The potential of vehicle cooling systems

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Abstract. Vehicle engine cooling systems have several functions. Excess heat removal from the engine helps to rapidly cool it, quickly reach operating temperature, maintain a constant engine operating temperature, and provide heat to the vehicle’s passenger compartment. Developments in the automotive industry, such as hybrid and electric vehicles, now also involve the temperature management of battery packs. Currently, the coolant used in cooling systems is water or an equivalent substance. Water as a coolant has low thermal conductivity. Therefore, researchers are trying to use nano-liquid as a coolant in the cooling system. Better results are expected by use of this alternative. Nano-liquids contain metal particles that enhance thermal transfer properties, so current and future cooling systems could operate more efficiently. Adding phase change materials to the cooling and air handling system will result in better efficiency in future vehicles. In the case of hybrid and electric vehicles, the addition of thermoelectric generators to cooling and exhaust systems increase efficiency. Present developments help increase a vehicles' usability and the possibility of achieving greater efficiency.

1. Introduction
Recently, the reduction of energy consumption and the drive towards energy management have become important issues. The rise of the earth's temperature, fluctuations in oil prices, and greenhouse emissions due to fossil fuels in most industrial applications are encouraging industry to adopt or develop alternative methods to improve systems’ efficiency. Heat exchange is one of the systems that must be effective in energy efficiency to transfer optimal heat between two different environments [1]. This paper discusses the problems facing vehicle engine cooling, that affects energy and fuel consumption, as well as a vehicle’s performance. This article explores different techniques to enhance vehicle engine performance and reduce energy consumption.

2. Overview of a basic cooling system’s operation
Before summarizing the research results, we present a brief overview of a basic cooling system's operation, and development directions of a radiator in a normal cooling system which is supplies coolant via a water pump to both sides of the cylinder block. Coolant flows around the cylinders and upwards into the cylinder heads, where it circulates by the cylinder head exhaust passages and the engine block. The coolant flows out of the front into the thermostat housing in the next step. The thermostat stops the main coolant flow when the engine temperature is below the thermostat opening temperature. In this case, a small amount of fluid is returned to the pump via a bypass branch. When the thermostat is open, the coolant flows back to the top of the radiator [2].
Between 1992 and 1996, General Motors used a reverse-flow cooling system in the Chevrolet Corvette LT1 engine. In these systems, the coolant first flows into the cylinder head and only then enters the engine block. Some imported vehicles also have such a cooling system. Other manufacturers use a traditional cooling system where the coolant reaches the cylinder heads last, before returning to the radiator for cooling.

![Diagram of a conventional cooling system](image)

**Figure 1.** Schematic diagram of a conventional cooling system [2].

The coolant circulating in a typical engine absorbs heat through the convection process. Figure 1 shows how the fluid flows from the hot side of the system to the cold side. The coolant returns, carrying the heat of combustion from the engine (hot coolant), to the radiator's top inlet where it enters the radiator itself. The heat is then transferred through a series of heat sinks to the air flowing through the radiator fins. At the outlet at the bottom of the radiator, the now chilled fluid is sucked out of the radiator by the water pump, where it returns to the engine to start the cooling process again.

The cooling system of an internal combustion engine may be closed or open. In a closed system, the engine coolant does not contact the outside air. In an open system, the coolant is in contact with the outside atmosphere.

3. Nanofluid

Coolant is one of the most important components of a high-performance cooling system. It should never be ignored because it transfers heat from the engine to the radiator. It protects the engine and cooling system from rust and corrosion. It prevents freezing of the system in cold climates. Most car engines remove excess heat by water cooling. However, the term water is antifreeze and a water-based coolant, not water alone. The automotive industry uses the term engine coolant which covers the function of primary convection heat transfer in internal combustion engines [3].

Continuous technological development and social change in the automotive industry have increased the demand for high-efficiency engines. In addition to high efficiency and performance, fuel economy and lower emissions are important factors. Weight reduction is also important to increase car performance. Thus, one of the optimized parameters is the radiator. To increase the radiator's efficiency,
the number of fins are greatly increased, which increases the cooling surface area. These modifications (an increase of fins and use of microchannels) can increase the cooling rate [4]. Nowadays, development has reached its foreseeable limits in increasing a radiator’s efficiency. After the structural modifications, the next development opportunity is the coolant fluid itself. The water and ethylene glycol-based coolants used today, have a relatively low thermal conductivity. The only way to cross this inefficiency threshold is if we use innovative heat transfer fluids in automotive radiators. Nanofluids have the potential to replace the conventional coolant blends used today. The coolant's heat transfer capacity can be increased by 15 - 40% when using nanofluids. Thanks to these excellent properties, a vehicle radiator’s size and weight can be reduced.

Figure 2. Effect of volume fraction of copper nanoparticle on coolant Prandtl and Nusselt number for constant air and coolant Reynolds number [3].

In contrast, the rate and efficiency of heat dissipation does not change. The biggest effect of reducing the radiator's size occurs during the vehicle's aerodynamic design. The resistance coefficient can be minimized, and this result greatly improves fuel economy. A nano liquid can be used with good efficiency when mixed with ethylene glycol copper nanoparticles. In such cases, it is important to investigate the effects of the volume fraction of copper nanoparticles and base fluid on the thermal characteristics or reduce the radiator's size. Copper nanoparticles have better thermal conductivity than other nanoparticles (such as aluminum oxide).

Figure 2 shows well, the effect of adding nanoparticles to coolants. A decrease can also be observed for Nusselt and Prandtl numbers. In contrast, the Reynolds number of the coolant is constant.

If copper nanoparticles are used in a 2% by volume ratio in the coolant, the increase in heat transfer is between 42.7 - 45.2%, increasing the Reynolds number of air flowing through the radiator from 4000 to 6000. The use of such a large amount of copper nanoparticles provides an opportunity to reduce the radiator's size by approximately 18.7%. Despite the many positive effects of nanoparticles, it is important to consider the negative effects on pumping effort. Pumping load increases by 12.13% when mixing 2% copper nanoparticles into the coolant.

The nanofluid coolant influences inlet temperature, which affects the radiator's heat output [5]. Therefore, both the heat transfer rate and the Nusselt number are affected, due to an increase in the
liquid's thermal conductivity and the decrease in viscosity; produced by an increase in the inlet temperature. Table 1 shows the increase in heat transfer as a function of inlet temperature, compared to heat transfer.

Table 1. Comparison of different coolants [6].

| Type of Liquid                              | Volume Fraction (%) | Heat Transfer Enhancement (%) Due to Inlet Temperature | Heat Transfer Enhancement (%) - Overall Increment in Heat Transfer |
|---------------------------------------------|---------------------|--------------------------------------------------------|---------------------------------------------------------------|
| Al₂O₃/water                                 | 1.00                | 6.00                                                   | 45.00                                                        |
| Al₂O₃/Ethylene Glycol                       | 1.00                | 7.00                                                   | 40.00                                                        |
| Al₂O₃/water + Ethylene Glycol               | 0.20                | 26.00                                                  | 30.00                                                        |
| MgO/water                                   | 0.06                | 6.70                                                   | 15.00                                                        |
| CuO/water + Ethylene Glycol                 | 0.80                | 19.68                                                  | 55.00                                                        |

International researchers have tested a wide variety of nanoparticles, such as Al₂O₃, ZnO, CuO, TiO₂, SiO₂ and CeO₂. However, CeO₂ (cerium dioxide) is not yet as widespread in the literature [7]. Measurement of all thermophysical properties (density, specific heat, viscosity, and thermal conductivity) are important parameters in heat exchange processes for various nanofluids (Al₂O₃, SiO₂, TiO₂, and CeO₂) leads to the selection of CeO₂ / water nanofluid [8,9]. The primary reason for choosing CeO₂ / water is its excellent thermophysical properties and affordable price [10].

Figure 3. Nano liquid base mixture (A: freshly mixed, B: a week later) [10].

Nanofluid obtained by mixing ion-exchanged water and CeO₂ nanoparticles was studied. 99.9% pure CeO₂ is commercially available (MK Impex, Canada). The particles have an average size of 25 nm and a density of 7.123 g/m³. CeO₂ is insoluble in water. A high concentration suspension can be prepared using an ultrasonic mixing unit which crushes agglomerates formed during mixing and improves dispersion. Then, the mixture can be diluted to the required concentration. Figure 3 shows the resulting mixture's stability (after 7 days).

Table 2. Comparison of different coolants [10].

| Type of Liquid       | Increasing in absorbed energy parameter (relative to water) - (%) |
|----------------------|---------------------------------------------------------------|
| water                | 100%                                                          |
| Al₂O₃/water          | 140%                                                          |
| CuO/water            | 132%                                                          |
| GNP/water            | 103%                                                          |
| CeO₂/water           | 134%                                                          |
The results show that the absorbed energy is 34% for CeO$_2$ / water nanofluid, 3% for graphene nanoplatelet (GNP) / water nanofluid, 32% for CuO / water nanofluid, and 40% for Al$_2$O$_3$ / water nanofluid increased. Another positive feature of CeO$_2$ / water nanofluid is its stability, (no sedimentation was observed in the studies after 7 days). The maximum increase in temperature difference is 37.3% when CeO$_2$ is used in a volume fraction of 0.035%. The use of nanofluid allows for more favorable operating conditions. However, an increase in heat transfer intensity results in extra pumping load (due to increased kinematic viscosity). Another issue with nanofluids is stability and the need for a proper (sedimentation-reducing) design of flow channels [11].

4. PCM – Phase Change Material

In motor vehicles, so-called latent heat storage is a great option. The currently best-researched direction of latent heat storage is phase change material (PCM). Vehicles, systems with a transient thermal profile are classified according to an operating temperature between 0 and 800°C. The low-temperature class ($T<100^\circ$C) mainly includes systems for stabilizing temperature conditions in the passenger compartment of the vehicle. The medium temperature class (100°C < $T <200^\circ$C) includes the chassis thermal protection system, engine cooling circuit, and high-performance electronics. Systems in thermal contact with hot exhaust gas are in the high-temperature class ($T>200^\circ$C) [12]. The available temperature ranges are shown in Figure 4 (several options for selecting and applying PCM).

![Figure 4. Exhaust gas temperature range for passenger cars [12,13].](image_url)

Heat storage options for automotive cooling systems: Most automotive engines use antifreeze coolant to keep the engine in the operating temperature range. The coolant is a mixture of pumped ethylene or propylene glycol and water, operating temperature range: 80 - 100°C. In addition to cooling the engine, it is also responsible for heating the passenger compartment and maintaining the other components’ appropriate operating temperature (e.g., gearbox). The coolant is under pressure in the cooling system, so the coolant is in a liquid phase even above 100°C [12]. For electric and hybrid vehicles, several cooling circuits are used. The maximum temperature values in the cooling systems are constantly decreasing, thus optimizing the cooling system further. The element most closely related to the present research topic is the cooling radiator, which could be reduced in size due to optimization. When designing cooling systems, they try to minimize oversizing, as peak load is only a fraction of the total operating time. Several studies investigate the possibilities of applying PCMs in connection with the cooling system. Figure 5 shows a possible application. A cooling system’s size and surplus high heat exchange capacity can be significantly reduced by adding heat accumulators. The accumulators offer the possibility of a faster warm-up time after a cold engine start. During low heat load conditions such
as idle or cruising; the accumulator can release excess stored heat, back into the cooling system to be carried away by the much smaller and lighter radiator.

Figure 5. Cooling system with PCM heat storage (heat accumulator) [14].

Polyalcohol erythritol is used as a moderate melting point PCM used in cooling systems. These lower melting temperature PCMs allow more space for the formation of thermal gradients in cooling systems. The PCM's melting temperature must be above the coolant's constant temperature. In this temperature range, high-temperature paraffin, fatty acids, and salt hydrates are suitable. Among the organic substances, sugar, sugar alcohols, and carboxylic acids cover the range up to 200°C. Mixtures of molten salts and metals cover the entire temperature range [15].

In addition to the heating and cooling system, further research is being carried out into the passenger compartment's proper temperature conditioning [16]. A PCM was used by placement between the car's roof and the interior roof trim. The PCM volume percentage is only 0.22% of the total car cabin. During the first tests (2 hours of outdoor parking), significant temperature stability was achieved (the inside compartment of the vehicle did not overheat at high summer temperatures). In winter, a PCM can contribute to the heating. The amount of PCM - (RT-27 Rubitherm) - used for the experiments was 4 kg (4.55 l), placed in a capsule in the car’s roof. Nowadays, the use of PCMs presents many opportunities for motor vehicles.

5. TEG – Thermoelectric generator

Internal combustion engines’ efficiency in the converting of chemical energy ranges from approximately 20% to 45%. During the conversion of chemical energy into mechanical energy, most of the energy is dissipated as heat in the exhaust gas and coolant. Thus, researchers are developing waste heat recovery systems to improve engine efficiency. A promising technology currently being discussed that has been found useful for this purpose is thermoelectric generators (TEG). TEG is present in the vehicle as a solid, passive, quiet, scalable, and durable device. TEG provides temperature control and design flexibility for researchers. TEGs have limitations such as low-temperature limits and relatively low efficiency. The waste heat recovery system can convert waste heat into electricity and reduce the car's fuel consumption by reducing the car's alternator load. TEGs use the so-called Seebeck effect, explained in Figure 6 [17].
When one side of the TEG heats up the other side cools, a voltage difference is created due to the temperature difference. TEG is generally 5% efficient and can generate energy from any temperature difference [18].

Major multinational automakers such as BMW, Ford, Renault, and Honda have shown interest in exhaust heat recovery to develop systems that use TEGs. TEGs are usually placed on the exhaust pipe's surface (in the form of a rectangle, hexagon, etc.), and the cold side is cooled by a heat exchanger in which the engine coolant is circulated [17].

Researchers have developed a waste heat recovery system to replace the conventional car radiator [19, 20]. No extra moving parts were added to the modified radiator. The system used a factory-installed water pump and a fan. The use of heat pipes and TEGs allowed heat transfer and power generation without introducing extra moving parts. The system consisted of 72 TEGs and 128 small-diameter heat pipes. Under idle conditions, the warm side was approximately 90°C, and the cold side was approximately 70°C. Under these conditions, it produced 28 W. When run at 80 km/h driving mode, the warm side was approximately 90°C and the cold side was approximately 45°C. Under these conditions, it produced 75 W. The assembled system, as shown in Figure 7.
For hybrid vehicles, TEGs could be used in serial or parallel mode. With the optimal application of TEG, energy and battery capacity management increases engine efficiency while reducing fuel consumption.

Increased engine efficiency can be achieved by the use of optimized TEGs to manage battery storage and energy. Many difficulties have to be solved during construction of a TEG network, such as the space restrictions and the implementation of various technical solutions (e.g., installing an exhaust system). Example of a complete TEG network: 20 TEG on the braking system (5 TEG/disc) and 30 TEG on the exhaust system. The complete system's power is approximately 100 W (at a vehicle speed of 40 km/h). A TEG network formed in a hybrid vehicle is shown in Figure 8 [21].

![Figure 8. TEG network and electrical system for a hybrid vehicle [21].](image)

The presented network must be treated and designed as a complex electrical system, so it is necessary to design it optimally (e.g., it is necessary to optimize the charging and discharging time of the battery, thus increasing its life). Experiments and prediction methods are needed to design and assemble the ideal system. At the end of a complex design process, we get an efficient and environmentally conscious hybrid system.

6. Conclusion
This study presented a vehicle cooling system's potential and the development direction expected by the advancements (increasing performance while reducing emissions). Conventional cooling systems are already optimized today and can achieve higher cooling capacity. The use of new nanofluid technology is an opportunity for increased efficiency. The use of the new coolant provides a prospect to reduce the radiator's size, which also results in weight reduction.

In addition to the development of coolants, there are various options for achieving a cooling system's optimal operation. One of the presented possibilities is the use of PCM, which allows, so to speak, for the equalization of thermodynamic processes. With the use of PCM, temperature balance can be better equilibrated, resulting in better engine efficiency.

In our study, the TEG system was presented, which, based on its flexible applicability, can be used in several places in the vehicle, and thus we can generate extra electrical energy. This extra electricity helps supplement the electrical network (it reduces the amount of electrical load on the generator, so we can achieve an increase in engine efficiency).
In hybrid and electric vehicles, the systems listed above could be used together, positively affecting both extractable performance and range.

The development of vehicle cooling radiators is continuous, adapting to changing needs (increasing trend of electric vehicles). During our laboratory research, we had the opportunity to gain insight into current industry developments and directions. Current developments include the optimizing of the cooling radiator [22] and the noise reduction of the cooling radiator component [23]. As a result of our joint industrial research, the units with improved efficiency are suitable for both conventional internal combustion engines and new electric vehicles. Future research directions include thermal management of vehicles and the developments we have followed throughout this work.

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