuel consumption (bsfc) describes the fuel consumption rate (grams/hr) of a prime mover (IC engine in this case) to produce 1 kW of power. The fact that the experiments were performed according to the IS are being reflected in the results as the nature of graph in Fig.4 is in qualitative agreement with the one reported in IS 10000: Part VI-1980. This particular nature of bsfc curve can also be explained based on the general argument of the functioning of a basic IC engine. Initially, at low speeds the engine requires little extra fuel to overcome its own inertia and that's probably the reason for the high fuel consumption rate at 1200 RPM. However as we move towards the part load-speed condition it's the combustion process that dominates the fuel consumption rather than the mechanical requirement of the engine, thus resulting in comparatively lower fuel consumption. Further at higher engine RPM's the demand for extra power raises the fuel consumption rate introducing a sharp rise in the bsfc curve at the end. Results show that when the commercial coolant is replaced with nanocoolant there is an overall reduction in fuel consumption (0.75% on average) specifically at part load-speed conditions (1.48% at 1500 RPM), thus pointing towards reduced frictional losses. This can be explained from the fact that the small amount of extra heat with the nanocoolant would help maintain optimum viscosity of lubricating oil thus aiding proper lubrication.

After passing through the engine block the coolant rises up to the engine head where it extracts the surplus heat generated during the combustion process, in a way governing the boundary conditions for the process. An analysis of the exhaust gas from the engine when nanocoolant was used showed an increase in concentration of NOx as compared to that of the base coolant.

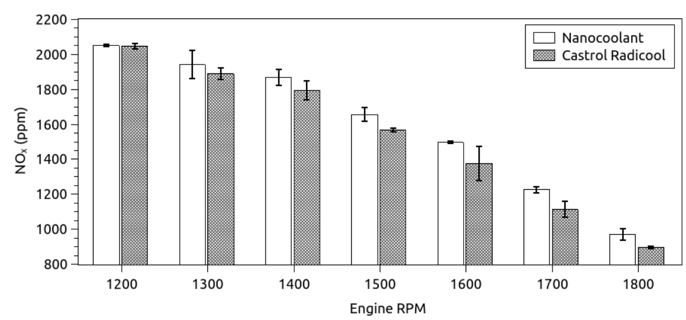

Figure 5 NOx (ppm) v/s Engine RPM for base coolant and nanocoolant

The fact that higher in-cylinder temperatures lead to high amount of NOx in the exhaust gas had long been established in the automobile industry. Figure 5 shows the variation of NOx with engine RPM for nanocoolant as well as base coolant. It is found that nanocoolant increases the amount of NOx to a maximum of 10% at 1700 RPM and an average of 5.7% as compared to base coolant. On the contrary oxygen concentrations in exhaust gas were found to be lower when nanocoolant was used. Figure 6 shows the variation of oxygen concentration with engine RPM for nanocoolant as well as base coolant. A maximum reduction of 9.5% at 1200 RPM and an average reduction of 5.8% were noted for the nanocoolant as compared to the base coolant.

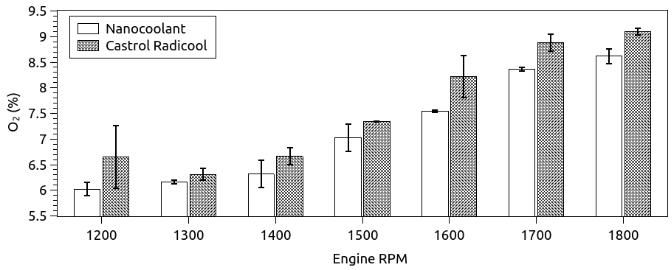

Figure 6 O_2 (%vol) v/s Engine RPM for base coolant and nanocoolant

The thorough explanation of these results is possible only when one goes in the details of how combustion happens in the IC engine and how different boundary conditions govern the chemistry of the combustion process. However, probabilistic explanations can be given based on literature and current experience. First and foremost, emissions like unburnt HC, CO etc. in the exhaust gas of an IC engine are nothing but undesirable products of combustion. Simply put, these undesirable products are a result of incomplete/improper combustion of fuel, which may happen due to numerous reasons like lack of proper mixing of fuel, improper ignition timing, improper temperatures inside the cylinder, lack of oxygen and many more. To make it short, good combustion: less harmful products while bad combustion: more harmful products. As mentioned earlier, engine coolant is allowed to pass through the cooling passages in the engine block (region outside and around the cylinder) and the engine head (regions outside and around the combustion chamber and exhaust valves). While passing through these passages it picks up heat rejected from inside the cylinder and combustion chamber, thus maintaining the inner surface (wall) of these parts at low temperatures. The temperature of the inner walls of cylinder and combustion chamber is critical to the whole process of combustion. For e.g.: especially in diesel engines, where the fuel is sprayed in a pressurized manner in form of very fine droplets inside the cylinder, too lower temperatures of the inner cylinder wall may cause fuel to be adhered to the wall resulting in incomplete combustion, whereas too high temperatures of the wall can cause self-ignition of the charge resulting in knocking. Thus, may be the effect of using nanocoolants is that, the inner walls of the engine are being maintained at higher temperatures, resulting in proper combustion of fuel.

CONCLUSION

The present work demonstrated a thorough performance comparison of an automobile engine subjected to two different cooling liquids. The fact that study of engine coolant should not be carried out in isolation with the engine had been clearly brought about by the results obtained. Commercial coolant was successfully converted into stable nanocoolant (with 1% vol. of nanoparticles) using patented top down approach. It was shown that overall heat transfer coefficient for the nanocoolant is 3.8% lower as compared to the base coolant for a three cylinder diesel engine equipped with conventional cooling system. Fuel consumption was also shown to be affected due to the change of cooling liquid. Savings of about 1.48% could be achieved using nanocoolant with 1 vol% alumina nanoparticles. Exhaust gas analysis showed an increase of 10% in concentration of NOx and reduction of 9.5% of oxygen for the nanocoolant as compared to base coolant. Literature showed that this increase in NOx concentration was a direct implication of higher in-cylinder temperatures. Thus, nanocoolants could be speculated to reduce thermal losses in the automobile engine eventually maintaining the engine at comparatively higher temperatures as compared to the base coolant. However, the dependency of the combustion process on the type of cooling liquid used needs to be looked at in great detail before concluding any further. Experiments need to be complimented with computer simulations to understand the physics behind engine cooling and its coupling with the combustion phenomenon.

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