

Impact on Performance, Emissions and Thermal Behavior of a New Integrated Exhaust Manifold Cylinder Head Euro 6 Diesel Engine

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ABSTRACT

The integration of the exhaust manifold in the engine cylinder head has received considerable attention in recent years for automotive gasoline engines, due to the proven benefits in: engine weight diminution, cost saving, reduced power enrichment, quicker engine and aftertreatment warm-up, improved packaging and simplification of the turbocharger installation. This design practice is still largely unknown in diesel engines because of the greater difficulties, caused by the more complex cylinder head layout, and the expected lower benefits, due to the absence of high-load enrichment. However, the need for improved engine thermomanagement and a quicker catalytic converter warm-up in efficient Euro 6 diesel engines is posing new challenges that an integrated exhaust manifold architecture could effectively address.

A recently developed General Motors 1.6L Euro 6 diesel engine has been modified so that the intake and exhaust manifolds are integrated in the cylinder head. Extensive CAD/CAE/CAM analyses have been employed in order to guide the design of the overall surface and the water cooling jacket that surround the exhaust manifold of the new engine version, and thus to be able to improve the low-frequency thermal fatigue resistance of the head.

The thus obtained prototype engine head has been tested on a highly-dynamic test bench at the Politecnico di Torino in order to characterize performance, emissions and thermal behavior in comparison to the baseline production engine.

The results have generally been very promising and have shown the possibility of maintaining the same performance rating over the overall engine speed range as well as comparable emissions and brake specific fuel consumption in steady-state conditions. Furthermore, appreciably faster engine and aftertreatment warm-up have been recorded due to the higher heat fraction that is transferred to the coolant and to the more favorable exhaust gas enthalpy management. The latter benefit is in fact very interesting as far as the control of HC and CO emissions within the NEDC homologation is concerned.

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INTRODUCTION

The need to further improve both engine efficiency and emissions has become of prime importance in recent years, since the European Union has defined CO₂ emission fleet-average targets for 2015 as 120 g/km ([1]) and the new Euro

6 regulation is coming into effect ([2]). Compliance with these regulations is a key driver in the planning of the powertrain portfolios of car manufacturers. Implementation of the integrated exhaust manifold cylinder head should be considered in this perspective ([3]). The exhaust manifold of standard internal combustion engines includes a number of

individual exhaust runners, one for each engine cylinder, which join together in a collector: both the runners and collector are made of either cast iron or fabricated steel and the structure is bolted to the engine block with a gasket in-between ([4]). If the exhaust manifold features are incorporated in the aluminum casting of the cylinder-head, an integrated exhaust manifold concept is obtained. The gasket from the hot end of the exhaust pipe to the cylinder head, which has just one discharge port for the gases, becomes significantly smaller and therefore cheaper ([5]).

The integrated exhaust manifold is not a new idea: aluminum water-cooled exhaust manifolds were used in the past in marine applications and there are many interesting examples of exhaust manifold systems integrated to the cylinder block ([6]). In the automotive context, integrated exhaust manifolds have already been implemented in gasoline engines ([7, 8, 9, 10]). The use of closely-coupled exhaust catalyst systems to help clean up exhaust emissions has considerably diminished the potential of tuning the exhaust runner lengths to enhance engine performance because of the very short length of the exhaust runners. As a consequence, exhaust runners and collector merely serve as transporters of exhaust gas from the exhaust port to the catalyst and the need of a separate exhaust manifold is thus reduced. On the other hand, integrated exhaust manifolds provide significant advantages over conventional external manifolds. The chief benefit of the integrated exhaust manifold is a reduction in engine weight ([4]): the different prototypes for the in-line 4 cylinder gasoline head offer a weight advantage of between 1.5 and 3 kg, in comparison to conventional external manifold setups. In general, a lighter engine, and therefore a lighter vehicle, is expected to require less fuel during acceleration and thus emit less CO₂. Propulsion system manufacturing costs are also reduced ([5]). Furthermore, the shift in operation to higher loads, which is a consequence of aggressive downsizing, requires overfueling to keep the exhaust gas temperatures within acceptable limits (the current threshold is close to 1050°C for very high-quality exhaust materials) and this also affects the fuel consumption of gasoline engines ([11]). In general, there is a continuous demand for lower exhaust gas temperature limits, in order to reduce the material costs required for high-temperature operation ([9]), but without affecting the engine performance ([5]). Finally, a reduction in the heat-transfer surface and heat capacity of the exhaust system contributes to a more rapid heating of the catalyst during warm-up ([12]) and to an early achievement of the light-off temperature (near 350 °C) on the catalyst surface. The implementation of the water-cooled exhaust manifold eliminates the need for full load enrichment ([13]). Moreover, the integration of the exhaust manifold in the cylinder head determines a reduction of approximately 30% in the overall surface area up to the turbine, and thus leads to a 20% diminution in the start time of the catalyst ([5]).

Nevertheless, the integrated exhaust manifold incurs slightly higher costs due to the potential upgrading to a larger radiator. As a general rule, radiators of integrated exhaust manifold engines usually have the same installation dimensions as in standard engines, but the cooler depth is increased ([5]). Furthermore, augmented stresses, due to higher heat rejection to the head, can increase thermal fatigue damage and thus require an accurate design of the cooling circuit of integrated exhaust manifold engines ([13]). Finally, the large amount of heat stored in the material, during rapid deceleration transients from full load, is discharged into the coolant liquid flow, in which velocity and pressure decrease dramatically due to the diminished water pump speed. As a consequence, the hot water jacket areas can be at risk to boiling ([13]) and this may result in damage to the head gasket.

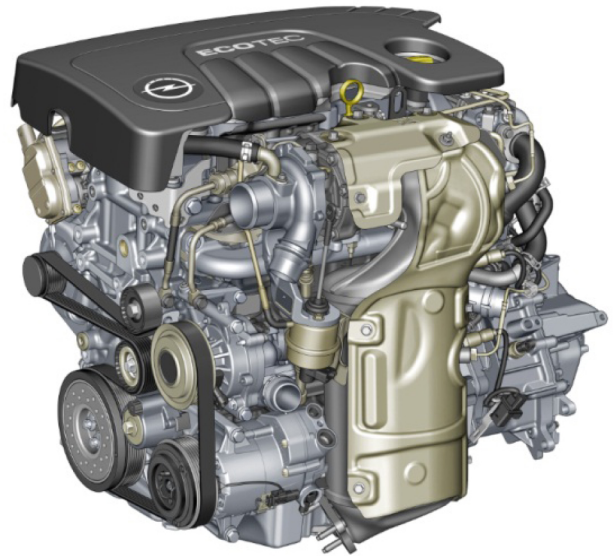


Figure 1. MDE layout.

Given this situation, General Motors (GM) Powertrain Europe has started to investigate the integrated exhaust manifold concept on its new generation of diesel engines ([14]). Many of the typical advantages of gasoline applications are still considered to be present ([15, 16]): cost and weight benefits, layout compactness, quicker warm-up of the engine and catalytic converter, the latter point being even more important for highly-efficient, clean diesel engines. Instead, high-load enrichment is dropped, since diesel engines do not include this practice, even though they may suffer from inlet turbine temperature limitations in some highly rated applications ([17]). On the other hand, the drawbacks mentioned for gasoline engines continue to exist, even potentially at a higher degree, given the complexity of the design of cylinder heads for diesel engines; this makes coolant flow distribution more challenging ([14, 15]).

A new cylinder head with a integrated exhaust and intake manifold has been designed and manufactured by GM Powertrain Europe, using the most recent CAD/CAE/CAM

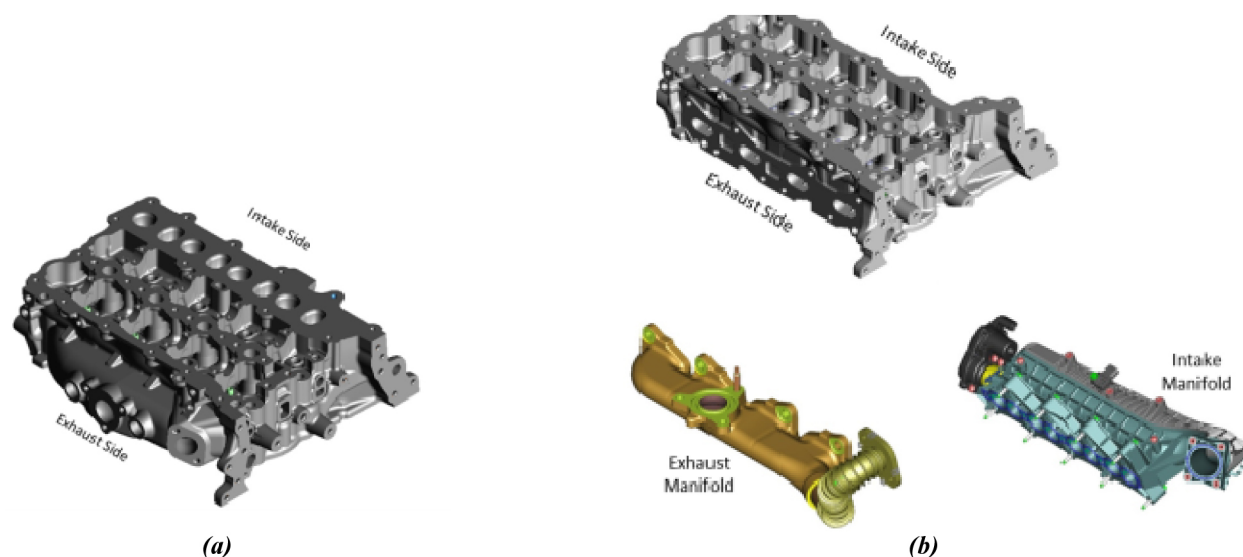


Figure 2. MDE head: IM (a) and Std (b).

tools, in order to achieve compatibility with the baseline engine block and interfaces. The prototypal head has been then tested on the engine dynamometer-bench at the Politecnico di Torino and the activity that had previously been carried out on the standard engine has been replicated. In order to provide a detailed overview, the experimental activities have involved both steady-state warmed operations and transient thermal characterization. The integration of the exhaust manifold can be implemented independently of that of the intake manifold: the matter is deepened in the paper and design keys are provided.

SYSTEM DESIGN AND SIMULATION

The integrated manifold concept has been prototyped on the 1.6L Medium-sized Diesel Engine (MDE) recently developed at the GM engineering center in Italy (Torino), in cooperation with GM research and development network centers in Germany (Russelsheim) and in the USA (Milford and Warren). The MDE will be produced in the new “Flex Plant” in Hungary (Szentgotthárd), starting in spring 2013, and will be installed in several vehicles (4 brands and 6 regional/global platforms, with 70 specific applications [14]).

The main features of the standard (Std) MDE are summarized in Table 1, while Fig. 1 reports a picture of the engine. A key goal of the development activity was to ensure excellent drivability, even for upper segment vehicles, while ensuring a significant fuel economy advantage, with 10% lower CO₂ emissions, and a similar performance rating as the GM 2.0 liter Euro 5 diesel engine. The weight of the 1.6L MDE is 25 kg lower than that of the GM 2.0L engine, also due to the aluminum block and to the other lightweight components.

Table 1. Main features of the MDE engine.

Certification:	Euro 6
Engine type	4 cylinders in-line
Bore x stroke [mm]	79.7 x 80.1
Displacement [cm ³]	1598
Compression ratio	16.0
Valves per cylinder	4
Nominal rated power and torque	100kW @ 3500-4000rpm 320Nm @ 2000-2500rpm
Engine control unit	GM D1P-E98
Injection system	Solenoid 2000bar 3 rd generation Common Rail
Turbocharger	Single stage VGT with rack position feedback
Swirl control	Rotary flap on secondary port
Catalyst system	Integrated closed-coupled DOC & DPF, under floor Urea-SCR

Figure 2 shows the compact and lean layout of the integrated manifold (IM) engine prototype compared to the Std version of the 1.6L MDE that is currently produced. Fig. 3 shows some pictures of the MDE cylinder-head with either integrated intake and exhaust manifolds (IM head, Fig. 3a) or conventional external manifolds (Fig. 3b). These pictures show the components that have been changed or modified and thus offer the possibility of perceiving the packing advantages of the tested IM solution. The previously separated intake and exhaust manifolds (the yellow and cyan components in the standard head in Fig. 2b) are visible as head bulges in the intake and exhaust sides of the IM head. The integrated exhaust manifold has just one central exit for the gases to the turbine and a side exit to feed the EGR circuit.

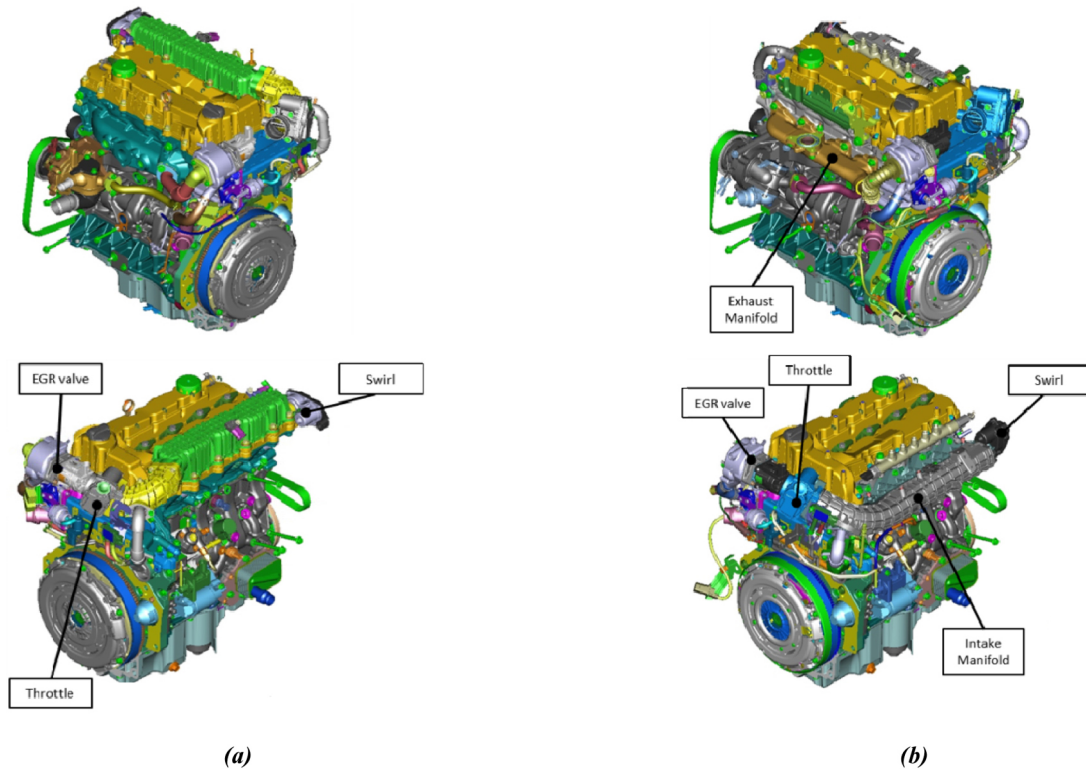


Figure 3. MDE with IM head (a) and with Std head (b).

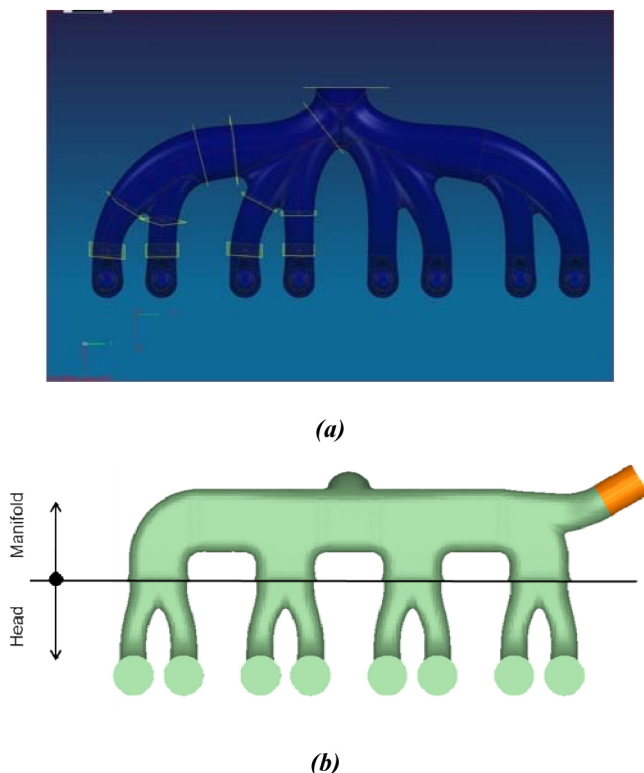


Figure 4. Exhaust gas fluid domain for the integrated exhaust manifold (a) and for the standard manifold (b).

Figure 4 shows a comparison of the exhaust gas fluid domains for the new design (Fig. 4a) and the standard MDE engine (Fig. 4b). The interface between the head and manifold is also reported in Fig. 4b to help distinguish the parts that have been modified in the baseline head and external exhaust manifold. The orange pipe in the standard exhaust manifold represents the outlet to the EGR circuit. Evidence of a smoother design of the pipe connections to the lower volume plenum, upstream of the turbocharger, is visible in the integrated exhaust manifold (Fig. 4a). Even though the dynamic impact of the exhaust runners is contained, because of their reduced length, the shape of the exhaust ports was designed to control exhaust gas fluid-dynamic interference as much as possible, as this phenomenon can have an appreciable effect in integrated exhaust manifold layouts ([12]). The volumetric efficiency of a diesel engine can in fact increase as much as 1%, due to the reduction in the interference between the pressure pulses from the different cylinders ([17]).

Figure 5, which shows the overlap of the two configurations, highlights how the design changes of the IM head affect the gas route in the final part of the head, where the bulge that contains the integrated manifold has been realized. When the exhaust manifold is integrated, the number and size of the mating parts between the exhaust manifold and head is significantly reduced and elimination of the threaded holes in the cylinder head leads to a reduced cycle time in modern CNC machines. Furthermore, the gasket

from the hot end of the exhaust pipe to the cylinder head (not reported in the picture) is significantly smaller and cheaper. Finally, heat shielding in the integrated manifold area of the turbocharged engine is not necessary to protect the components against overheating because of the lower heat rejection to them, which is caused by liquid flow cooling and the thermal connection to the cylinder head.

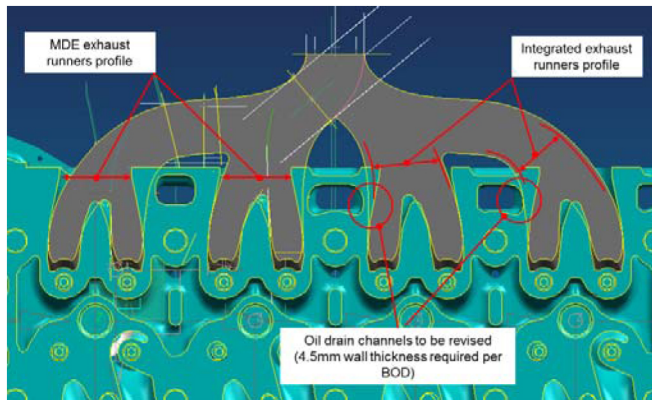


Figure 5. Overlap of Std (green) and integrated exhaust manifold (grey) designs.

Figure 6 reports a schematic of the main components of the standard coolant circuit: cylinder block, cylinder head, cabin heater, radiator, oil cooler, thermostat, pump, EGR cooler and EGR valve. The numerical value of the coolant flow rate at engine rated power speed is also indicated. Colder pipes that arrive from the radiator are represented by blue lines, while a red color is used for the warmer pipes that return the coolant flow from the engine to the radiator. A cross-flow layout circuit, which is the typical configuration of modern engines, has been applied. The liquid coolant is fed by the pump on the exhaust side of the block, sent upward to the head, passes through the head to the intake side and finally returns downward to the block, at the outlet of which the oil cooler is located. Fig. 7 shows a 3D rendering of the MDE coolant circuit jackets for the Std engine: the exhaust- and intake-side views are reported at the bottom and top of the figure, respectively. First, the picture can help the reader visualize the cross-flow layout reported in Fig. 6 by highlighting the coolant path in both the block and head as well as the pipe connections between these two subsystems. Then, the colors codify the coolant velocity close to the heat exchange surface: red represents the highest speed regions, while blue indicates more quiescent areas. The coolant velocity is a relevant quantity for the estimation of the risk of local coolant boiling (the lower the velocity, the higher the risk of boiling) and the consequent reduction in heat rejection capability.

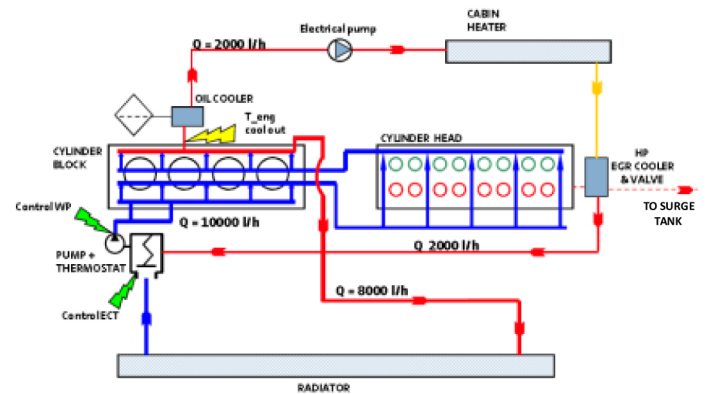


Figure 6. Standard MDE coolant circuit schematic.

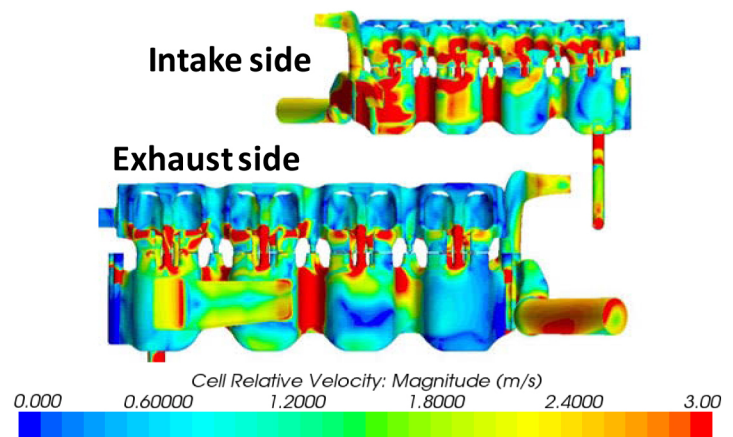


Figure 7. MDE Std head: coolant wall velocity field.

Figure 8 outlines the modifications that have been made to feed the exhaust manifold water jacket in the IM head. The yellow lines in Fig. 8a indicate the additional cooling jacket that have been drawn around the exhaust ports (reported in red). Two cooling layers can be observed, one above and the other below the integrated exhaust manifold. The coolant flow comes from the block (thick blue arrow) and is split into two flows that have been named M1 and M2 and indicated with thin red arrows. The M2 flow cools the exhaust seats and the injectors, whereas flow M1 passes through the cooling jacket of the exhaust manifold. Finally, the M1 and M2 flows join in the intake side of the head (represented in blue) and go back down to the block (thick red arrow in Fig. 8a). If the system is observed from the top (Fig. 8b), the same coolant flows are visible, with details of the upper junction to the baseline part of the cooling jacket, to the exhaust valves and to the injector seats. Casting hole plugs C1 and C2 are also shown.

Figure 9 represents the exhaust gas temperature close to the manifold walls: Fig. 9a refers to the IM engine, while Fig. 9b refers to the Std engine. A significant drop in gas temperatures at rated power conditions, roughly 50°C at the turbine inlet interface, which is also consistent with previous findings on gasoline engines, is clearly visible ([5]).

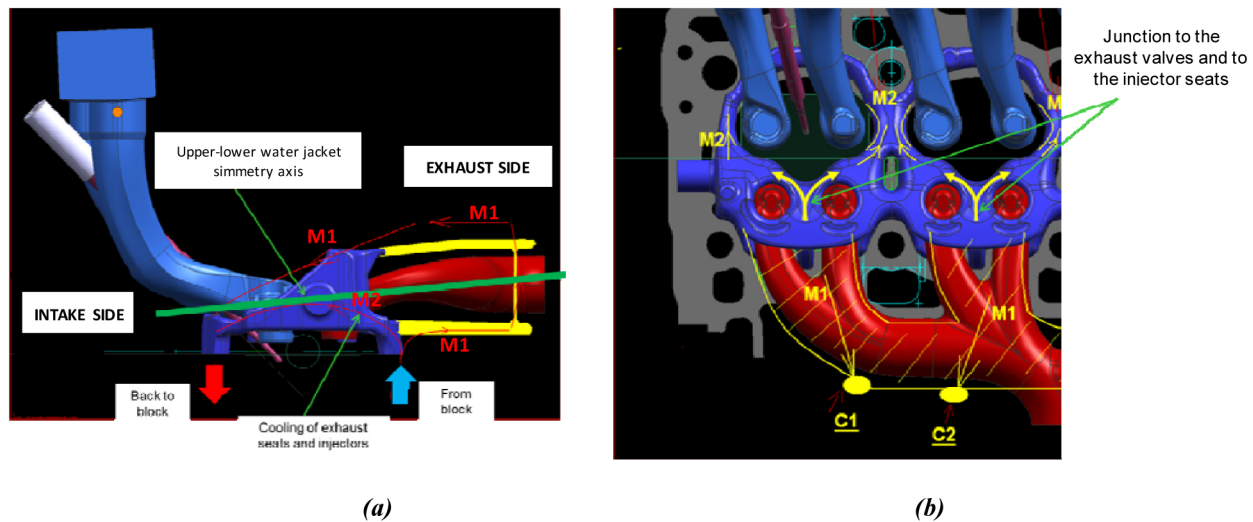


Figure 8. IM coolant jacket: side view (a) and top view (b). Coolant flow directions are indicated by arrows.

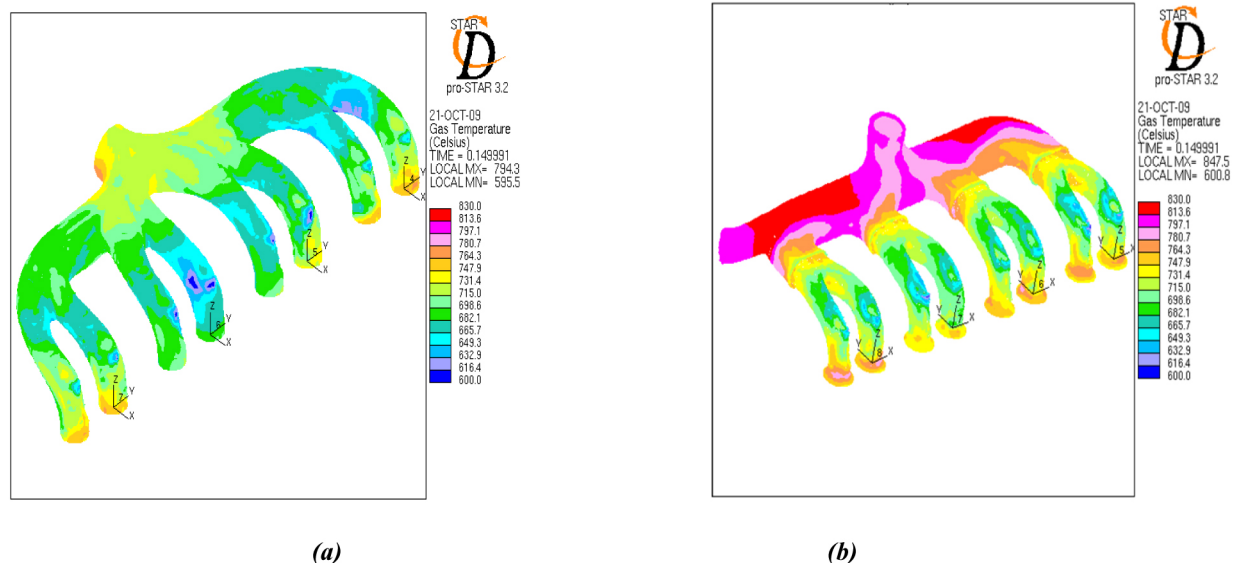


Figure 9. Exhaust gas temperatures close to the wall for the integrated exhaust manifold (a) and for the standard manifold (b).

EXPERIMENTAL SETUP

The IM engine prototype has been tested on a dynamic test bench at the Politecnico di Torino, where a complete engine instrumentation has been setup in order to characterize engine operation under steady-state and transient conditions ([18]). The vehicle coolant circuit, which is external to the engine, was replicated and both the pipes and radiator capacities were selected as close as possible to those used in the real vehicle. Two instantaneous flow meters were installed, one at the main engine outlet going towards the heat exchanger (radiator in the vehicle application) and the other at the bypass line that passes through oil and EGR cooler and then enters the main circuit downstream of the thermostat (Fig. 10).

The installation also included several thermocouples to fully characterize the temperature distribution in the coolant circuit, in the cylinder head metal and in the exhaust gas circuit as far as the aftertreatment system inlet. This has proved to be important in order to highlight any potential difference between the two different exhaust manifold setups and ensure that the thermal limits were not exceeded for the various engine components. Fig. 11 illustrates the locations of the temperature and pressure transducers at the turbine inlet for the two configurations, whereas Fig. 12 shows the position of the thermocouples in the cylinder head close to the firedeck. The measurements in the cylinder head were used to determine the temperature distribution inside the head and thus calculate the thermal gradients in both the longitudinal and transversal directions. These gradients are in