Effect of coolant temperature on performance and emissions characteristics of I.C. engines: A Review

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ABSTRACT

Cooling systems of conventional engines are designed for full load operating conditions but these engines most of the times operate at part load conditions, so a significant portion of thermal energy of the fuel is lost in cooling. Various engine parameters like warm up time, performance and emission are affected by the coolant temperature. This paper presents a critical review of significant studies that are relevant to effects of coolant temperature on performance and emissions. In addition, this paper reviews the published results and discussions on the heat transfer intensification methods including changing of fins design, increasing fin surface roughness and introducing perforation in case of air cooled engine. From this review, it has been observed that increasing coolant temperature had a significant effect on reducing the emissions e.g. O_2 and CO. Increasing the coolant temperature also decreases the fuel consumption rate, warm up time at time the brake thermal efficiency increases. In contrast, NOx emission was observed to increase in case of increasing coolant temperature. Thus it could be concluded that the engine should be cooled up to a certain limit as over cooling as well as under cooling, both are disadvantageous.

***Keywords*: Emissions, Engine Performance, Heat Transfer, Fins, Perforation, Roughness, Cylinder Block.**

I. INTRODUCTION

When an internal combustion engine is operating at a full throttle, the maximum temperature reached due to burning of charge may be as high as 2700^{o}C. The expansion of the gas during the power stroke lowers the temperature inside combustion chamber. However, the minimum operating temperature of the gas that occurs during the exhaust stroke may be as high as 800^{o}C. The entire engine absorbs some heat from the hot gas and the amount of heat absorbed is proportional to the temperature, the area exposed to the gas and the duration of the exposure. This heat raises the temperature of the components of the engine and sometimes the temperature of the exhaust gas may go above the melting point of engine materials such as aluminum due to knocking.

The heat transfer occurring within an engine is very important for its proper operation. About 35% of the total chemical energy that enters an engine in the form of fuel is converted to useful work and about 30% energy is lost in exhaust.

This leaves about one-third of the total energy, which is dissipated to the surroundings of the engine by some mode of heat transfer through coolant fluid [1]-[14]

Materials used in the making of some components of the engine may not withstand the high temperature reached during the combustion process and would quickly fail if they are not properly cooled. Appropriate temperature distribution is highly critical in the correct functioning of the engine and its components and preservation of the lubricant [2].

The combustion chamber wall, piston crown, the upper end of the cylinder and the region of the exhaust port are exposed to the hottest gases and reaches the highest temperature in engine. The resulting thermal expansion of these parts distort them from their correct shape, causing gas leakage, loss of power, valve burning, gasket hardening and possibly even cracking of the cylinder head. So, a proper cooling system is must in an engine that can provide necessary cooling so that these problems can't occur.

In this paper, an investigation is reported that could bring a huge resources and energy saving, reduce pollution and increase productivity of the automobile industry by the means of changing the coolant temperature[8] and also by shape, size and modifying the fin structure in air cooled engines. Fins are extended surfaces that are used to enhance the heat transfer from the engine surfaces to reduce the metal temperature [15]-[27]. Fins on the 2S engines are generally longer and wider than 4S engines as thermal loads on 2S engines are higher than corresponding 4S engines [25].

A. Effect of overheating/under cooling.

The electrical and electronic components can be affected by high temperature, which may cause malfunctioning and poor performance of the major components of a vehicle and result in engine stalling [2]. Moreover, the oil film that should lubricate the piston and the cylinder walls may be burnt or carbonized, causing the parts to rub against each other resulting to excessive wear and even seizure of the piston. Power is lost by the heating of the fresh gas entering the cylinder, which reduces the volume of air intake and thereby reducing the power output. Lastly, an increase in temperature of the fresh gas increases the ability to detonate in case of SI engines. Some parts of the surface of the combustion chamber may be hot enough to cause pre-ignition, which may result in serious damage to the engine in case of S.I engines.

B. Effect of overcooling/under heating

It is, however, important not to overcool the engine. Heat is necessary to assist in vaporizing the fuel inside the cylinder during the compression stroke. When the engine is overcooled, some of the heat which may be utilized to expand the gas may be lost. Reduction in vaporization may cause gas produced by combustion to condense on the cylinder wall [2].This leads to dilution of the oil in the sump and the addition of harmful corrosive acids.

II. Effect of Coolant Temperature on Engine Performance Parameters

Various parameters show different trends on changing the coolant temperature of engine. Various studies have been conducted to study the effect of coolant temperature on engine parameters like volumetric efficiency, warm-up time of engine, fuel consumption, power produced and specific fuel consumption. Coolant temperature listed in this paper indicates water outlet temperature exiting the water jacket.

In this study we are going to study the effect of change in coolant temperature alone.

A. Effect of coolant temperature on brake thermal efficiency and specific Fuel consumption

Brake thermal efficiency depends upon the power produced by the engine, mass flow rate of fuel being consumed and heating value of fuel. These variables are measured and brake thermal efficiency is found out which is given as-

$$\frac{Brake\ power}{(mass\ flow\ rate\ of\ fuel) \times (heating\ value\ of\ fuel)}$$

It has been found that with increase the coolant temperature, mass flow rate of fuel decreases and brake power increases as the cooling losses are decreased when coolant temperature is increased. [1]

Coolant losses are the function of coolant temperature. As we increase the coolant temperature the temperature gradient between engine and coolant decreases which in turn decreases the heat transfer rate between engine and surrounding. So, it can be said that by reducing the coolant losses power output of engine can be increased. Figure 1, shows the variation of Bake Specific fuel consumption (BSFC) of a SI engine [7].

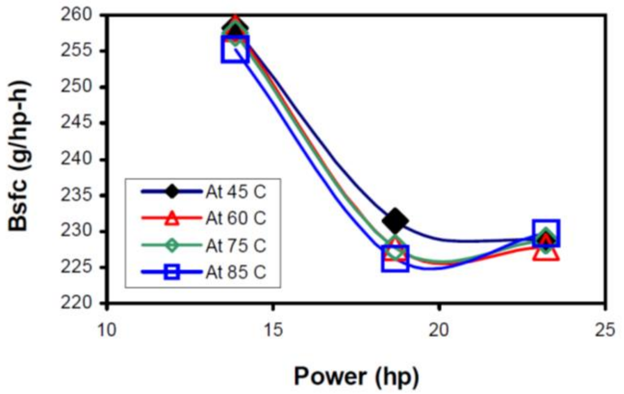

Fig.1 - Variation of BSFC at different loads with coolant temperature [7]

As the cooling water outlet temperature is increased from 45°C to 85°C, small improvement on bsfc (about 1-2%) was noticed. Small reduction in heat losses to the cooling water mainly is responsible for this change.

B. Effect of coolant temperature on volumetric efficiency and brake power.

Volumetric efficiency of engine denotes the amount of air fuel mixture that can be sucked in during suction stroke and for a four stroke engine it is given by-

$$\frac{2 \times Va}{Vswept \times N}$$

where V_a is the volume flow rate of air intake and is measured by airbox method, V_{swept} is the swept volume of the engine cylinder and N is rotational speed of engine . Since the increase in temperature of engine cylinder leads to increase in the temperature of fresh charge, thereby reducing its density which reduces the mass flow rate of intake charge. Thus, by increasing the coolant temperature, the engine cylinder temperature goes up and mass flow rate of fresh charge during suction decreases, thus decreasing the volumetric efficiency. Due to decrease in volumetric efficiency there should be decrease in brake power but since the coolant losses are also minimized, brake power may increase or decrease.[8]. It can be observed in fig-2 that volumetric efficiency decreases on increasing the coolant temperature at various speeds.

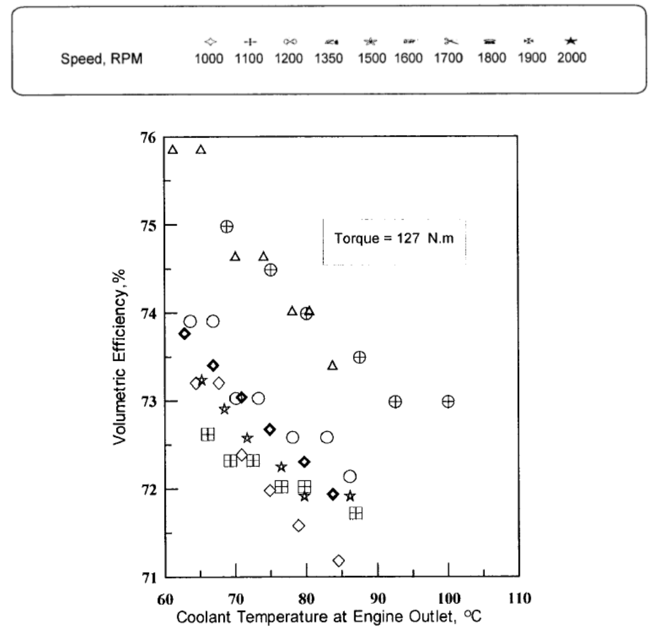

Fig.2 -Effect of coolant temperature on volumetric efficiency [1]

C. Effect of coolant temperature on warm-up time of engine.

Conventional cooling system has a water pump coupled with engine shaft directly. Speed of the pump is proportional to speed of crankshaft. During the starting or warm up time of engine the coolant is supplied at the same rate as that to the steady state condition. Due to this the engine warm-up time is more as the coolant is continuously flowing in the water jacket. Advance cooling techniques include electric operated pump or a heater that provide hot coolant water to the engine instead of cold water. These techniques lead to reduction in warm-up time of engine, thereby decreasing the fuel consumption rate and harmful emission during warm up time.

By controlling the coolant flow path cross section area i.e. by increasing the coolant temperature warm-up time can be reduced which is verified experimentally. [6][9]

III. Effect of Coolant Temperature on Emissions

There are various techniques to reduce the harmful emissions from engine like Exhaust Gas Recirculation (EGR), using oxidation catalyst, particulate filter, etc. Although these techniques show promising results but they need to be installed separately in the exhaust system of engine. A much simpler technique of reducing emission is regulating the coolant temperature or flow rate according to engine operating conditions.

Combustion in IC engines comprises of too many chemical reactions, these reactions are temperature driven and thus the quantity of end products is dependent on temperature such as by keeping the cylinder wall hotter oxygen, carbon mono oxide (CO) can be decreased while emissions like nitrogen oxide (NO_x) and carbon dioxide (CO_2) can be increased. These results may vary a little with change in speed and load of engine.

A. Effect on oxygen (O_2) emissions

If the coolant temperature is increased at constant speed, there is a slight decrement in percentage of oxygen emissions. This is because at higher temperature the reaction of oxygen and hydrocarbon is more predominant as compared to when the coolant is at lower temperature. This increases the combustion efficiency. However it has been noted that the oxygen content decreases with increase in speed of engine because of turbulence of charge at high speed which cause more even mixing of fuel and oxygen.[1]

B. Effect on Carbon monoxide (CO) emissions

Carbon monoxide emissions are the indication of improper combustion or non-availability of oxygen in the charge. Since the increase in coolant temperature increase the combustion efficiency of charge, better oxygen and hydrocarbon reaction takes place which reduces the amount of carbon monoxide in emissions [1]. This trend remains same in all types of engine weather it is diesel engine, petrol engine or a CNG engine [2].

It can be clearly seen that the CO emissions decreases with coolant temperature as shown in fig 3.

C. Effect on Carbon dioxide (CO_2) emissions.

Since the CO emissions decreases with increase in coolant temperature because of better combustion, CO_2 emissions increase. This can be explained by the combined effect of lean mixture and increased charge temperature.

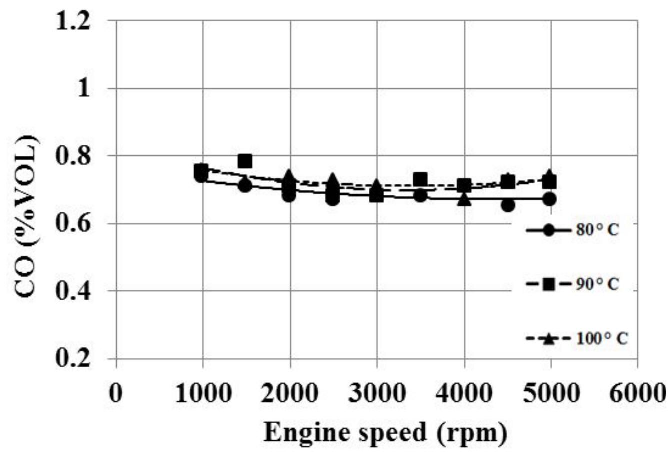

Fig.3 - carbon monoxide emissions versus engine speed at different coolant temperature at half load [4]

D. Effect on Hydrocarbon (HC) emissions.

Hydrocarbon emissions are the indication of wastage of fuel due to improper burning of fuel and some of the fuel may go unburned. Hydrocarbon emissions are very less influenced by the increase in coolant temperature. Thus, the HC emissions are same as those of base case unless the coolant temperature is kept too low [1][6].

E. Effect on NO_x emissions.

NO_x emissions depend upon availability of oxygen, temperature of charge and duration of combustion. By changing the coolant temperature we can indirectly change temperature of charge in the combustion chamber. It has been observed that high temperature favors high NO_x content in emissions. Therefore, increasing the coolant temperature increases the NOx content. For all the other emissions, their percentage in emission decreases or remains constant by increasing the coolant temperature but on contrary NO_x emissions are increased. It can be seen in the figure that NO_X emissions increase when the coolant outlet temperature is increased from 85^{o}C to 105^{o}C of a CI engine.

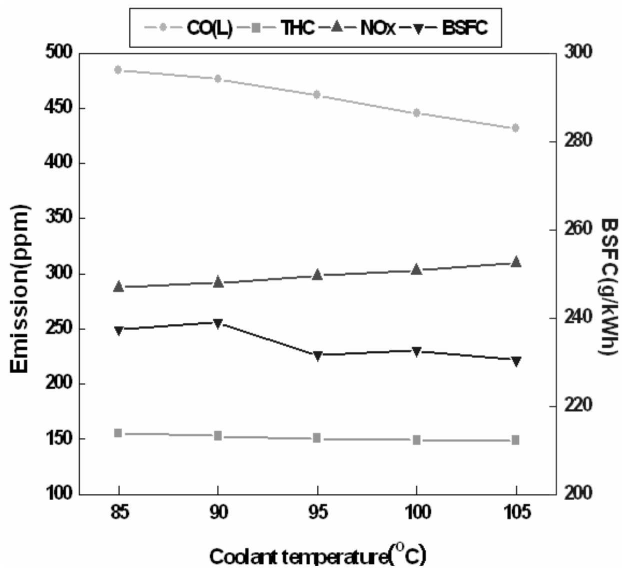

Fig.4-Effect of coolant temperature on emission characteristics and BSFC [7]

IV. Effect of Rate of Cooling in Air Cooled Engines

Air cooling methods is used only in low powered engines as the heat transfer coefficient of air is very low as compared to water. These engines are generally S.I. engines or Single cylinder low power C.I. engines.

Extended surfaces or fins are used to enhance the heat transfer in air cooled engines. Enhancement of heat transfer through fins can be done in many ways such as changing the shape of fins, changing the material of fins, changing the wind velocity and changing the roughness of fin and cylinder.

There are many studies done on fins of engine which includes changing the shape of fins i.e. concave and convex geometry of fins [15], changing the slot size in existing fin geometry [16], changing the roughness of fins and cylinder from 250 microns to 400 microns etc. [17]. Many alloy materials like Aluminum 6061 have high thermal conductivity of 167 W/mK which can replace conventional material and thus increase the heat transfer rate [24]. These studies are done using modeling tools and simulation software like ANSYS workbench. It is observed that appropriate fin shape could result in improved heat flux and also reduce the engine weight by developing lighter fins and hence lower engine cost.

Increasing the heat transfer rate or heat flux from the cylinder block directly effects engine performance and emissions as increasing the heat transfer rate is equivalent to decreasing the coolant temperature of coolant water in case of water cooled engines which means if the heat transfer rate is increased by modification in fins design, there is a decrement in NO_X and CO_2 emissions and there is decrement in CO and HC emissions and decrement in fuel consumption in case of decreasing heat transfer rate through fins surface.

V. Conclusions

- Volumetric efficiency increases on decreasing the coolant water temperature.
- Mass flow rate of fuel consumed decreases on increasing the coolant temperature and thus specific fuel consumption decreases and brake thermal efficiency increases. Also warm up time can be decreased which decreases the high fuel consumption and harmful emissions during warm up time.
- Cooling losses from the cylinder surface and head of engine decreases on increasing the coolant temperature. From the studies it has been observed that that the coolant losses decreases from25 % at T_{Cout}=60°C to 15°C at T_{Cout}=100°C at constant speed and torque condition.
- NO_x emissions increase on increasing the coolant temperature as high temperature favors NO_x emissions but CO emissions decreases on increasing the coolant temperature. However, HC emissions show insignificant variation
- Heat transfer rate can be increased by changing the shape of fins in case of air cooled engines. Therefore lighter fins can replace the conventional one and weight of the engine block can be reduced.
- More effective fin designs obtained by simulation results can also be implemented in case of cooling of heat sink and other industrial applications where heat has to be dissipated by air.
- By selecting the optimum shape of fins having maximum heat transfer rate problem of pre-ignition can be avoided in case of S.I engines.

- Working of engine cooling system affects the performance and emission characteristics of engine; therefore the parameters like coolant temperature, fin shape, coolant flow rate should be selected according to proper functioning of engine.

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