

Water Cooled Exhaust Manifold and Full Load EGR Technology Applied to a Downsized Direct Injection Spark Ignition Engine

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ABSTRACT

Gasoline engine downsizing is one of the main technologies being used to reduce automotive fleet CO₂ emissions. However, the shift in operating point to higher loads which goes with aggressive downsizing means that real world fuel economy can be affected by the amount of over-fuelling required to maintain exhaust gas temperatures within acceptable limits. In addition there is a drive to lower the exhaust gas temperature limit in order to reduce the material costs required for high temperature operation.

A water-cooled exhaust manifold is one technology, which can be used to minimize the over-fuelling region. This paper investigates the effects of this technology applied to a twin-charger 1.4-litre gasoline direct injection engine. Data is presented which quantifies the benefits in conjunction with other downsizing technologies including cooled EGR and variable geometry turbochargers. The thermal and combustion phasing benefits are found to provide significant advantages over a wide operating region on this highly boosted engine. The downside of the approach is the requirement for increased heat rejection from the coolant and this is also quantified.

INTRODUCTION

Emissions legislation and fleet CO₂ targets have led to engine manufacturers looking at methods for improving fuel economy. Significant reductions in fleet CO₂ were initially achieved in Europe with the wide adoption of diesel engines, however distillation of crude oil results in both diesel and

gasoline so from a Well-to-Wheel (1) point of view the expansion of the diesel market cannot continue indefinitely. In fact recent studies of market trends have shown that gasoline downsizing is being increasingly applied.

Gasoline engine downsizing allows for improvement in fuel consumption via load point shifting, operating the engine at lower pumping loss regions of the operating map for a given power requirement. However, as the degree of downsizing is increased the component protection over-fuelling region becomes more significant, thus limiting the fuel consumption benefits. Although this does not impact standard emission cycle fuel consumption results, it will affect “Real World” fuel consumption and therefore customer satisfaction. Also it is possible that additional legislative cycles will be employed to deal with this issue in the future. [Figure 1](#) shows the over-fuelling region of a typical gasoline downsized engine.

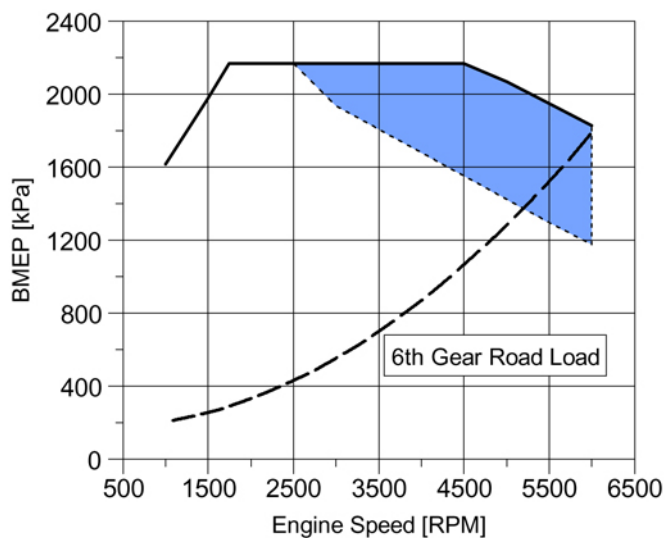


Figure 1. Typical downsized gasoline engine component protection over-fuelling region.

Over-fuelling is required for component protection; at higher loads and therefore higher peak cylinder pressures and temperatures the tendency for the engine to “knock” is increased. In order to mitigate this the ignition timing is retarded; however, retarding of the ignition timing leads to a later burn and therefore increases the exhaust gas temperature at Exhaust Valve Opening (EVO). This temperature must be limited to that which can be stood by the exhaust manifold and turbocharger assembly materials. Typically on a gasoline downsized engine the limiting temperature is pre-turbine. Of course this temperature limit can be increased by changing the material of the exhaust manifold and turbocharger components to higher nickel content cast stainless steel, however this has cost implications (5,6).

The following paragraphs briefly describe research that has been carried out into methods to reduce full load over-fuelling.

A much-researched method of reducing over-fuelling is the use of cooled external EGR (3,4,7,8,9,13,14). This method feeds cooled EGR back into the intake, either pre or post-compressor, and increases the specific heat capacity of the cylinder charge reducing the peak cylinder pressures and temperatures. This in turn reduces the gas temperature at EVO and therefore reduces the over-fuelling requirement. One benefit of cooled external EGR is that it has been demonstrated to give combustion phasing improvement; however, the addition of EGR does lead to an increase in burn duration.

Water Cooled Exhaust Manifold (WCEM) is another method available for reducing over-fuelling requirements (2,5,6,7,8,13,19). The WCEM replaces the downsized engines cast stainless steel manifold with a water-cooled

manifold, typically made from cast aluminum. It can either be independent, as described in this paper and by Ito et al (2) or integrated into the cylinder head as used by Borrmann et al (5,6) and Turner et al (13,19). WCEM technology works by cooling the exhaust gas temperature between the exhaust port and turbine, therefore allowing a leaner AFR to be achieved. A downside of running a leaner AFR is that the combustion phasing has to be retarded due to increased tendency to knock and as a consequence boost pressure needs to be increased to maintain torque. However the cooler pre-turbine temperatures that the WCEM provides does allow for the potential to use a diesel VGT as discussed by Kapus et al (7,8). The combination of WCEM and EGR has been studied in the literature with differing results (7,8,13); however, both technologies are potentially complimentary leading to reductions in over-fuelling and fuel consumption.

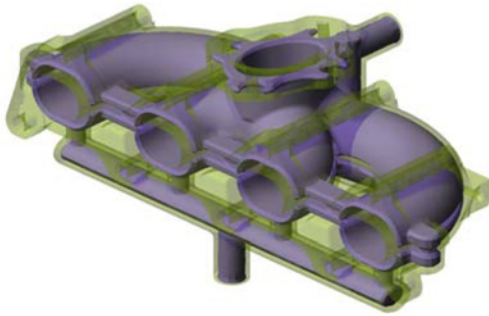
Lean boost is another method for engine efficiency improvement that has been researched (3,4,8,10,11,12,14). This method uses mixtures leaner than $\lambda=1$ and results in a cooler exhaust gas at EVO. This method obviously reduces over-fuelling however it does lead to more retarded combustion phasing, as the use of lean mixtures as a knock suppressant at high loads is not realized (3,4,8,10) thus leading to instability. However there is a trade-off as the lean mixture leads to higher un-burnt gas temperatures that promote the knock, but they do have a higher ratio of specific heat capacity that leads to higher thermal efficiency. Another major consideration is that the lean mixture renders the NO_x conversion efficiency of the three-way catalyst to almost zero and therefore alternative aftertreatment methods, such as a costly NO_x trap or Selective Catalytic Reduction (SCR) (20), are required. It is for this reason that this method of over-fuelling reduction is not considered in this paper.

This paper considers the application of WCEM technology to a downsized gasoline turbo Direct Injection Spark Ignition (DISI) engine and demonstrates the addition of full load cooled EGR as a complementary technology for reducing the requirement for over-fuelling.

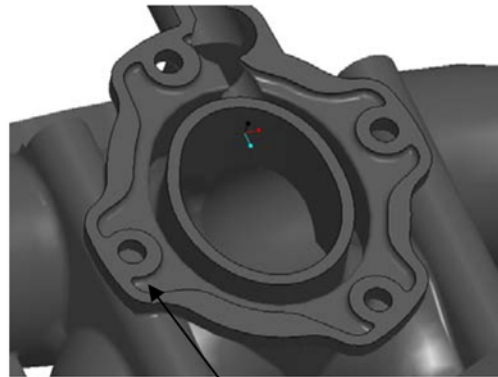
MANIFOLD DESIGN

In order to assess the benefit of a WCEM a non-integrated, thin walled (3mm) aluminium standard manifold was designed. The gas path was maintained as a direct replica of the original to isolate the effect of the water-cooling on the exhaust temperatures. This is with the exception of the exhaust splitter, which was removed, as it was not considered possible to supply sufficient cooling to maintain acceptable metal temperatures. An iterative process of 3D design, CFD and thermo-mechanical FE analysis was used to optimise the cooling jacket design and ensure no potential “hot spots”. A distribution rail was designed to feed coolant to the underside of each runner. The coolant jacket was split into two halves along the centre-line thus allowing the casting cores to be

Water Jacket View



Section Through Turbo Flange



Water-Cooling Around Bolts

Figure 2a. Images of WCEM hardware.

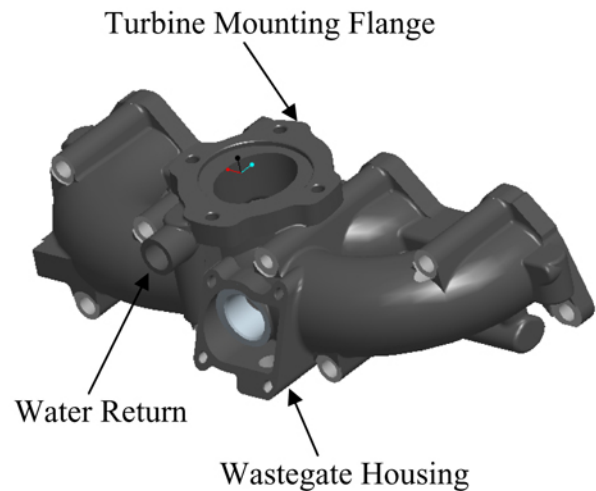
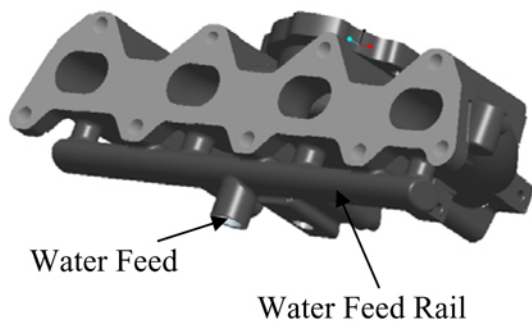


Figure 2b. Images of WCEM hardware.

assembled. Additional cooling was provided around the turbine fixing points to conduct heat away that is fed in through the studs; this can be seen in [figure 2](#). This optimisation process led to a design with a single coolant entrance and exit points that allowed sufficient cooling of the whole manifold.

In addition to the base manifold design an additional take-off point was integrated and was used as either an external wastegate in conjunction with the diesel VGT, or alternatively as a high-pressure EGR circuit take-off. [Figure 2](#) shows details of the WCEM and water jacket design.

<[figure 2](#) here>

EXPERIMENTAL SETUP

ENGINE SETUP

All of these experiments were performed using a production 1.4-litre turbo-charged gasoline engine with 4 valves per cylinder and a side-mounted direct injection system. Some general details of the engine are presented in [table 1](#).

<[table 1](#) here>

As standard the engine has a two-stage charging system consisting of a turbocharger and a mechanical “Roots” type supercharger. For all of the WCEM testing the supercharger was removed. The air-to-water charge cooler was controlled using a boost control rig, with an air charge set point of $30 \pm 1^\circ\text{C}$. Pre-catalyst emissions were measured using a Horiba 7200EGR analyser; this is also used to determine the EGR rate by measuring the CO_2 in the intake manifold.

Table 1. Basic engine characteristics

No of cylinders	4
Bore (mm)	76.5
Stroke (mm)	75.6
Geometric Compression Ratio	10:1
Variable Valve Timing	Inlet Only VCT (40°c.a.)
Fuel Injection	Magneti Marelli Solenoid Multi-hole (OEM)
Spark Plug	NGK Single Electrode
Ignition Coil	Magneti Marelli (OEM)
Fuel	98 RON ULG
Turbocharger	Borg Warner K03
ECU	Flexible Development ECU

The engine was instrumented with water-cooled Kistler 6061B in-cylinder transducers and intake runner pressures were measured using a Kistler 4045A5 pressure transducer. Indicating data was collected in 300 cycle logs using a SMETEK Combi indicating system and processed using AVL Concerto V3.8.

WCEM AND EGR COOLING CIRCUITS

The WCEM was cooled by an independent rig, which allowed coolant flow rate to be varied. The coolant out temperature was controlled by the rig to 90°C for all testing. Coolant flow rate was measured using a turbine type flow meter and the exhaust gas temperatures were measured using K-Type thermocouples. In order to correlate to the analysis and to monitor metal temperatures the WCEM was instrumented with 18 “grounded” K-Type thermocouples in both the inner and outer manifold walls. These thermocouples were located at the high temperature regions identified by analysis. The engine was fitted with a high pressure EGR circuit. This takes exhaust gas from the WCEM (pre-turbine) via the integrated wastegate; the EGR is then cooled through an EGR pre and main cooler. The EGR rate is metered by an EGR valve and drawn into the intake pre-charge cooler. An independent cooling rig was used to cool the EGR to less than 100°C. A schematic of the WCEM and EGR circuits is shown in [figure 3](#).

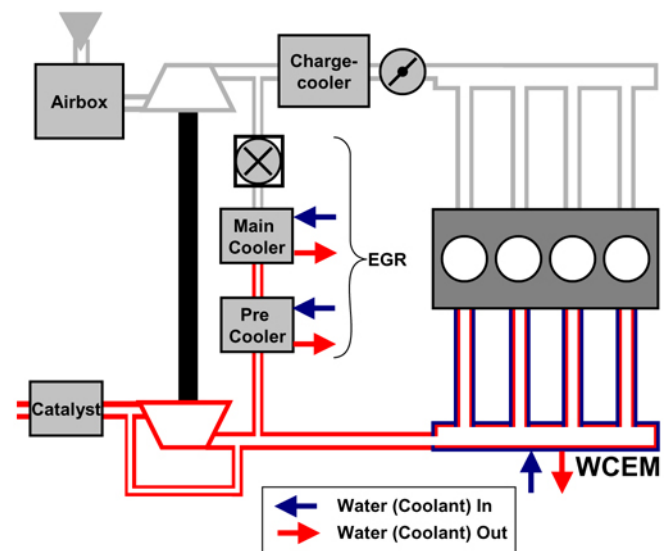


Figure 3. Schematic showing the EGR circuit and WCEM

RESULTS AND DISCUSSION

WCEM FULL LOAD

Analysis of the over-fuelling region showed that the greatest fuel consumption benefit from the WCEM would be yielded at full load, where the component protection requirement is highest. So with the WCEM fitted to the engine the coolant flow rate was set at 43 l/min, a flow rate that had been identified by analysis that would give good metal temperature headroom. A power curve was performed where the fuelling was reduced at constant load to yield the leanest feasible operation within the hardware limits. The ignition timing was always adjusted to Border Line Detonation (BLD)-1°c.a.

Shown in [figure 4](#) are the resultant power curves. It is clear from the comparison of the two baseline power curves, with and without the supercharger, that the turbo is sized to

compliment a twin-charger configuration delivering 90 kW/l, therefore the delayed run-up line performance is expected. The inlet only VCT and base valve timings do not allow for deployment of aggressive scavenging strategies required to improve low-speed performance. It can be seen that the addition of the WCEM further delays the run-up line; this is as a result of the WCEM removing heat from the exhaust gas leading to lower pre-turbine enthalpy. The turbo sizing means that this deficit is emphasised, with target Brake Mean Effective Pressure (BMEP) not achieved until 3000 RPM.

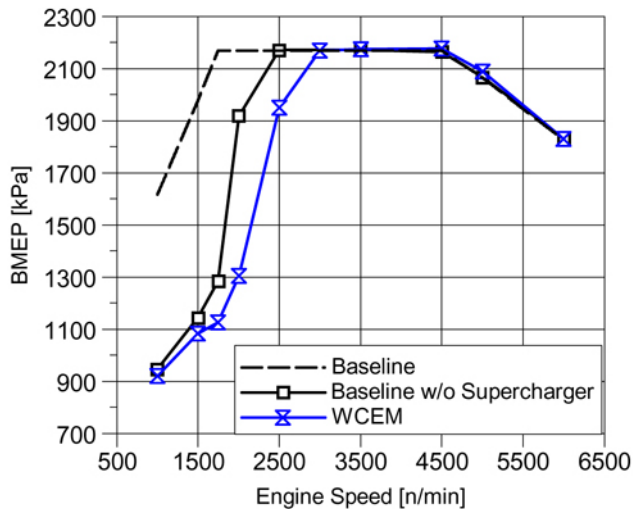


Figure 4. Effect of WCEM on the achievable BMEP

In addition, the WCEM does not have a pre-turbine splitter, which in the standard manifold separates cylinders 1-4 from 2-3. This lack of splitter means that the WCEM suffers with reduced pulse separation and therefore increased cylinder stuffing, which degrades steady state run-up line torque.

The highest metal temperatures were observed at peak power and leanest Air Fuel Ratio (AFR) with a peak at 161°C on the turbo to WCEM flange, where there is the greatest heat transfer from the un-cooled hot turbine assembly to the WCEM. Metal temperatures elsewhere in the manifold were measured at <140°C, which is well below acceptable metal limits for the material.

Because of the significant loss in low-end torque with the WCEM installed the subsequent tests with a reduced coolant flow rate were performed. The WCEM coolant flow rate was reduced from 43 l/min to 17 l/min to see if the pre-turbine enthalpy could be increased and give an improvement in low-speed BMEP. It was found that there was no sensitivity to WCEM coolant flow in the range of flows tested, however the hottest metal temperature increased from 161°C to 174°C at the 17 l/min flow. The small change in metal temperature results in little difference in the pre-turbine gas enthalpy

therefore no difference in run-up line BMEP. It is therefore considered that it is the “gas-wetted” surface area, which is critical to attaining good run-up line performance, which is inline with findings of Kuhlbach et al (6)

Initial fitting of the WCEM and running the baseline lambda demonstrates the cooling capacity of the WCEM with ~130°C reduction in pre-turbine temperature being observed. However the removal of the splitter combined with the reduction in pre-turbine enthalpy means that a higher plenum pressure is required to achieve target torque.

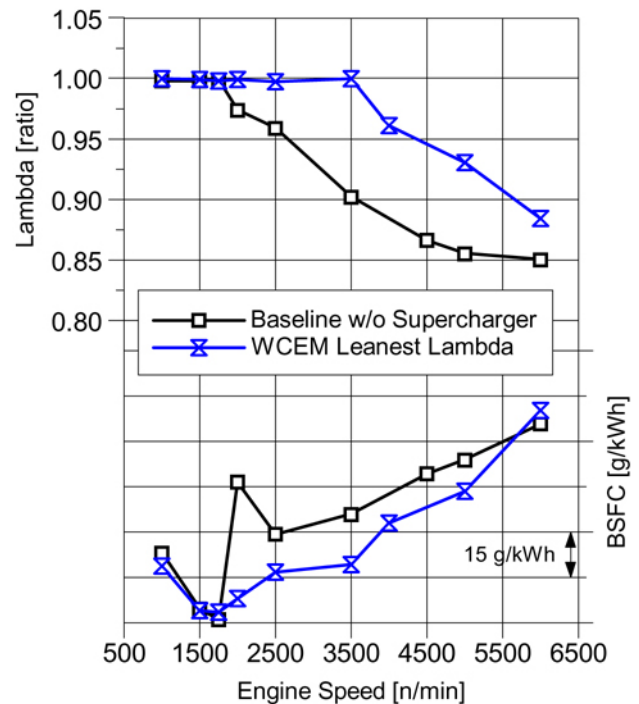


Figure 5. Over-fuelling requirement and fuel consumption effect of WCEM

Figure 5 shows the exhaust lambda and fuel consumption effect of the WCEM when running the leanest AFR. The extent of the over-fuelling reduction with the WCEM is limited by the exhaust port temperature hardware limit, which was set to 950°C and was defined from the testing carried out on the base engine configuration¹; this resulted in the maximum pre-turbine temperature of 915°C. This result can be interpreted two ways:

1. The WCEM cooling capacity is too high and therefore the design should be re-optimised to ensure that the exhaust port temperature limit is reached at the same point as the pre-turbine temperature limit. This would reduce the “gas-wetted” area of the manifold and enhance low-speed BMEP performance.

¹Incidentally other published WCEM studies, have not identified port temperature as a constraint.