Engine Thermal Management System: A Review

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A review of the various engine thermal management strategies developed over the years is presented in this paper. The conventional cooling system of the engine consists of passive components with many constraints on them which limit the engine to operate at its full potential. Also, the design of the conventional cooling system is bulky and can be compacted by adopting new features which are presented in this paper. Over the years, the various components of the cooling system have been reviewed and have been replaced with electronically controllable components which provide independent control over its operation with quick response time and less parasitic loss. Apart from this, the design of the cooling system has been modified with the introduction of various cooling strategies like split-cooling, precision cooling, reverse cooling and ultimate cooling strategies which reduces the coolant mass and makes the system much more compact. Engine thermal management system also interacts with the combustion process which provides another parameter for engine calibration. Control of the engine temperature with engine thermal management system provides a means to reduce the engine friction with reduced fuel consumption and reduced emissions.

***Keywords*:** thermal management, coolant, precision cooling, lubricating oil

Introduction

Today's modern engines with their new technologies have become more complicated as they require controlling the operating temperature of the coolant, lubricating oil, charged air and fuels. Conventional cooling components of the engine are not very efficient in terms of its power consumption and correct monitoring and maintaining temperatures of multiple components. They can consume up to 15% of the available engine power at high load conditions with multiple parasitic losses [1].

Numerous researches are being conducted on the engine in order to improve the fuel economy and meet the stringent emission standards. One of the methods is maintaining the combustion conditions within an optimum temperature range by improving the cooling system design of the modern engines. Precise control of the temperature of the combustion process will help in minimizing pollutants resulting from incomplete combustion. The term "Thermal Management" refers to controlling the various interaction between the cooling system, lubrication system, demisting, and air conditioning system, intake and exhaust system with each other so that all the system work symbiotically and helps in improving the performance of the engine while meeting the current emission norms.

In this paper, first the effect of coolant temperature on the engine performance is discussed along with recent developments in the cooling system of the engine with its advantages and disadvantages. Over the past 20 years, various alternative cooling strategies have been proposed in order to reduce the system weight and reduce the cost of the cooling system. Some of the strategies which are presented in this paper are Thermal Management Intelligent System (THEMIS), Evaporative engine cooling, Precision cooling, Split Cooling, Reverse cooling, The Cool Master strategy and Ultimate Cooling strategy [2].

Effect of Coolant Temperature

The engine coolant temperature directly influences the performance and emissions from the engine as the gas temperature is dependent upon the coolant temperature. The gas temperature affects the engine head and block temperature. There is a limit up to which the engine wall temperature can be increased or decreased which affects the engine performance. At a higher wall temperature above a certain value, the lubricant film breaks down which results in metal to metal contact of moving components increasing frictional loss. While lowering the wall temperature increases the oil viscosity but it also increases the volumetric efficiency which increases the peak power [3].

Thomas et al. [3], Abdelghaffar et al. [4], Mohamed[5] and Hossain et al.[6] independently studied the effect of varying the coolant temperature on different engines with different fuels on the performance and emissions.

Some of the common observations by increasing the coolant temperature were, the volumetric efficiency decreases with reduction in fuel consumption and decrease in BSFC and CO_2 emissions and increase in NOx emissions.

The results of Thomas et al. showed a increase in CO and decrease in THC emissions. The results of Abdelghaffar et al. showed nearly constant CO and THC emissions. Hossain et al. used biodiesel blend and diesel and the results using biodiesel were completely different as compared to diesel.

Active Control of the Cooling System (THEMIS)

A conventional engine cooling system consists of three vital components, a mechanically driven pump, a wax type thermostat, and a fixed speed fan. These components have certain disadvantages which are overcome by the use of electrical pump, electric thermostat and a variable speed fan which gives the cooling system an active control over its operation. The mechanical pump is coupled with the crankshaft of the engine by a belt or gear drive and it rotates at a speed in accordance with the speed of the engine irrespective of the engine load at that speed. The cooling is done in proportion with the engine speed and not in the proportion of heat rejection rate of the engine. Another drawback of the mechanical pump studied by Kim et al. is the cavitations phenomenon arising due to high pressure drop which is overcome by the use of electric pump [7]. Also because of its low efficiency at the idle condition, the mechanically driven pump cannot provide adequate coolant flow for the cabin heating.

Chalgren et al. experimentally showed improvement in performance in terms of fuel consumption and emissions by replacing mechanical pump with electrical pump. One drawback with the electrical pump is it requires high voltage which is very difficult to achieve in vehicles with a typical internal combustion engine [8].

The second passive element in the conventional cooling system is the wax-thermostat which is placed at the entrance of the radiator used to regulate the coolant route through the radiator by opening or closing of the valve. When there is a rise in temperature of the water, the wax melts and opens the valve through which the hot water enters the radiator for cooling.

The disadvantage of the conventional wax-type thermostat are its slow response to the rapid changes in thermal loading which causes undesirable temperature fluctuations, being able to sense the temperature at only one location, they are restrictive in nature and they provide high resistance to the coolant flow as compared to the electrical thermostat [9].

Kim et al. [10] and Krause et al.[11] independently studied the effect of employing electrical thermostat on the performance and emissions from the engine. Both of them showed a reduced warm-up time by employing electrical thermostat with reduced fuel consumption and emissions.

Other researchers like Page et al. [12], Cho et al. [13], Chanfreau et al. [14] and Choiet al. [15] also showed the advantage of employing active controllable elements in the cooling system over conventional cooling system.

Most of the research on active thermal management of cooling system focuses on steady-state conditions and does not consider the effect of transient conditions but in the real world, a wide range of operating conditions are experienced by the engine in quick succession. The active thermal management system should be able to achieve the right temperature for different operating conditions and since the operating conditions are not always constant but change rapidly with time depending on the real world conditions, the system should be able to achieve the right temperature without any delay. The thermal inertia will cause a delay in reaching the desired temperature if the control scheme of the system is not fast enough.

Precision Cooling

This technique focuses on cooling inside the critical areas of engine head and engine block by adjusting the piping arrangements of the coolant flow. In this technique, the coolant velocity in the critical area is adjusted by adjusting the cross-sectional area of the flow passage in order to extract the exact amount of heat by matching with the local heat flux in that region. This technique avoids excessive cooling or insufficient cooling by matching the coolant velocity with the local heat flux.

Clough showed that this technique gives reduced warm-up time with a reduced peak temperature and overall temperature distribution across the engine which reduces the thermal loading and increases the reliability of the engine [16].

Mulemane et al.[17], Finlay et al.[18] and Vagenas et al.[19] individually showed that this technique decreases the coolant mass considerably thereby making the system compact but accompanied by a rise in pressure drop.

Evaporative Cooling

Evaporative cooling of the engine is based on the principle of making use of enhanced heat transfer rate during liquid to vapor phase transition during boiling of coolant as compared to conventional liquid cooling which extracts heat only in single-phase convective heat transfer mode only. In this technique, phase change takes place within the cylinder jacket only. The vapor resulting from phase change is released, collected and condensed from its vapor state and again circulated back to the cooling circuit as a liquid. Therefore by making use of latent heat of vaporization of the coolant, the heat is extracted from the engine. Several advantages of this technique are reduced coolant mass and overall compact cooling circuit, reduced mass flow rate of the coolant with very less pumping power, uniform cylinder head temperature, reduction of parasitic losses and reduced emissions[20].

Reverse Cooling

In this cooling strategies, the coolant is first supplied through the head and then through the block, unlike the conventional cooling system. In doing so, maximum heat transfer takes place through the head while maintaining the block temperature at a higher temperature than the head.

Split Cooling

In this cooling strategies, as the name suggests two different coolant circuits are provided for the head and the block. Just like reverse cooling, this technique also allows the block to be maintained at a higher temperature than the head by providing colder coolant to the head. In this way, both the head and the block can be maintained at a different temperature independently which gives another parameter for engine optimization. Since the head temperature can be maintained at a colder temperature, the volumetric efficiency of the engine increases as it makes the air more dense which results in more rapid and complete combustion with high power output with reduced harmful emissions. Also at the same time, the block can be maintained at a higher temperature which results in a less frictional loss with reduced fuel consumption and lower in-cylinder pressure.

Kobayashi et al. studied the effect of split cooling technique by maintaining different head and block temperature and reported reduction in fuel consumption with improvement in volumetric efficiency and peak power [21].

Rehman et al. also studied the dual circuit cooling and compared the results with conventional cooling. With increase in load, dual circuit cooling showed a greater reduction in BSFC and HC and CO emissions [22].

Cool Master Strategy

This technique is equivalent to THEMIS technique as it uses the same components, except that it uses two pumps separately, a mechanically controlled pump is used to circulate the coolant in the cooling circuit of the engine and a small electric pump is used to regulate the cabin temperature even when the engine is turned off [2].

Ultimate Cooling System

In this cooling system, the engine coolant is used exclusively to cool all the various fluids in the vehicle like air, lubricating oil, refrigerant, exhaust gas and fuel. The charge air cooler is replaced by a water charge air cooler; the refrigerant-air condenser is replaced by refrigerant-water coolant condenser. In order to modify the front end design of a vehicle to meet the pedestrian crash test specification, all the different heat exchangers at the front which are cooled by air will be replaced by a multi-temperature radiator moving the new heat exchangers cooled by water (coolant) under the hood. And all these heat exchangers placed closer to the heat source making the system much more compact [23].

Conclusion

This paper focuses on the various thermal management systems and their effect on various system parameters. The various components of the thermal management system need to be improved in order to increase the efficiency and performance of the engine. While active thermal management strategy focuses on increasing the efficiency of the cooling system by decreasing the pumping work with the use of electronic components, other strategies like precision cooling, reverse cooling, split cooling and evaporative cooling focuses on improving the heat transfer rate of the cooling system thereby reducing the pumping power as well as coolant mass making the system more compact. Latest development in the thermal management is the Ultimate cooling strategy which makes the system much more compact by replacing the heat exchangers at the front end of the vehicle for various fluids like refrigerant, air, exhaust gas and lubricating oil under the hood near to the engine where the heat exchange takes place with the coolant of the engine only. The thermal management system also interacts with the combustion process of the engine as it determines the operating temperature of the engine which in turn affects various other parameters like volumetric efficiency, ignition delay, fuel consumption, in-cylinder temperature and pressure and emissions from the engine.

Nomenclature

BSFC	brake specific fuel consumption
CNG	compressed natural gas
CO_2	carbon dioxide
CO	carbon monoxide
ECU	engine control unit
EGR	exhaust gas recirculation
HC	(unburned) hydrocarbon
NOx	nitrogen oxides
PM	particulate matter
ppm	parts per million
rpm	revolution per minute
THC	total unburned hydrocarbon
THEMIS	Thermal Management Intelligent System

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