The analysis of the thermal barrier coating using Ansys software

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Abstract. The main source of energy for the propulsion of automotive and trucks is still internal combustion piston engines. These are constantly improved in such a way as to achieve the lowest possible consumption of low-emission fuel. The results of the simulation of new technologies are confirmed in experimental stands, thus being the basis for the development of internal combustion engines. This paper shows the theoretical simulation of temperature distribution and thermal flow distribution when a thermal barrier is applied to the engine combustion chamber components. More specifically, the impact of thermal barriers on the surface of the piston crown shall be investigated.

1. Introduction

The most used engines in the propulsion automotive industry are the internal combustion engines. These engines can use diesel fuel, gasoline, alcohol or mixtures of oil and diesel fuel known as biodiesel. The energy released from the combustion process is consumed in proportion of 30-40% to produce mechanical work [1], and 5 - 15% is exhausted in the atmosphere through the exhaust gases. The energy of the exhaust-gas is partially recovered by using turbochargers and some part is used by catalytic converters to reduce pollutant emissions. These turbochargers compress the air from the cylinders, thus improving the engine volumetric efficiency.

According to studies, more than 1/3 of the gas energy in the cylinder is lost through the heat transfer [2]. Considering the possibility of recovering a small percentage of exhaust gases energy, the attention of researchers focuses on the possibility of reducing the thermal transfer from the engine, maximizing the mechanical work. Thus, a new concept of engines has appeared: Low Heat Rejection Engine. This concept uses thermal barriers in the combustion chamber to reduce the thermal transfer. In this paper a comparative study of temperature and thermal flux is made in the case of using a thermal barrier with different thicknesses.

2. Theoretical concept

The internal combustion piston engines are used on a large scale in the transport of persons, in the goods transport, for both land transport and sea transport. According to studies between 5 and 15% of the heat energy released in the combustion chamber (figure 1) is released into the atmosphere by means of the exhaust gases. A part of this energy is recovered by the turbo-compressor in order to increase the volume efficiency of engines, including the power, or used in pollutant emission reduction systems. These values are valid on high load tests specific for heavy-duty engines operating mode.
The internal combustion engines of automotive operate mainly at medium to low load, where the thermal efficiency of the engine is lower. In this case, the losses are higher.

More than 30% of the burned gas energy is lost by thermal transfer towards the metal parts of the engine. This energy is dissipated in the atmosphere through the cooling system. The study aims to perform the theoretical simulations with the aim of eliminating the loss through thermal transfer. The thermal barrier applied to the surfaces of the combustion chamber reduces the amount of energy absorbed by the metal parts, so a higher amount of energy is available that can perform mechanical work. Thus, the increase of the thermal efficiency of internal combustion engines, leads to decreasing of the specific fuel consumption.

The Autodesk Inventor software was used to create the 3D model and simulate the application of a thermal barrier after the piston (figure 2) was previously sized [3]. Ansys is one of the most complex software in analyzing the static, dynamic, thermal and CFD models.

For thermal analysis [4][5], the Steady-State thermal module has been used. The 3D model was imported into the Ansys Software, where thermal analysis was performed on the assembly: piston, rings and cylinder. The mesh is classified in 152883 elements and 237586 nodes.
2.1 Calculation method
The coefficient of thermal convection of the burned gas is dependent on the constructive model of the internal combustion engine. According to the Brilling method [6] for compression ignition engine, the thermal convection coefficient of the burned gas from the engine is dependent on the average speed of the piston, the pressure of the gases in the cylinder and the instantaneous temperature of the gases:

\[
\alpha = 0.99 \cdot (2.45 + 0.185 \cdot w_{pm}) \sqrt{\frac{P_g}{T_g}} \quad [\text{kcal} / (m^2 \cdot h \cdot K)],
\]

(1)

where:
- \( w_{pm} \) - the average speed of the piston [m/s];
- \( P_g \) - instantaneous gas pressure [bar];
- \( T_g \) - instantaneous temperature of the gases [K].

To simplify the model, it has been considered a constant temperature of the engine block cooling channels. Also, on the Steady-State Thermal analysis module it has been considered the heat transfer between piston – rings – engine block, without being taken into account the oil film.

As most manufacturers of compression ignition engines use pistons made of aluminum alloy to reduce the inert masses moving in translation. In order to achieve the theoretical study ceramic coatings with two material: Alumina 96% and YSZ (Yttria-stabilized zirconium) are used. The thermal properties of this material are shown in the table below.

| Material      | Thermal Conductivity [W/(m K)] |
|---------------|--------------------------------|
| Aluminum Alloy| 170                            |
| Alumina 96%   | 25 [7]                         |
| YSZ           | 2.5 [8]                        |

3. Results and Discussions
The simulations were carried out under the same conditions ranging only to the thickness of the deposited ceramic layer (200 \( \mu \)m respectively 400 \( \mu \)m) and the material used (Alumina 96 % and Yttria-stabilized zirconia). Temperature distribution analysis shows that in the case of using a thermal barrier
with yttria-stabilized zirconia (figure 4b), the temperature of the piston head surface increases compared to the model without ceramic coating (figure 4a).

![Figure 4. Piston temperature distribution.](image)

On the other hand, the temperature of the piston with ceramic coated is lower. This is possible due to the low thermal conductivity of the ceramic material applied to the surface of the piston head. This high difference of thermal conductivity 2.5 [W/(m·K)] in the case of the ceramic coating YSZ compared to 170 [W/(m·K)] in the case of the aluminum alloy reduces the amount of heat transfer by the piston from the burned gas. Figure 5 shows that in case of using a ceramic coating with YSZ the recorded temperatures are higher than if using a coating with Alumina 96%. At the same time, the surface of the thermal insulation is dependent on the thickness of the filed coating.

![Figure 5. Piston surface temperature.](image)

Furthermore, it is noted that the thermal flow (figure 6) to the engine cylinder is smaller when a ceramic coating is used on the piston surface. If in the previous case the temperatures have increased when a higher thickness YSZ is used, a decrease is observed in the case of heat transfer to the cylinder. So, the smallest value recorded is when using a 400 μm YSZ ceramic coating. This barrier reduces the heat flow to the cylinder by 5.6%.

In this case the use of the thermal barrier has a direct bearing in the energy balance of the internal combustion engine. The amount of heat that is usually removed by heat transfer is now re-directed in
two possible directions: mechanical work and exhaust gases. In the experimental tests it has been observed that the use of thermal barriers increases the exhaust gas temperature (figure 7) regardless of excess air or engine operating load.

![Figure 6. Heatflow.](image)

![Figure 7. Exhaust gas temperature [9].](image)

Also, other tests show that thermal efficiency is higher by a few percent in the case of using thermal barriers. As expected, the high temperature of the ceramic coating makes the volumetric efficiency of the engine to get lower (figure 8). This changes after the turbocharger recovery more energy from the exhaust gas, thus increasing engine efficiency.

![Figure 8. Thermal Efficiency Diesel Engine with ceramic coating [10].](image)
The simulation has been performed for both the uncovered and the heat-insulated pistons with Alumina 96% and YSZ, in two different thicknesses of 200 μm and 400 μm. It can be observed that the thermal barrier increases the temperature of the piston crown surface (the ceramic-coated area). This leads to better self-ignition of the injected fuel, which means a better combustion. On the other hand, the high temperature of the surfaces in the combustion chamber leads to a decrease in the volumetric efficiency of internal combustion engines. This can be an advantage at idle speed and low load by a lower specific fuel consumption. However, at high load this may limit the maximum engine performance, especially for naturally aspirated engines.

On the other hand, on the experimental tests it was observed that the temperature of the exhaust gases increases when the thermal barrier is used. This has an advantage for engines using turbocharger. A higher amount of energy in exhausted gas can turn into an advantage for turbocharged engines and thus compensate for the lower volumetric efficiency of the engines. New turbo-compressors technologies used on Formula One engines have an electric generator coupled to the turbocharger that can supply electrical power to the hybrid system of the power train when a higher amount of energy is available in the exhaust gas. The generator can also function as an electric motor, thus eliminating the turbo-lag.

4. Conclusions
The thermal barriers represent a way to change the energy balance of the internal combustion engine. The study shows that using a thermal barrier reduces the thermal flow between piston and engine block with 5.6% while the surface temperature of the piston crown (the temperature of thermal barrier) is increasing with 63%, causing a lower volumetric efficiency comparing with the standard engine. To improve the efficiency of the engine, in the future, it can be developed new materials with lower thermal inertia.

In conclusion, it can be said that thermal barriers reduce the heat flow to the surface of the cylinder, thereby losing a smaller amount of heat through the engine cooling system. In this case, a higher amount of energy is available which can be used in producing mechanical work or it may be recovered from the exhaust gas.

5. References
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