Optimisation of Engine Cooling for Knock Suppression of Turbocharged Gasoline Engine.

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ABSTRACT:

Various approaches for improving the thermal efficiency of Gasoline internal combustion engines are turbo-charging, increase in compression ratio and use of exhaust gas recirculation. However, the occurrence of knock poses an obstacle to the use of higher boost air at higher compression. Prevention of knock based on a clear understanding of its characteristics; means of enhancing thermal efficiency. Intake gas temperature and end gas temperature play very vital role for knock phenomenon in the gasoline engines.

In turbocharged gasoline engine, air is always boosted in to intake manifold which can be taken for combustion which leads to heavy knocking at higher loading condition of the engine i.e. in the max torque range area. In this paper knocking tendency of an engine is reduced by optimizing charge temperature at the end of a compression stroke which effectively suppresses knock. Using coolant flow optimization through cylinder head and crankcase, we succeeded in suppressing the knock. Optimistion of engine cooling helps to operate the engine at high thermal loads. By decreasing the wall temperature on the exhaust side by about 9K while maintaining the wall temperature on the intake side, it was possible to advance the spark timing and improve the thermal efficiency over the operating speed range. This leads to improvement in BSFC of an engine.

Keywords: Knock, Cylinder Head, Crankcase, CFD, BSFC

1. INTRODUCTION

Individual transport is facing more and more constraints. In the past decade regulations and car manufacturers have focused above all on decreasing pollutant emissions. Even though it has always been a major part of research, fuel economy has now become the number one priority because of the CO_2 greenhouse effect. In the long term, hybridisation presents the best potential but in the short term, downsizing will allow for a substantial reduction in gasoline engine fuel consumption

In fact, turbo-charging a gasoline engine while reducing its cubic capacity - downsizing - is a major way to reduce CO_2 emissions. Considering the efficiency chain that leads to the final global efficiency of an engine, and by comparing it with a conventional naturally aspirated gasoline engine, this approach reduces pumping and friction losses. Today, the question is to reap the benefit in terms of fuel consumption while preserving a high level of drivability, fun to drive and reasonable production costs for the engine. In fact, turbo-charging allows for high torque and power densities but has some drawbacks on low-end torque and knock sensitivity that may have an impact on compression ratio.

Air-charged spark-ignited combustion also presents high knock propensity that requires a lower compression ratio and the use of retarded spark timing. This leads respectively to a lack of thermodynamic efficiency and cycle efficiency. In order to take full advantage of downsizing, the challenge is then to find a suitable combustion process that is knock resistant keeping in mind the interest for high low-end torque.

Now a day engine cooling optimization is attracting the attention of researchers as a means of making engines comply with increasingly stringent demands for lower fuel consumption and lower exhaust emissions. Whereas the conventional objectives of engine cooling optimization were to satisfy material durability requirements and prevent abnormal combustion, automotive engineers are now focusing on the additional benefits of engine cooling, such as improvement of engine output through intense cooling and improving fuel consumption by reducing losses resulting from unnecessarily intense cooling. The improvement of engine output through intense cooling is due to the increase in charging efficiency and the spark advancing effect it yields. The amount of spark advance is usually determined by listening to knocks by the human ear. However, this method is inaccurate because there are unavoidable differences in sensitivity between evaluators and variations between individual engines. Further, improvement of cooling results in only a small amount of spark advance which is minute relative to the setting resolution in the ignition timing. To determine accurately the effects of improving engine cooling on suppressing knocks without being affected by any of the abovementioned causes of inaccuracy, engine cooling optimistion done to drop in cylinder gas temperature at the end of the compression stroke, which is closely related with the occurrence of knocks.

2. ABNORMAL COMBUSTION: KNOCK AND SURFACE-IGNITION

Abnormal combustion, more commonly known as knock or detonation, has been the limiting factor in internal combustion engine power generation since the discovery of the otto cycle itself. To tune an engine for maximum power, you need to understand this undesirable yet ever-present problem. Abnormal combustion manifests in many different ways. To the typical enthusiast, all abnormalities are referred to as knock or detonation. In practice, though, when the undesired flame front is initiated and how it is propagated define the cause and, in turn, the appropriate cure. Abnormal combustion got the nickname knock from the noise that is transmitted from the colliding of the multiple flame fronts and the increased cylinder pressure that causes the piston, connecting rod and bearings to resonate. Any sort of abnormality in the combustion process has serious consequences in the power output, longevity and emissions generation of an engine.

Another part of abnormal combustion i.e. surface ignition is the ignition of the fuel-air mixture by any hot surface, other than the spark discharge, prior to arrival of the flame. It may occur before the spark ignites the charge (preignition) or after normal ignition (postignition). The ignition of the fuel-air mixture by a hot spot on the combustion chamber walls such as an overheated valve or spark plug, or glowing combustion-chamber deposit: i.e., by any means other than the normal spark discharge

The end-gas temperature and the time available before flame arrival are the two fundamental variables that determine whether or not knock will occur.

The effects of practical engine variables such as compression ratio, spark advance, speed, inlet pressure and temperature, coolant temperature and fuel/air ratio on knock can be explained in terms of these two fundamental variables. The attempt has been made to cool the charge and to cool the combustion chamber by optimizing engine coolant flow optimisation.

3. KNOCK SUPPRESSION TECHNOLOGIES IN GASOLINE ENGINES

Westbrook et al [4] explained that addition of antiknock compound such as Tretra-Ethyl Lead(TEL) made it possible to increase the operational compression ratio. However, environmental concerns have led to elimination of such antiknock compound. Another strategy used to permit higher compression ratio is blending of hydrocarbon species including aromatic species to increase the effective octane number rating of an automotive fuel. Unfortunately, these higher octane fuels are more expensive to produce than older conventional gasolines. It is also indicated that kinetic fuel modification lead to reduce or even enhance knock tendencies.

The FEM approach has been successfully applied by Sonke Carstens[2] to model combustion chamber resonances. The frequency and amplitude modulations of the resonances corresponding to their metamorphosis were estimated and a sensor characteristic to assess pressure sensor positions was proposed. Applying transient analyses it was demonstrated that the random excitation of the resonances is very likely caused by the random origin of knock.

The knock suppression approach [3], including the use of stratified ethanol addition and the use of other antiknock fuel additives (reference). The ethanol injection is carried out so as to maximize evaporative cooling which occurs when it is directly injected into the engine cylinders. The gasoline can be introduced into the intake port in conventional port-fueled injection. The reduction in temperature of the fuel/air charge from the ethanol evaporative cooling is the major factor in enhancing the fuel octane rating and suppressing knock. The knock suppression allows the highly turbocharged, high torque engine operation.

Intensified cooling in cylinder Head [5] by addition of water jacket over the intake valve bridge. And slit cut in between bore to bore space of the crankcase. While slit cut of 2mm and less will be difficult to manufacture and will take more process time and chances of leakage over the cylinder head gasket will be increased. With different piston design cooling, incylinder gas temperature has been reduced to 7 to 8K.

To avoid knock, the engine compression ratio is limited to between 9 –10. Significant efficiency gains are possible if the compression ratio could be raised. The major difficulty in operating an engine closer to the knock limit is quantifying the on-the-road knock problem sufficiently précised.

Knock sensors and a feedback control are increasingly used to adjust spark timing so that the engine can operate close to its knock limit.

Reduction of intake charge temperature by inter-cooling for turbocharged gasoline engines. Optimistion and use of correct heat value spark plug for an engine. Surface ignition and hot spot can be suppressed by designing the combustion chamber by avoiding common problem areas are sharp edges of metal either on the piston or in the combustion chamber. For instance, if the piston has a valve relief cut into it, there is usually a very defined edge that the cutting tool leaves. This sharp edge is greatly prone to super heating and will actually retain enough heat that it will start to glow. If the fuel should hit this glowing edge either prior to the lighting of the spark plug or even after ignition, it is very likely that another flame front will initiate. If this unintended ignition occurs very early in the compression stroke, then the piston will be forced up against the increased pressure of the burning gas and will result in a form of abnormal combustion referred to as preignition. When this happens, the end result, if severe enough, is that the piston damage, connecting rods bend and bearing failures. Turbocharged engines are specifically prone to this phenomenon.

4. ENGINE COOLING OPTIMIZATION

The effects of ignition timing advance were obtained by charge air cooling, intensified cooling of the cylinder head, cylinder block. The details of cooling optimisation for air charge, combustion chamber in turn cylinder head and crankcase are described below:

4.1 Charge Air Cooling: While downsizing and developing engine, size and packaging play very important role without compromise of performance. Initially tests was conducted with 6.5 kW intercooler and knocking has been observed and subsequently 8 to 12 deg retardation in ignition timing done by EMS to operate engine at rich mixture and prevent the damage of engine. As shown in Figure 1 towing trial conducted on vehicle in which effect of intercooler temp rise is seen on retardation of ignition timing and knocking. This leads to increase in fuel consumption and bad performance of the vehicle.

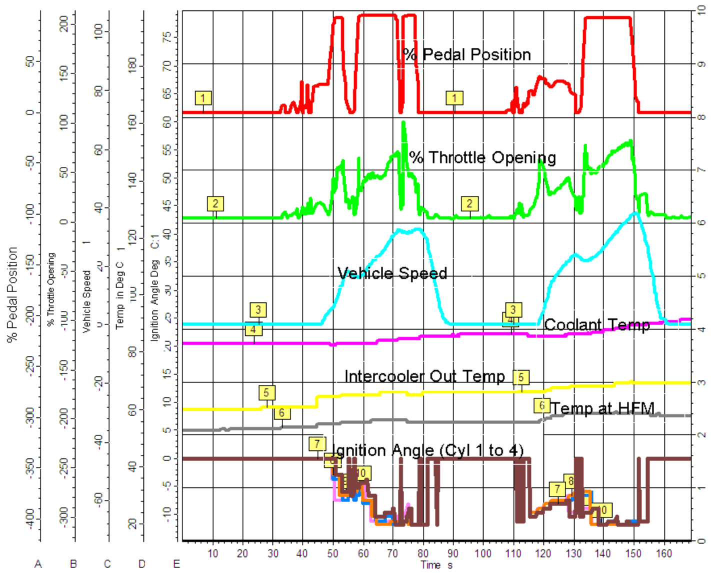

Figure1. Effect of Boost Air temperature on Ignition Angle

To overcome the problem engine has been tested optimized 9.2 kW intercooler for the same engine and vehicle. Obviously there may be change in intercooler specification in view with engine to engine and vehicle configuration. 9.2kW intercooler gives more boosts required for engine with improvement of charge cooling. Thus intensity of knocking has been reduced as discussed in section 5 and shown in Figure 16. It can be beneficial with advance of spark timing by 4-6 deg at high load points. Figure 2 shows temp out and effectiveness of both intercoolers.

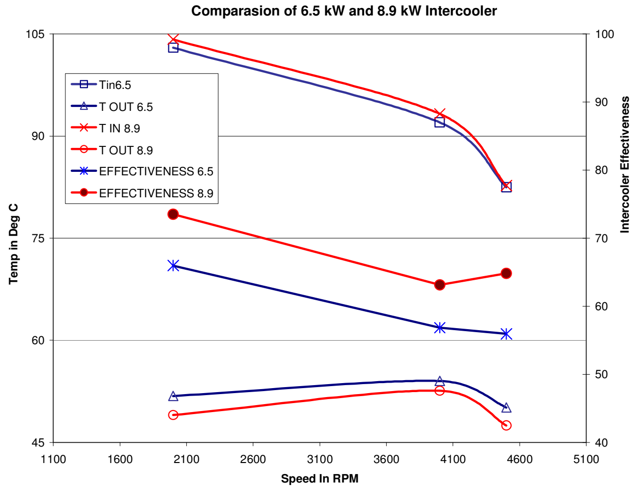

Figure 2. Intercooler Performance Comparisons

4.2 Coolant Flow Optimistion:

Surface ignition or hot spot can be reduced by providing optimized cooling to combustion chamber. End gas temperature may burn and create knock if there will be hot spot or non-uniform wall temperatures around the combustion chamber. Figure 3 show the importance of coolant temperatures on knocking. If coolant temperature is not controlled and it may increase suddenly and surface ignition takes place which lead to knock and ignition angle will be retarded due to knocking. Below section explains the coolant jacket optimistion.

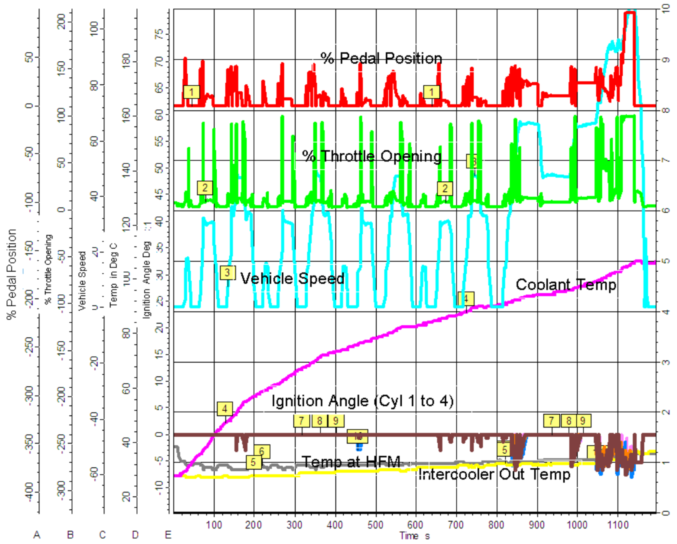

Figure. 3 Effect of Coolant temperature on Ignition Angle

4.2.1 Intensified cooling of cylinder head

In modern four valve DOHC gasoline engine, design of combustion chamber, port intake and exhaust and its cooling are critical. Combustion chamber has been cooled in turn; cylinder head exhaust side has been extensively cooled by addition of cooling passages over exhaust port and well optimized wall thickness of combustion chamber. This cooling passage has effectively cooled the combustion chamber from exhaust side which reduces possibility of the hot spot. Also cooling passage over intake port has been optimized. Thus there will not be spontaneous end gas temperature on higher side and tendency to knock the engine will be reduced. Homogeneous heat transfer coefficient is obtained as compared to previous design by optimizing the cylinder head coolant jacket.

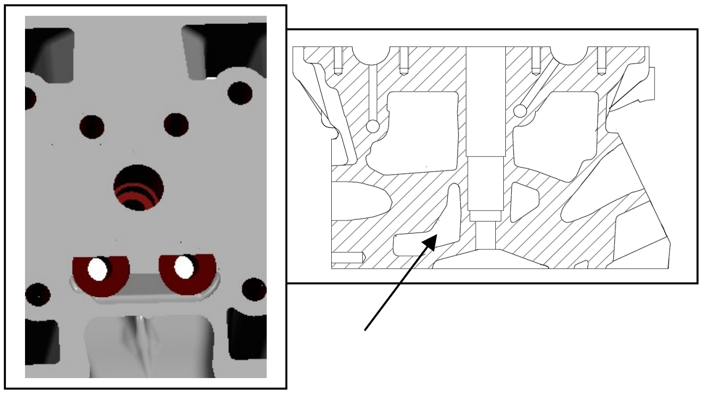

Figure 4. Cylinder Head Coolant jacket before design optimisation.

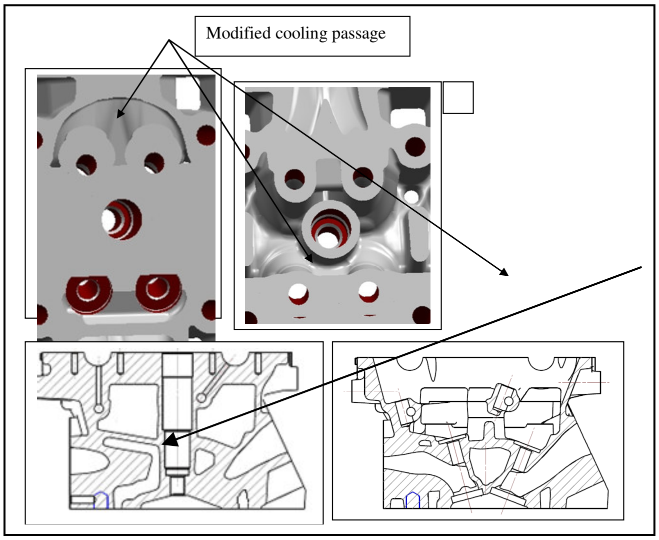

Figure 5. Cylinder Head Cooling jacket optimised design

Figure 4 shows design before optimistion and Figure 5 shows optimized cylinder head coolant jacket. CFD analysis has been done both the cooling jackets and it has been seen homogeneous heat transfer coefficient over the chamber in optimized design as shown in Figure 6 shows the model heat transfer coefficient from both designs.

New coolant passages were added shown in Figure 5 and the entire thickness of the combustion chamber walls was optimized in order to restrain the heat transfer to gas during intake strokes and lower the temperature of the entire cylinder head. As a result, the temperature of the combustion chamber walls decreased by more than 9 K as shown in Figure 7 in the critical area of combustion chamber i.e exhaust valve bridge which helps to decrease end gas temperature at the end of the compression stroke and surface ignition.

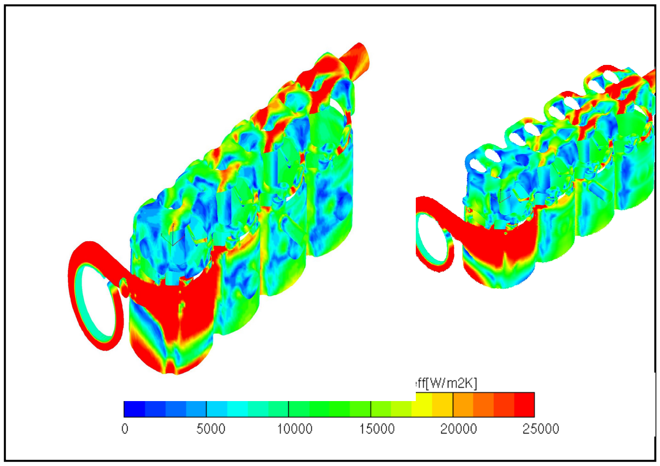

Figure 6. Heat Transfer Coefficient of Head Cooling Jacket

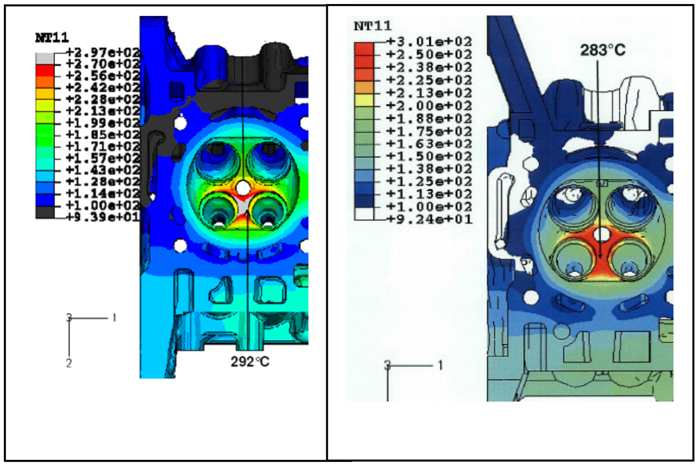

Figure. 7. Temperature Distribution over Combustion chamber

4.2.2 Intensified cooling of Crankcase Area

In this section engine crankcase cooling jacket has been analyzed in detail. The Turbocharged Gasoline engine uses water cooled turbocharger and it is essence to provide coolant for cooling of bearing housing of turbocharger even though it is cooled and lubricated by lubrication oil. Optimistion has been done in coolant jacket in view with outlet connection required to engine accessories like turbocharger outlet. CFD analysis has been carried out the actual boundary conditions on cooling jacket with and without modifications and it has been seen that there is drastic increase in Heat Transfer coefficient which can reduce localized hot spot or high source temperature area.

Figure 8 shows supply of coolant connection from exhaust side of engine to turbocharger on crankcase. Figure 9 shows velocity distribution at the turbo water outlet connection and at inlet while Figure 10 shows Heat transfer coefficient when coolant flow from crankcase to cylinder head without and with turbocharger coolant connection. In first design flow velocity towards the turbo water outlet was high hence coolant passing through crankcase to cylinder has been reduced and fourth cylinder prone to high temperature and which has been knocked. This increase in 4th cylinder end gas temperature and created localized hot spot near to high surface temperature area. In fact in that area knock has prone to the tendency and piston has been completed eroded as shown in Figure 11. This has also affected 2nd cylinder there is comparatively heat transfer coefficient is on lower side.

In optimized design as shown in Figure 10, right side, coolant connection has been removed from the water jacket and it has been given from engine cylinder head main coolant outlet pipe which will not disturb the overall coolant flow through jacket. There is drastic increase in heat transfer coefficient over the exhaust side passage.

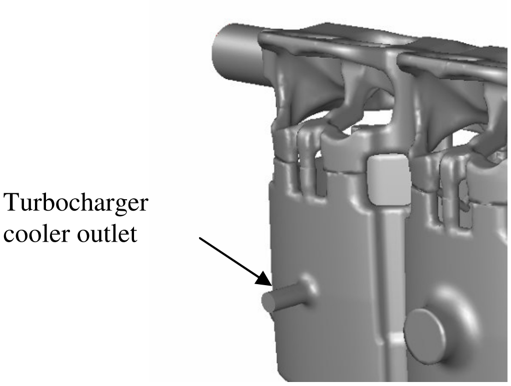

Figure. 8 Turbocharger Coolant Outlet Connection

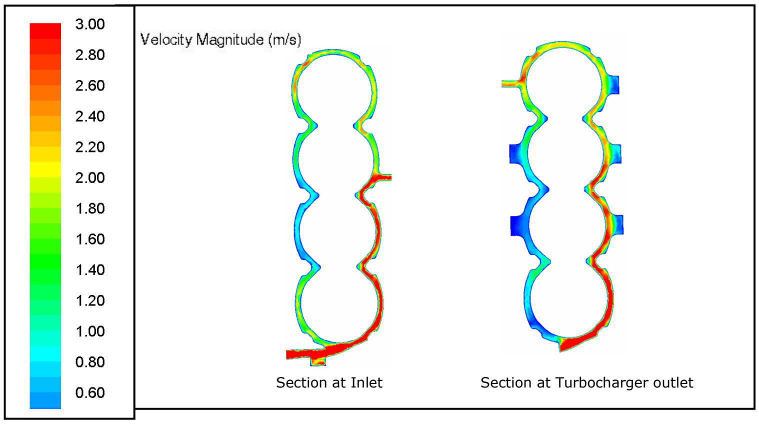

Figure 9. Velocity Distribution of Crankcase Section

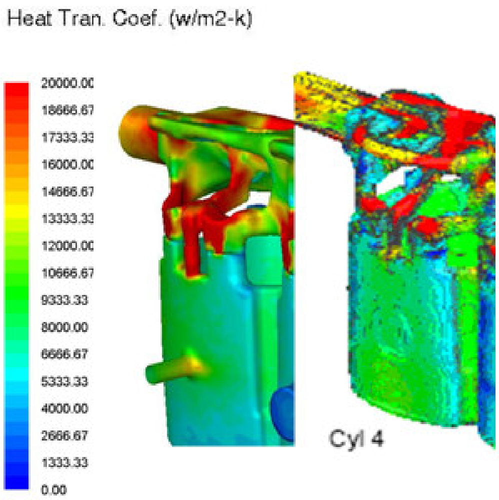

Figure 10. Heat Transfer Coefficient over chamber and coolant jacket for both design i.e without & with turbocharger coolant connection.

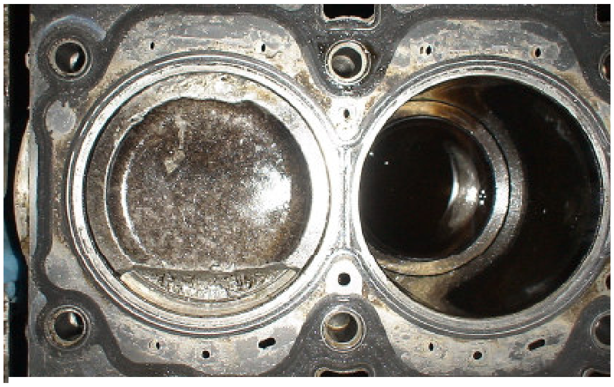

Figure.11. Piston Failure Due to Heavy Knock

Optimistion of the coolant jacket at the entry area of coolant jacket has been done as shown in Figure. 12 and Improvement towards the distribution of heat transfer coefficient is shown in Figure 13 for both designs. Flow distribution has been drastically changed and homogeneous HTC will play role that not create hot spot which lead for surface ignition.

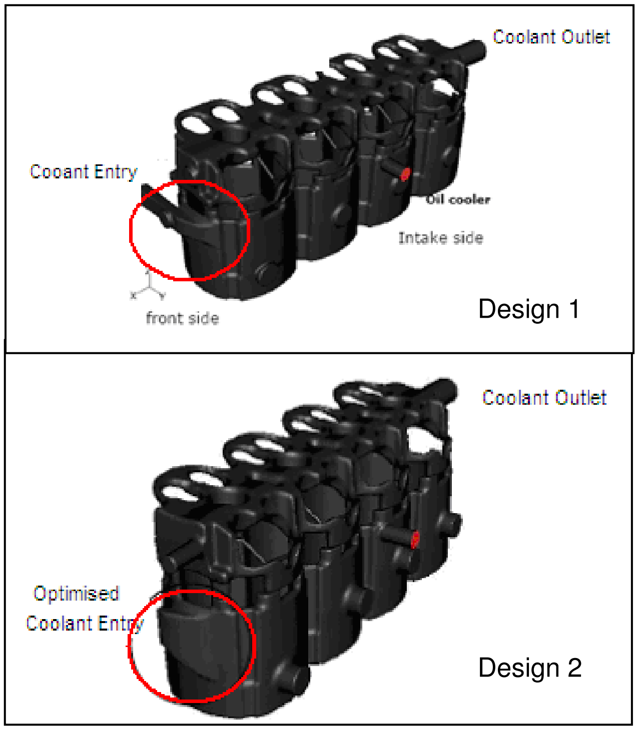

Figure 12. Coolant Jacket Entry Area Design

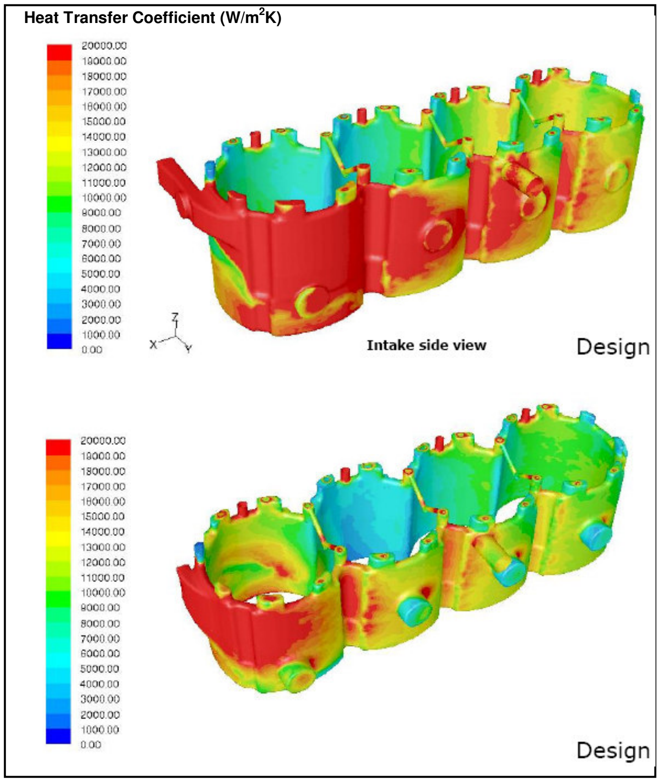

Figure 13. Heat Transfer Coefficient due Entry Design Change of the Crankcase coolant Jacket.

The cylinder bore or liner bridge has been effectively cooled by cross drilling for which temperature distribution has been shown in Figure 14. Vertical capped passages at the exhaust side, so called jets, are considered for an effective local cooling of the cylinder liner bridges. This helps to reducing the temperature near bore edge and high temperature area or hot spot inside the combustion chamber.

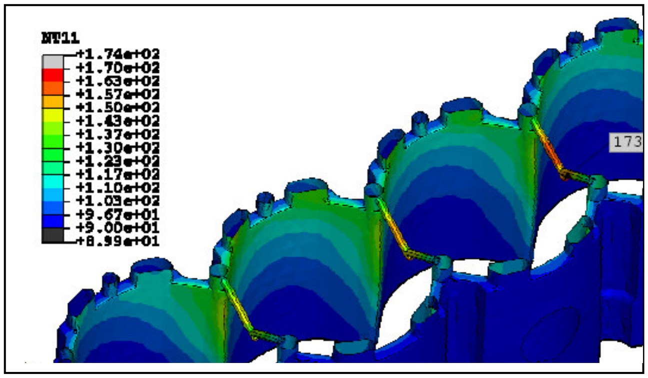

Figure 14. Temperature Distributions at Liner Bridge.

5. Results:

We have tested Vehicle with Gasoline Turbocharged engine with load point at120 KMPH in 5th gear on Vehicle (at 3200 rpm with 80% relative load) as shown in Figure 15. There is a clear trade of is that, with the advance of ignition angle there is improvement in Engine Torque & BSFC. Optimal ignition timing is achieved with ignition advancement.

We have tested vehicle in chassi-dyno as per NEDC cycle with optimised engine cooling as shown in Figure 16 and we observed that ignition angle is advanced by 5-6 Deg which is giving benefit of 10gms/kWHr BSFC with 4 % improvement at Peak Torque conditions as compared to results shown in Figure 1 and 3. This improvement is overall result of charge cooling and reduction of combustion high surface temperature by 9K, optimized coolant entry, turbocharger auxiliary connection and Liner Bridge cooling

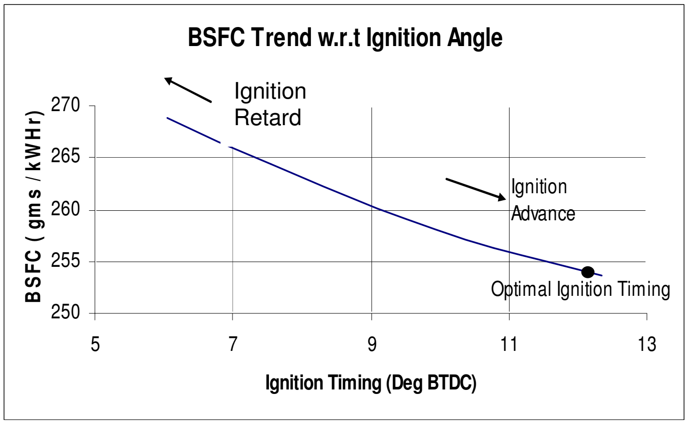

Figure 15. BSCF Trend w.r.t. Ignition Angle

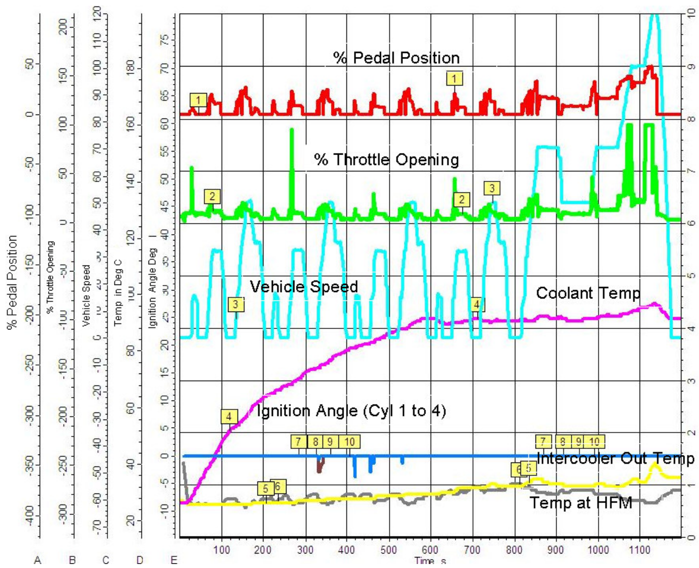

Figure 16. Results after Optimized Engine Cooling

6. CONCLUSION

Describing knock in the SI engine, usually self-ignition of unburned gas considered at the late stage of combustion. The phenomenon is often called end-gas knock. The end-gas knock is determined mainly by the temperature of unburned mixture which is pre-heated and compressed by the propagating flame and it is cooled by the heat transfer to the cooling system via cylinder walls. Engine cooling optimistion helps to decrease air charge temperature and hot spots over and around the combustion chamber. This results in advancement of ignition timing.

Charge Air cooling i.e Boost Air cooling play very important role in case gasoline turbocharged engine. If charge air temperature is not controlled then there will be heavy ignition retardation. By cooling air with efficient and optimized intercooler there is tremendous effect on ignition timing advance of approximately 6-8° CA during increase in vehicle speed. This helps in the suppression of Knock.

As the effect of reducing the cylinder temperature at the end of the compression cycle is considered to be significant for suppressing knock. Cylinder head jacket optimistion reduce temperature about 9K at critical areas of combustion chamber. Coolant entry optimistion gives more homogeneous heat transfer coefficient across cooling passage. Any auxiliary coolant connection should be optimized in such way that it will not disturb the flow across crankcase to cylinder head. Cross coolant cooling in between liner or bridge helps to cool liner bridge area. These measures intensified the cooling of the cylinder head and cylinder block led to an improvement of ignition timing advance of approximately 2-3° CA.

There is good trade of between ignition timing advancement over engine torque and bsfc.

The in-cylinder gas mean temperature has perhaps the greatest influence on knock. Since the knock phenomenon is caused by a complex combination of many factors, these methods should be used for evaluating in relative terms, not absolute terms, the occurrence of knock in engines.

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ABBREVIATIONS:

K-Temperature in Kelvin
CFD- Computation Fluid Dynamics
NEDC- New European Driving Cycle.
EMS- Engine management system
BSFC- Brake specific fuel consumption

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