

Numerical Investigation on the Effects of Different Thermal Insulation Strategies for a Passenger Car Diesel Engine

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ABSTRACT

One of the key technologies for the improvement of the diesel engine thermal efficiency is the reduction of the engine heat transfer through the thermal insulation of the combustion chamber. This paper presents a numerical investigation on the effects of the combustion chamber insulation on the heat transfer, thermal efficiency and exhaust temperatures of a 1.6 l passenger car, turbo-charged diesel engine. First, the complete insulation of the engine components, like pistons, liner, firedeck and valves, has been simulated. This analysis has showed that the piston is the component with the greatest potential for the in-cylinder heat transfer reduction and for Brake Specific Fuel Consumption (BSFC) reduction, followed by firedeck, liner and valves. Afterwards, the study has been focused on the impact of different piston Thermal Barrier Coatings (TBCs) on heat transfer, performance and wall temperatures. This analysis has been performed using a 1-D engine simulation code coupled with a lumped mass thermal model, representing the engine structure. A time-periodic wall conduction model has been used to calculate the wall temperature swings along the combustion chamber surface and within the engine cycle. Two different TBC materials, Ytria-Partially Stabilized Zirconia (Y-PSZ) and anodized aluminum, and different layer thicknesses have been simulated.

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INTRODUCTION

The in-cylinder heat rejected in internal combustion engines represents a significant fraction of the input fuel energy. Improvement in engine thermal efficiency can be reached with the so called Low Heat Rejection Engines (LHREs), in which the heat losses are reduced and utilized to increase the piston positive work, as well as to provide higher exhaust gas temperature for the downstream energy recovery systems.

LHREs are realized by covering the combustion chamber walls (pistons, liners, head, valves), the exhaust ports and manifold with insulating materials, called Thermal Barrier Coatings (TBCs). In particular, the ceramic materials can operate at much higher temperatures with respect to the metals, causing a considerably reduction of the heat transfer through the walls.

In the past a large number of works were conducted on the reduction of heat rejection from the combustion chamber applying ceramic coatings on the chamber walls, but the results have been often inconclusive and contradictory, not bringing to the benefit expected by the research community.

Nowadays, the idea of repurpose the Low Heat Rejection technology, coupled with the aftertreatment systems, on the new generation diesel engines can lead to benefits in terms on performances and emissions. In particular, the insulation strategies, increasing the exhaust gas temperature, can considerably improve the aftertreatment performance and accelerate the catalyst light-off. Moreover, the coatings can be combined with other engine control strategies to produce emission benefits, limiting power loss and fuel economy penalty. Further improvements in fuel economy and emissions can be achieved by combining the Low Heat Rejection Engines with new technologies of thermal management, as split cooling system, switchable pumps, etc.

Furthermore, the very stringent limits in terms of pollutant and CO₂ emissions are leading to the use of more expensive technologies to meet the regulations (Figure 1). In this scenario, a high-priced technology, as thermal insulation, returns competitive.

The cycle simulations are often used to evaluate the potentials of the insulated engine before conducting costly experimental campaigns. Several simulation works have been carried out to estimate the performance, fuel consumption and emissions of the LHREs.

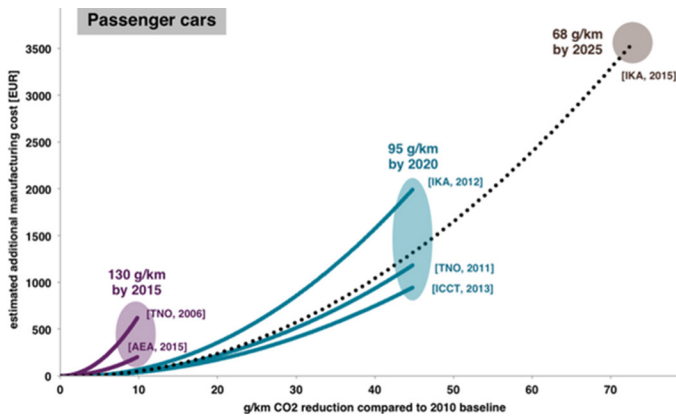


Figure 1. 2015, 2020 and 2025 cost curve estimates for passenger cars in the EU. Source: ICCT [1].

T. Morel et al [2, 3, 4] have developed an analytical numerical model to represent the heat transfer process in a diesel engine. Their methodology was able to catch the wall temperature swings along the combustion chamber surfaces solving a transient one-dimensional heat conduction code in the thin solid layers adjacent to the combustion chamber. The work was focused on a 14 liter, 6 cylinders, turbocharged, intercooled engine (Cummins NH) and the results indicate an improvement of about 5% in thermal efficiency in the case of 1.5 mm of Zirconia Plasma Spray (ZPS) coating on pistons and head with a cooled metal liner.

On the same engine, D. N. Assanis and J. B. Heywood [5] studied the effects of thermal insulation on performances and efficiencies through a quasi-steady simulation model coupled with a heat transfer model. They stated that the surface temperature variations over the engine operating cycle are higher for engine surfaces insulated with low-conductivity materials, such as ceramics. Considering a time-periodic approach of conduction problem, they estimated surface temperature variations in the order of 250 K around the quasi-steady value. This resulted in less degradation of volumetric efficiency and thus in an improvement in system efficiency with respect to the prediction based on quasi-state heat transfer.

In addition to the above mentioned, other researchers focused their works on this topic [6, 7, 8, 9, 10, 11, 12]. More recently, G. de Paola et al [13] investigated on the effects of the combustion chamber walls insulation using a 3D Computational Fluid Dynamics (CFD) tool-chain, coupled with a 0D thermal model. They concluded that the piston is the component with higher potential for the thermal efficiency improvement, leading to about 3 % decrease in High Pressure Indicated Specific Fuel Consumption (HP ISFC). The authors also compared the piston coating solution with the steel piston technology: both solutions lead to HP ISFC benefit, respectively around 3% and 2%.

In their experimental campaign on a turbocharged, 6-cylinder, 10.8 liters diesel engine (Volvo/Mack MD-11), J.R.Serrano et al [14] found out a 3% increase in BSFC using insulated pistons with a 1 mm coating of agglomerated-sintered Y_3O_2 - ZrO_2 . They have attributed this worsening to the slowing down of the diffusion phase

of the combustion process. Moreover, they discovered that the combination of the pistons and the exhaust manifold insulations can reduce the BSFC of 1%.

Toyota Central R&D Labs and Toyota Motor Corporation [15, 16, 17, 18] recently developed and proposed a new material, anodized aluminum with silica filler, as piston TBC. It presents the advantages of low thermal conductivity and low heat capacity that allow not only to insulate the combustion chamber but also to prevent the intake air heating. Differently from the traditional ceramic insulations which present higher surface temperatures during the entire engine cycle (including the intake stroke), anodized aluminum coating exploits the thermo-swing property, which is the temperature fluctuation of the combustion chamber walls following the transient gas temperature. The higher surface temperatures during combustion and expansion strokes cause the heat loss reduction, while lower surface temperatures during the intake stroke prevent the intake air heating and the decrease in volumetric efficiency. Y. Wakisaka et al [16] found out, through the analysis conducted on a optically accessible diesel engine, that the temperature oscillations during the engine cycle, on the combustion chamber surfaces coated by the anodized aluminum, result to be in the order of 140 K, under mid-load conditions at 1200 rpm. Moreover, Toyota proposed to apply an anodized aluminum coating of 100 μ m to an aluminum alloy piston (only on the crown area) in the new 2.8 liter ESTEC 1 GD-FTV engine. This particular insulation ensures about 2% increase in the engine thermal efficiency [18].

This paper presents a numerical investigation on the potential of different thermal insulation strategies applied on a passenger car diesel engine. Firstly, a 1D engine model has been used to quantify the theoretical maximum capabilities in heat transfer and BSFC reductions due to the thermal insulation of the different components of the combustion chamber (pistons, liner, firedeck and valves). Secondly, coupling the engine model with a 0D thermal model of the combustion chamber, the benefits of different piston TBCs have been assessed. In particular, two materials have been analyzed: Yttria-Partially Stabilized Zirconia (Y-PSZ) and anodized aluminum.

MODEL DESCRIPTION

Engine cycle simulations have been carried out using a 1D commercially available simulation code, GT-POWER, developed by Gamma Technologies. The simulation software is able to solve the Navier-Stokes equations (the conservation of continuity, momentum and energy) in the one-dimensional formulation [19]. A predictive multi-zone combustion model, DIPulse [20], developed by Gamma Technologies, was implemented for the burn rate calculation. The convective heat transfer model is based on the in-cylinder flow, including swirl motion and turbulence. This model, developed by T. Morel and R. Keribar [21], allows a more accurate prediction of the heat fluxes distribution between the engine components with respect to the traditional heat transfer models (Woschni, Annand, etc.) because it is based on the in-cylinder flow field which is spatially not uniform. Further details and a comparison between Flow and Woschni heat transfer models can be found in the Appendix. Wall

thermal models have been implemented for the calculation of pipes and engine wall temperatures, solving the 1D, steady-state equation of conduction heat transfer in the material layers adjacent to the gases. The injection rate profiles have been calculated through a Common Rail Injector model, starting from Energizing Times (ETs), Dwell Times (DTs) and injection pressures (as discussed in [22]). Additionally, engine load and boost pressure are controlled in closed loop by the injected fuel quantity and the turbine rack position respectively. The only other inputs used in the simulations are: the injection timing, the measured boost pressure, the EGR level, the ambient pressure and temperature, coolant and oil temperatures.

Case Study

Table 1. Main engine specifications.

Engine type	DI Turbocharged Diesel /EURO6
Displacement	1598 cm ³
Cylinders	Inline 4
Bore x stroke	79.7 mm x 80.1 mm
Compression ratio	16:1
Turbocharger	Single-stage with VGT
Fuel injection system	Common Rail
EGR system	High-Pressure & Low-Pressure (cooled)
Maximum power and torque	100 kW @ 4000 rpm 320 Nm @ 2000 rpm

A turbocharged, direct injection, four-cylinder diesel engine was analyzed in this work. The engine specifications are reported in Table 1.

Simulation Matrix

The engine operating points selected for the numerical assessment of the thermal insulation technology are reported in Figure 2. This particular simulation matrix allows the evaluation of the influence of engine speed and load on the thermal insulation (engine speed and load sweeps). All the simulations were run in warm engine condition (with 90 °C of coolant temperature).

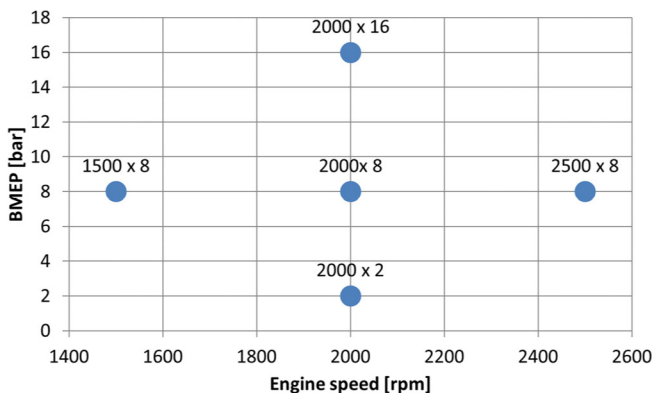


Figure 2. Matrix of the simulated engine operating points.

Validation

The engine model was initially run in the baseline configuration and the results were compared with the experimental data (Figure 3).

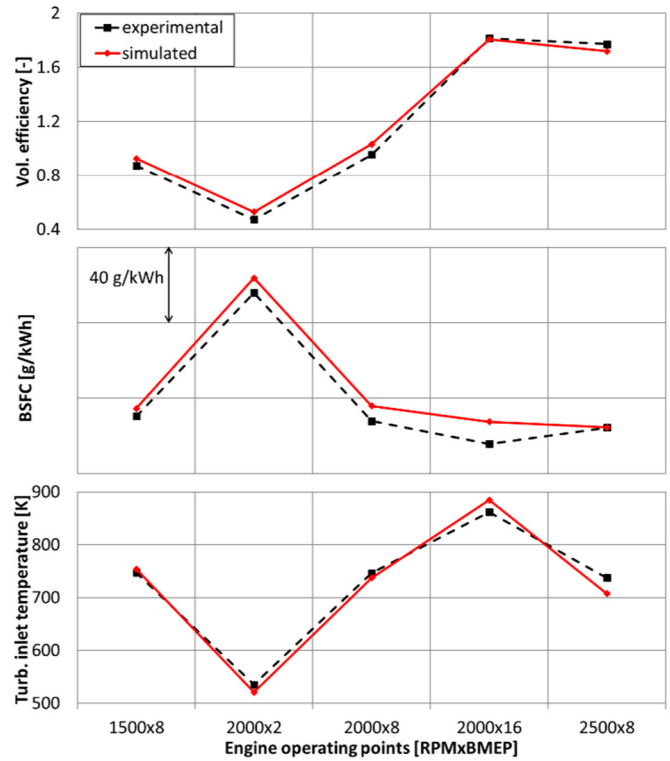


Figure 3. Comparison of predictions and experimental data.

The results of the engine simulations at low-medium loads and speeds are more than sufficient in the engine performance prediction: an averaged error of -2.6% in BSFC prediction has been reached. Further validation, regarding heat fluxes and wall temperatures will be performed as soon as the experimental data will be available.

USE OF THE SIMULATION FOR COMPONENT HEAT TRANSFER STUDIES AND ENGINE PERFORMANCE

Once the model has been calibrated and validated, the next step was the study of the effects of the complete and ideal insulation of the engine components: pistons, firedeck, valves and liner. In this analysis, the heat transfer coefficients between gas and components were individually forced to zero to simulate the total insulation of the component from the in-cylinder gas. The in-cylinder heat transfer and BSFC reductions due to the component insulations are reported in Figure 4. The simulation results show that the greatest portion of in-cylinder heat loss is through the piston, followed by head, liner and valves. More than 45% of the total heat transfer is reduced with the only piston insulation, and more than 35% is reduced with the total head insulation (firedeck plus valves). This result is due to the fact that head and piston surfaces are more exposed to the combustion gas near to the top dead center firing (TDCF), which is the part of the cycle with the highest heat loss. Moreover, the combustion is

intentionally directed towards the piston bowl surface, causing an increment of the gas velocity and temperature and, consequently, an increase in HTC and heat flux through the component [13].

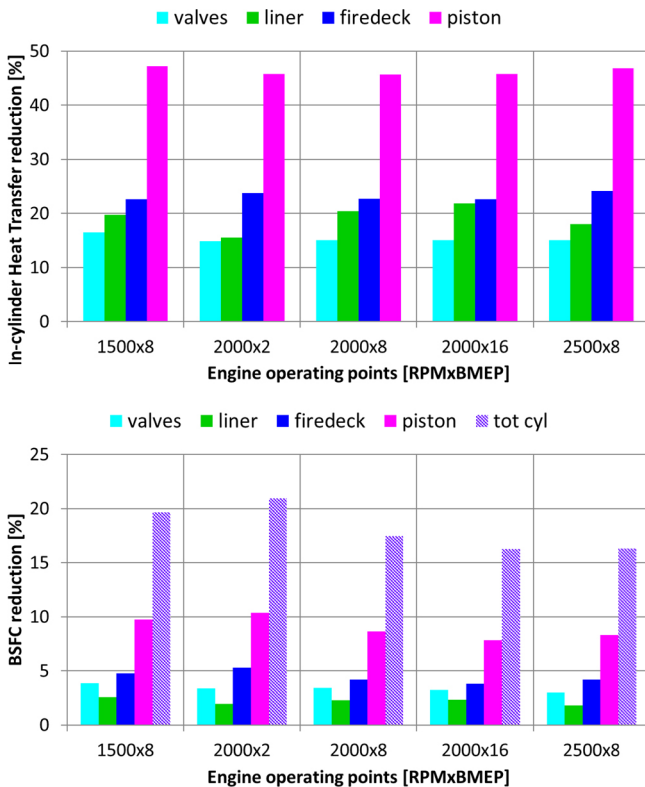


Figure 4. In-cylinder Heat Transfer reduction (top) and BSFC reduction (bottom) due to the component insulations.

Contrarily, the liner insulation seems to be not enough efficient in the BSFC reduction. As Morel et al [2] affirmed, the liner insulation does not affect the heat loss near to the top dead center firing, so the BSFC improvements are not relevant. The majority of the analyzed papers confirm that the piston results the component with the largest potential in BSFC decreasing [2,5,6,13].

Figure 5 shows the effects of thermal insulation on the volumetric efficiency and turbine inlet temperature. The valve insulation is the most effective strategy in increasing the volumetric efficiency since the zeroing of the heat transfer from the intake valves to the inducted air causes a reduction of the in-cylinder gas temperature during the intake. Heat transfer and in-cylinder gas temperature with valve insulation are presented in Figure 6 and compared with the baseline and piston insulation strategy.

Insulations also provide increment in turbine inlet temperature, except for the valve insulation. In fact, with this insulation, the lower inducted air temperature (of about 20 K at 2000x16) affects the gas temperature during the entire engine cycle, including the exhaust phase.

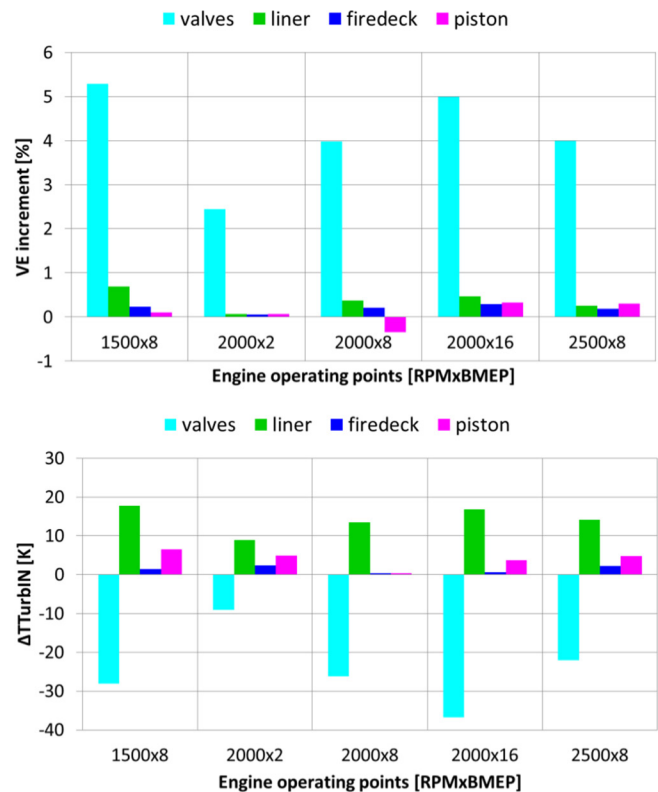


Figure 5. Volumetric efficiency increment (top) and turbine inlet temperature variation (bottom) due to the component insulations.

Figure 7 shows the heat transfer reductions for the different insulation strategies, normalized respect to the component surface areas (as shown in Equation 1).

$$\text{Area-normalized HT reduction} = \frac{HT_{\text{baseline}} - HT_{\text{insulated}}}{\text{surface area of the component}} \quad (1)$$

The liner insulation exhibits the higher peak of the normalized heat transfer reduction in correspondence of the TDCF due to the small liner area. Moreover, the liner insulation presents a drop of the normalized heat transfer reduction just before TDC (scavenge), in correspondence of the intake valve opening. This could be caused by higher exhaust gas temperature (Figure 5) which provokes an increase in the heat transfer with the inducted air. As described previously, the valve insulation is the most effective strategy to reduce the heat transfer during the intake phase and to increase the volumetric efficiency. This explains the negative normalized heat transfer reduction during the intake.

Even though all insulation strategies present comparable area-normalized heat transfer reductions, the piston insulation results the most efficient strategy in reducing heat transfer because of the larger surface area near the TDCF.