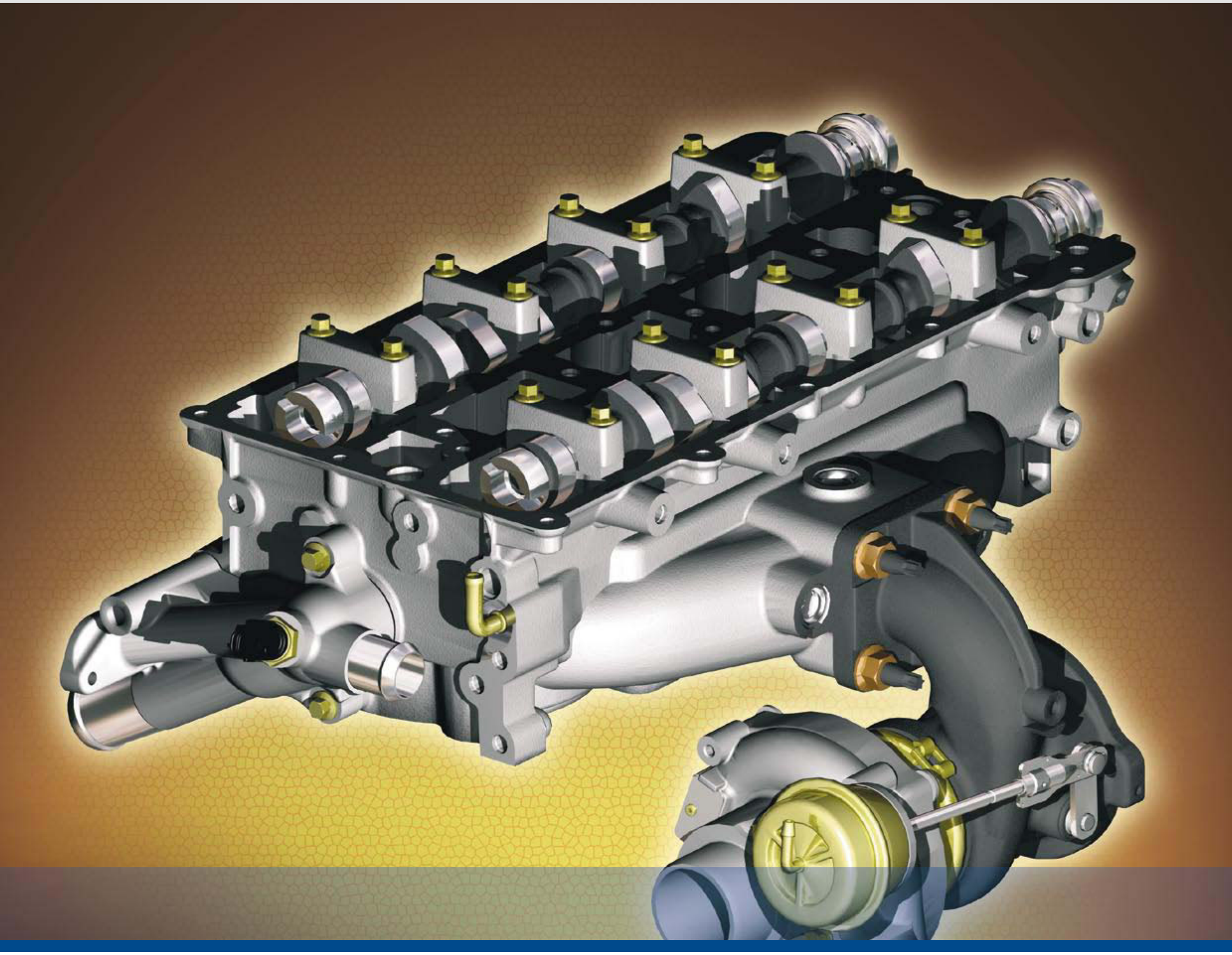

Cylinder Head with Integrated Exhaust Manifold for Downsizing Concepts

A study by the Ford European Powertrain Research department has shown that there is a significant potential to be tapped by using a cylinder head integrated exhaust manifold with turbo charged engines. It offers a win-win employment of technology providing improvements in the relevant attributes as well as a cost reduction.

1 Introduction

The European Union has defined its CO_2 emissions fleet target for 2015 as 130 g/km. From 2012 onwards the emission targets will be reduced step by step to meet this. The compliance with this limit is the key driver in the planning of powertrain portfolios at the car manufacturers. Important steps to achieve the targets are the introduction of new gasoline combustion methods such as stratified combustion or controlled auto ignition and through the introduction of downsizing for the European small and middle class car markets. Important for the breakthrough is meeting the customer expectations with regards to the fuel consumption under real world conditions, fun to drive, NVH and cost. Especially for downsizing concepts, where the intensive use of higher load areas is part of the concept, fuel enrichment in view of protecting components of the engine should be avoided as well as good transient response has to be ensured. Further the supply of sufficient heat in highly effective small car engines will be increasingly difficult. Put into this perspective the implementation of the cylinder head integrated exhaust manifold has been investigated and evaluated in view of the different functional effects and cost.

2 System Description

Key to the construction is the complete integration of the conventional external exhaust manifold into the aluminium cylinder head. The result of this is a single pipe feeding directly into the turbo charger. If necessary this can be made even more compact when vehicle package allows it, **Figure 1**.

In this instance, the overall cylinder head turned out to be only 32 mm wider and 200 g heavier than the conventional head. This is due to the fact that the flange area was significantly reduced. To be able to meet the durability requirements and as a result of high component and material temperatures, a totally new cooling concept in the cylinder head has been developed. This was proved out using CAE simulation to optimize the structure and fluid flow before being validated during the subsequent development phases on a test rig.

3 System Effects

3.1 System Cost

Downsizing with the aid of turbo technology, as well as the future introduction of Downspeeding is going to mean changed load collectives for the gasoline engine. This turns out that a higher percentage of time will be spent at higher engine loads. In order to realize the most of the CO_2 potential the stoichiometric range at high loads needs to be expanded as far as possible, which leads to high temperature resistant material choices. Gas temperatures for such materials allow typically a maximum of 1050 °C. This subsequently increases the cost. Presently an austenitic steel with up to 37 % Nickel content is used in both the exhaust manifold and the turbo charger. The world market price for Nickel has risen considerably and was traded at around $ 40 per kg. With an average weight of 3 to 4 kg, the elimination of an external exhaust manifold of an inline four cylinder engine creates a cost benefit on material costs alone. On top of this comes the elimination of the complicated and expensive machining of the external cast steel exhaust manifold. In comparison with this, the integrated exhaust manifold incurs a slightly higher cost by a potential upgrade to a larger vehicle cooler, **Table**. With respect to Downsizing of the gasoline architecture in a vehicle environment, the next larger cooling pack needs to be selected. That means within the same vehicle, the cooling pack for diesel engines or from the more powerful petrol engines needs to be used.

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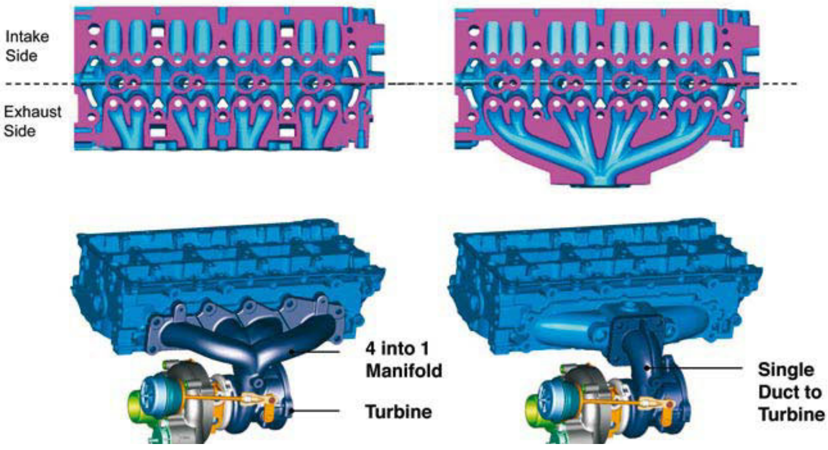

Figure 1: Section through the cylinder head (conventional and with integrated exhaust manifold)

Table: Cost saving on components

	casted steel manifold + mating components = 100 %	
Components In-line 4 Gasoline Turbo	**case 1**	**case 2**
Case 1: Eliminate 4 into 1 steel cast iron manifold (35 % Nickel)	– 95 %	–
Smaller heat shield and gasket, less bolts and nuts	– 5 %	– 5 %
Cylinder head add on	+ 5 %	+ 5 %
Next size radiator / fan (if required)	+ 15 %	+ 15 %
Case 2: Eliminate 4 into 1 sheet metal manifold	–	– 65 %
Case 1: Cost save vs. Steel cast manifold 1050 °C capable Engine weight save vs. steel cast manifold 3 kg	– 80 %	–
Case 2: Cost save vs. Steel sheet metal manifold Engine weight save vs. steel sheet manifold 1 kg	–	– 50 %
Further Potential: Eliminate electrical supplemental PTC heater	(– 60 %)	(– 60 %)

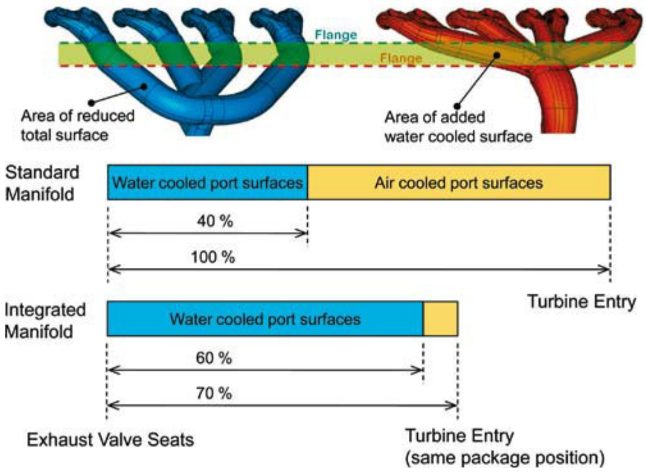

Figure 2: Comparison of the exhaust side port surfaces pre turbine (CAD model) and equivalent pipe surface schematics

As a general rule, the coolers usually have the same installation dimensions, simply increasing the cooler depth.

3.2 Emissions

The comparison of both systems (external and internal exhaust manifolds) with regards to the port wall surfaces from the exhaust valve seats to the entry of the turbine/catalyst lead to considerable difference. Using a normal four cylinder motor the following effects can be seen, **Figure 2**:

- a reduction by approximately 30 % of the overall surface area up to the turbo. (relevant e.g. for catalyst light-off)
- roughly a 50 % increase of the water-cooled surfaces (relevant for the air fuel ratio at higher loads and engine warm-up).

The main contributor that influences the quick starting of the catalyst conversion (reaching an operating temperature of 350 °C on the catalyst surface) is the size of the surface area on the exhaust side all the way to the catalyst. In relation to the time frame required to heat the catalyst after a cold start it doesn‘t make a difference whether the surface is water or air cooled. According to results from the test rig, which used the same base engine but with different cylinder heads and the same position of the turbo, the integrated exhaust manifold delivered a 20 % reduction in the start time of the catalyst, **Figure 3**.

This results in a solid potential to reduce emissions and improve fuel economy after a cold start. Due to the reduced total port surface and port lengths with the integrated exhaust manifold, significantly increased exhaust gas temperatures pre-turbine and catalyst were observed in the first minutes after cold start, **Figure 4**. With increasing warming up state of the engine, when those walls that are water-cooled stay more and more cool in comparison to those that are air-cooled from the conventional system, the measured exhaust gas temperatures are getting closer and then equalize at a certain point in time (load dependent). Finally when the engine is fully up to normal operation temperature, the integrated exhaust manifold cylinder head delivers at steady state lower exhaust gas temperatures which make stoichiometric operation possible under all loads.

3.3 Fuel Economy

Through the integration of the exhaust manifold into the cylinder head, the engine achieves better fuel economy in the warm up phase and also at normal operating temperature. During the warm up phase the quicker catalyst light-off contributes as well as the reduced friction because of the added heating to cylinder

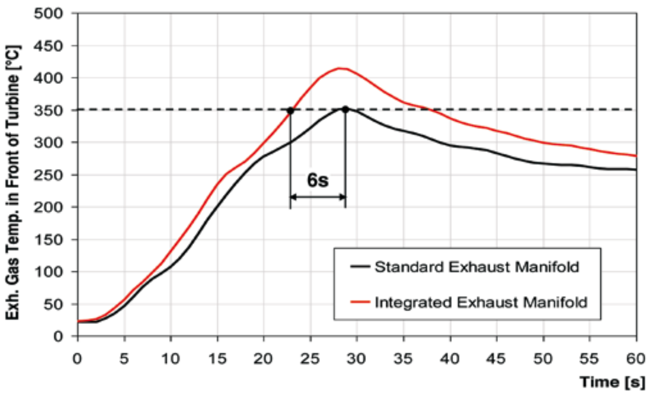

Figure 3: Exhaust gas temperature pre catalyst after cold start

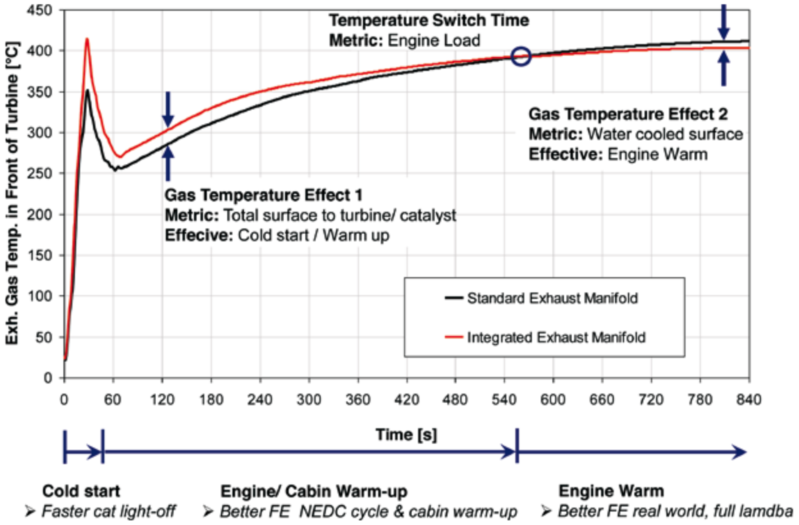

Figure 4: Exhaust gas temperature during warm-up at 1500 rpm and 1 bar bmep

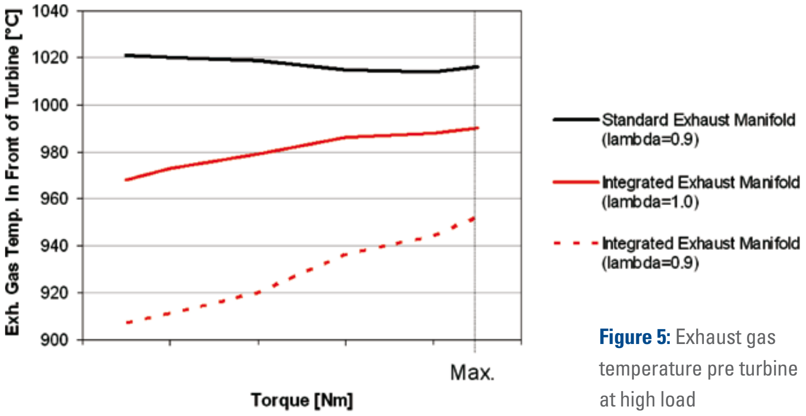

Figure 5: Exhaust gas temperature pre turbine at high load

head structure and coolant. Using the NEFZ, (New European Drive Cycle) fuel economy improvement between 1 to 2 % can be expected dependent on the warm-up relevant surface design as shown in Figure 2.

In the operating points near full load, depending on the materials used and temperature specs of the turbo housing, an improvement on fuel economy up to 15 % can be achieved. In the conventional design, even if the parts are made of heat resistant material, the exhaust gas temperatures at high load have to be decreased by over fueling significantly to avoid overheating and component damage. Typical temperature limit for high quality exhaust materials is 1050 °C.

The exhaust port lengths and diameters as well as the plenum surfaces represent the water cooled surface as a design parameter and can be optimized e.g. with 1D/3D simulation tools. Important factor is the amount which the exhaust gas needs to be cooled at full load to allow full stoechometric Lambda 1 operation as well as the transient response requirements, **Figure 5**. This system provides a real contribution to decreasing the fuel consumption both for NEFZ as well as real world operation.

3.4 Warm-up Behavior

The heat input into the cylinder head and into the coolant at steady-state operating conditions increased approximately 20 % for the fully warmed up engine with integrated exhaust manifold. **Figure 6** outlines the influence of the integrated exhaust manifold on the thermal load of the coolant in a part load operating point.

In the cold-start and warm-up phase the heat input increases as well. The heat flow can be quantified making use of the first law of thermodynamics, however the internal energy of the water jacket needs to be considered. Dyno tests proved that the additional usage of exhaust gas heat increases the heat input into the coolant during the warm-up phase up to 25 %.

$$\frac{dU}{dt} = m_{waterjacket} \cdot c_{cool} \cdot \frac{T_{cool\text{-}out}}{dt} =$$

$$\dot{Q} - \dot{m} \cdot c_{cool} \cdot (T_{cool\text{-}out} - T_{cool\text{-}in})$$

As previously outlined, this leads to a reduction of friction and hence fuel consumption. Furthermore market specific supplemental heating devices, e.g. PTC heating elements can be deleted or combustion strategies do not have to be modified in order to achieve a quicker cabin warm-up. This could lead to further cost and fuel consumption reductions.

3.5 System Weight

The integrated manifold prototypes for the in-line four-cylinder head have an overall system weight advantage of 3 kg in comparison with a conventional external

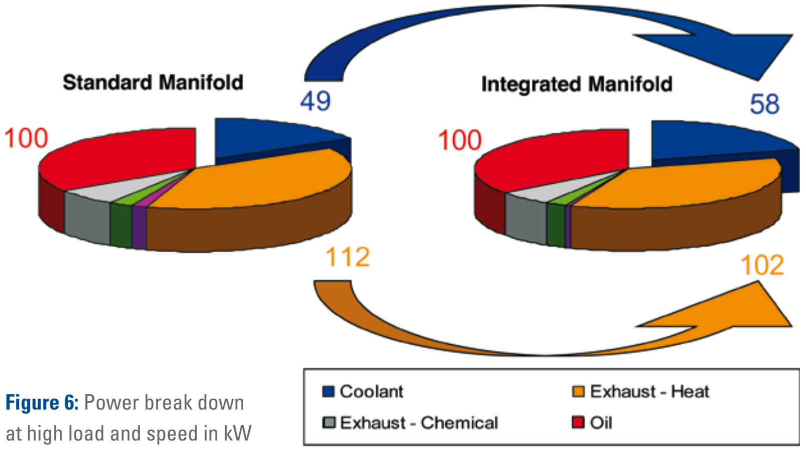

Figure 6: Power break down at high load and speed in kW

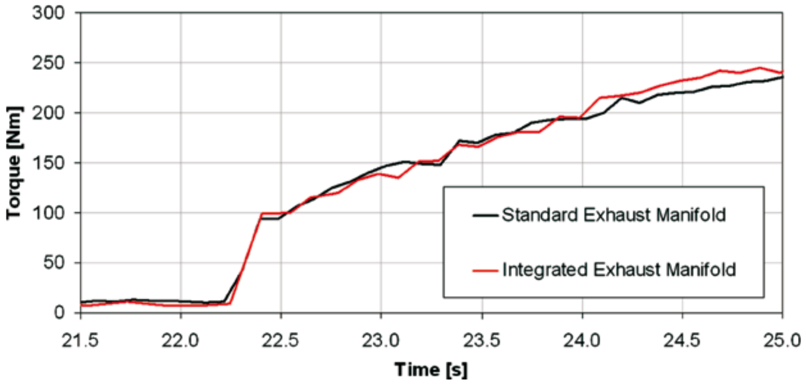

Figure 7: Transient response after full load request from 1500 rpm and 1 bar bmep

steel cast manifold. If compared with an external sheet metal exhaust manifold design there will be still an advantage of 1 kg for the engine system.

3.6 Complexity

Besides the elimination of the conventional separate exhaust manifold another advantage of the integrated design is the significantly reduced number and size of mating parts. The required amount of high-temperature-resistant studs can be reduced dependent on the amount of cylinders and design of the exhaust flange. This has not only a positive effect on part costs, but has also significant advantages in terms of logistics, assembly and service. The elimination of threaded holes in the cylinder head leads to reduced cycle time of modern CNC manufacturing. The gasket from the exhaust hot end to cylinder head, which is a remaining single gas discharge is significantly smaller and therefore cheaper. Normally conventional exhaust manifolds of turbocharged engines have to be fitted with complex heat shielding to protect surrounding components against significant heat input. Heat shielding in the area of the integrated manifold is not necessary due to less heat rejection which is relieved by cooling and thermal connection to the cylinder head. The general heat input into the engine bay and thermal requirements on surrounding devices accordingly decrease as well. This is a further contribution to a reduction of cost, complexity and demand of package space.

3.7 Full Load Characteristics

The turbocharged four-cylinder engine with integrated exhaust manifold that was tested showed equal torque and power characteristics on the test rig, as well as the same low end engine speed where it initially reached peak torque. The lower gas temperature before turbo during steady state operation with integrated exhaust manifold has no negative impact on transient behavior after a full load request. The potential temperature effect appears compensated by the mentioned reduced heat transferring surface and smaller gas volume before turbine (hardly a smaller volume can be realized if the turbine is directly attached to the cylinder head). Similar to the situation after cold start, the exhaust gas temperature before turbo after a load step of an engine at hot running conditions is either not or only slightly reduced. Dyno measurements of the transient response characteristics after a full load request showed the same delay to maximum torque for both tested configurations according to Figure 1, **Figure 7**. This shows that the integration of the manifold into the cylinder head is the preferred solution compared to a water cooled external manifold.

4 Durability

4.1 Methods

The integration of the exhaust ports and the plenum area leads to an additional heat input into the cylinder head and hence thermo-mechanical stresses which could result in local exceptional loads in the engine structure. The evaluation of the cylinder head design has been performed considering the increased load conditions applying network simulation methods, FEM (Finite Elements Method) and CFD (Computational Fluid Dynamics). **Figure 8** shows the workflow of the performed simulations and their interactions.

4.2 Flow Calculation

CFD methods are commonly used during the development process to compute the flow as well as the pressure distribution in the water jacket of cylinder head and block [2]. A first calculation was done with constant coolant properties in order to avoid solving the energy equation as shown in **Figure 9**. This is possible because of the incompressibility of the coolant and the thermal decoupling of flow and temperature. The cylinder head gasket openings were widened to realize

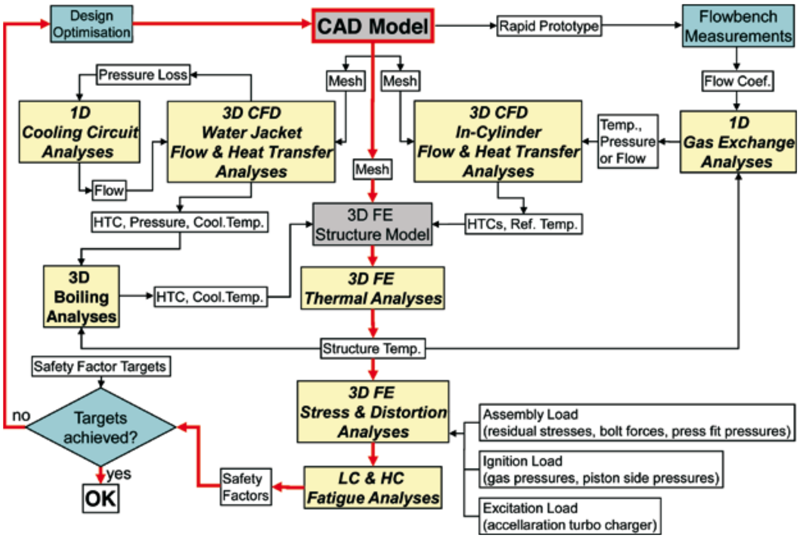

Figure 8: CAE workflow

sufficient cooling of the extended exhaust ports. On the one hand the pressure loss across the engine could be reduced and hence the volumetric flow rate through the engine increased. On the other hand the cooling of thermally and mechanically stressed areas as the exhaust valve bridges and the turbocharger flange has been improved significantly by increasing the amount of crossflow in the cylinder head.

In order to determine the temperature distribution in the cylinder head structure the heat input from the exhaust gas needs to be known. The crank angle resolved flow distribution in the combustion chamber as well as in the inlet and outlet ports is calculated using a 3-D simulation tool. The resulting average values for gas side heat transfer coefficient and reference temperature are calculated using the following formula:

$$\bar{\alpha} = \frac{1}{720\,°\,KW} \int_{\varnothing=0}^{720\,°KW} \alpha\,(\varnothing)\; d\;\varnothing$$

$$\bar{T} = \frac{1}{720\,°\,KW \cdot \bar{\alpha}} \int_{\varnothing=0}^{720\,°KW} \alpha\,(\varnothing) \cdot T\,(\varnothing)\; d\;\varnothing$$

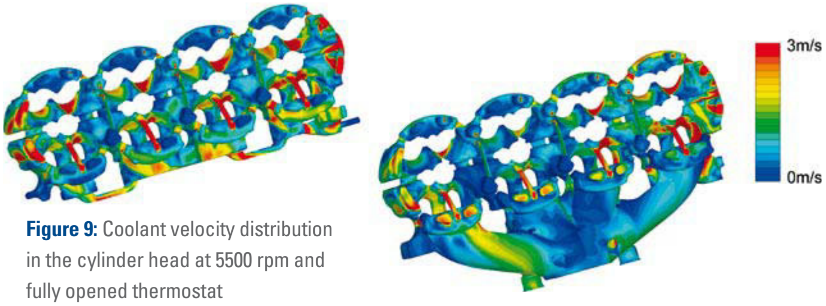

Figure 9: Coolant velocity distribution in the cylinder head at 5500 rpm and fully opened thermostat

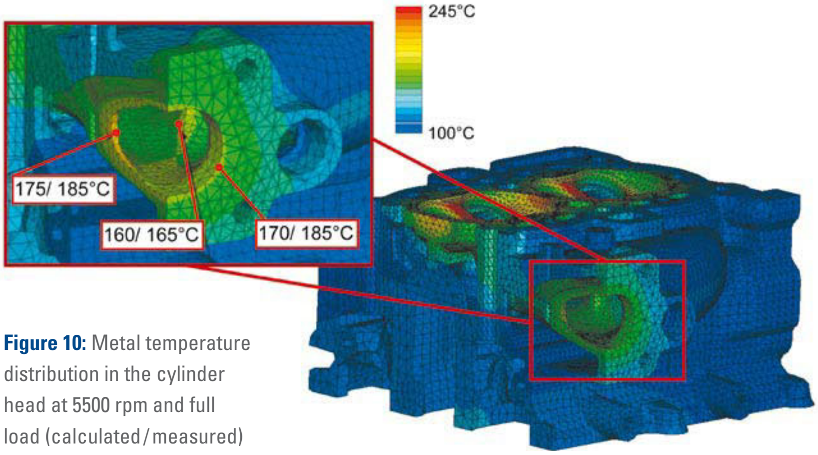

Figure 10: Metal temperature distribution in the cylinder head at 5500 rpm and full load (calculated / measured)

4.3 Temperature Calculation

As shown in **Figure 10** the maximum temperature can be observed in the exhaust valve bridge area, due to the heat transferred from the combustion chamber as well as the exhaust ports into the cylinder head structure and the heat conducted from the valves additionally into the valve seat area. However, not even in critical operating modes such as rated speed and full load, the maximum temperature limit for the aluminum alloy is exceeded in any location of the cylinder head. Due to the extensive mechanical load, the stiffness in the area of the turbo flange needs to be high and the temperature level low.

4.4 Material Fatigue Calculation

Following the calculation of the structure temperature distribution the next important step is the determination of the thermo-mechanical loads and the prediction of the resulting component fatigue life. This considers the manufacturing loads (casting residual stress and assembly loads) as well as the operating loads (thermal stresses and gas and inertia forces). Low cycle fatigue (LCF) is caused by plastic and creep strain amplitudes which arise due to the inherent temperature gradients during cyclic heating and cooling of the engine. Lower frequency phenomena typically occur less than 10000 times over the entire component life.

The calculation of high cycle fatigue (HCF) simulates the high frequency operating loads of an engine. For purposes of the fatigue calculation, the cylinder head, in its assembled environment needs to be considered. This means all connection points, cylinder head, block, bolts, gaskets and the mounting of the turbo to the exhaust system. For final evaluation local safety factors need to be calculated which are based on a combination of local mean and amplitude stresses. In the performed cylinder head simulation the HCF and LCF safety factors were well above 2.5 in the entire integrated exhaust manifold area and lower but not critical in the cylinder head bolt areas.

5 Outlook

This investigation has shown that the application of a cylinder head integrated exhaust manifold provides a significant win-win step. As well as improving the attributes, it also provides a great scale cost reduction especially for the turbo engine architecture. This approach can also lead to attractive downsizing opportunities for the larger vehicle segments. Areas of next level research could include testing to see whether the degree of integration used here can be extended further as well as whether this technology can also be applied in a diesel environment.

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