EFFECTS OF PLASMA SPRAYED ZIRCONIA COATINGS ON DIESEL ENGINE HEAT RELEASE

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Abstract. Paper presents comparative analysis of heat release in baseline and insulated (piston crown with plasma sprayed zirconia coatings) diesel engine. The explanation of the efficiency loss mechanism was also given.

1. Introduction - characteristics of ceramic thermal barrier coatings

Experimental research of insulated diesel engine incorporating thermal barrier coatings (TBC) has produced controversial results. Some publications report that engine efficiency increases with insulation [e.g. 1, 6] while others argue that efficiency decreases [e.g. 17, 21]. There are also reports presenting a mixed picture [e.g. 1, 11, 21].

Materials (used for engine combustion chamber coatings) can be classified as conductors or insulators according to their thermal (electrical) conductivity. The properties of them depend on the binding forces between their molecules (atoms) and the thermal energy of motion. Two types of bonding mechanisms occur in ceramic materials: ionic or covalent [15]. The dominant bonding mechanism depends on the differences in electronegativities of their elements. Many ceramics (e.g. alumina, zirconia) contain both ionic and covalent bonding [14]. In an insulator, electrons completely fill the valence band (the highest energy band occupied by electrons) and the energy gap between valence band and the next band (conduction band) is large. In their pure state, most ceramics are wide-band-gap insulators [13]. This means that there is a large ($E_g > 3$ eV) gap between valence band and conduction band. When light (or other form of radiation) strikes a ceramics, it may be transmitted, absorbed or reflected. If this band is larger than light (radiation) energy (for visible light the energy range is from 1.8 to 3.1 eV), these ceramics will be optically transparent (sapphire – crystal form of Al$_2$O$_3$, cubic zirconia – diamond simulant) [13]. Crystalline imperfections and pores (more porous materials are better insulators) within the grains of ceramics are scattering the radiation and may contribute to the ceramics partial opacity (translucency). That is why the industrial ceramics is rather translucent than transparent. Optical properties of typical crystalline insulators may be found in [17].
2. Heat transfer through translucent ceramics coatings

In engine heat transfer conduction, convection and radiation participate simultaneously. Radiation is considered to be important mode of heat transfer especially in diesel engine (up to 15-35% of total heat transfer [2, 5]). For engine combustion radiation (0.2-5 μm), the energy range is 0.2 to 6.2 eV. It means that ceramics may transmit part of its energy in both visible and infrared (near and middle) region. Ceramics partial transluence to heat radiation is of concern since some of their effectiveness as heat barrier may be lost as a result – the significance of the radiation heat transfer is raised. Buchanan and Wilson state: “yttria stabilized zirconia samples were optically translucent at 1mm thickness” (av. grain’s size 0.2±0.4 μm) [3]. Analytical and experimental studies of Wahiduzzaman and Morel [19, 20] proved that thick (>1.5 mm) zirconia-based ceramics are optically thick, but thin ceramics are partially transparent (30% transmittance for 1 mm thickness and 40% for 0.5 mm, wavelength 2.5μm) to thermal radiation in wavelength region characteristic of diesel engine (0.5-5μm) and this transluence can have significant detrimental effects on heat barrier effectiveness under realistic diesel engine conditions. It was found that the absorption coefficient of plasma sprayed zirconia (PSZ) is relatively small in the band 1–4 μm. Beyond 4 μm it starts to increase very sharply (it was noted that the samples exhibited similar reflectance and transmittance spectra despite different compositions [20]). As ceramic TBC become less opaque, the total heat flux transferred through the ceramic layer increases. The performance of the investigated ceramics and the mechanism of heat transfer were found to depend on surface condition, especially on soot deposition [20]. Formation of soot is a feature of all hydrocarbon flames. Soot particles make the flame luminous and opaque. The radiation of soot in diesel engine flame is about 5 times the radiation from gaseous combustion products and relative absence of soot in SI engine flame is the reason why the radiative heat transfer (radiation from gases) in SI engine is small in comparison with convective heat transfer [5]. The radiation performance of zirconia TBC (for turbine engine) has been examined by Siegel [e.g. 16]. It was found that for soot coated thermal barrier (translucent for thermal radiation), the radiative effects increased the temperature of metal wall compared with the temperature for opaque coatings. The role of ceramic materials transparency was also acknowledged in [12] and [18].

The results based on direct comparison of heat transfer through temperature probe, have shown:
- for SI engine - a decrease;
- for diesel engine - an increase

in mean heat transfer through insulated (PSZ) probe, compared to that of uninsulated one at all engine loads. Fuel economy measurements, made on both spark-ignition and diesel engine, were consistent with heat transfer experiments - ceramic zirconia coatings of diesel engine piston crown resulted in inferior fuel economy, compared to the standard engine [8, 9]. The indicated specific fuel consumption results revealed that ceramic thermal barrier of diesel engine resulted in inferior (compared to the standard piston engine) fuel economy by 2-5%, across the load range [8, 9].

Heat transfer measurements, made on experimental bench for various kinds of thermal excitation [8, 9, 10], proved that plasma-sprayed zirconia coatings are not effective for radiant heating. It was found that plasma-sprayed zirconia ceramic barriers are being partially transparent to thermal radiation. The negative effect of transluence is strongly enhanced when the heat-transferring surface is covered with soot deposits. The high radiation absorbing capacity of soot layer is the reason why the incident radiation is almost fully absorbed by the surface deposits. Its energy is afterward reradiated into the translucent ceramic coating and

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can increase the temperature on the ceramic/metal interface. In diesel engine it can augment the heat flux rejected from the combustion chamber.

3. Analysis of cylinder pressure data

According to the calculation results [6,7], thin (0.2-0.3 mm) ceramic plasma sprayed zirconia coatings were applied to the piston crown of the tested diesel engine (Table 1).

<table>
<thead>
<tr>
<th>Table 1. Diesel engine specifications</th>
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<tbody>
<tr>
<td>Type</td>
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<tr>
<td>Number of cylinders</td>
</tr>
<tr>
<td>Bore</td>
</tr>
<tr>
<td>Stroke</td>
</tr>
<tr>
<td>Compression Ratio</td>
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<td>Combustion System</td>
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<td>Speed</td>
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Engine specifications and operational conditions (ignition timing, air-fuel ratio) were practically the same for baseline and insulated engines. During the tests, the in-cylinder pressure measurements were made [9]. Diesel engine was loaded with asynchronous generator and the mechanical (brake) parameters were not recorded. The low speed of diesel engine was deliberately chosen [8] – the positive effects of TBC (if any) should be seen at low engine speeds (vide e.g. [1]).

Quantitative information on the progress of engine combustion may be obtained using cylinder pressure vs. crank angle data over the engine operating cycle. The method of analysis [4,5] is based on the first law of thermodynamics:

\[
dU = dQ - dL
\]

Where \(dQ\) is the net heat transfer rate across the system boundary, \(dL\) is the rate of work transfer and \(dU\) is the rate of internal energy change.

The apparent net heat-release rate is the difference between the apparent gross heat release rate (being the function of heat released by fuel combustion) and the heat transfer rate to the walls of cylinder volume [5]. Assuming that the cylinder content is constant and can be modeled as ideal gas, net heat release rate versus crank angle can be expressed as

\[
\frac{dQ_n}{d\varphi} = \frac{k}{\kappa - 1} \frac{dV}{d\varphi} + \frac{1}{\kappa - 1} \frac{dp}{d\varphi}
\]

where \(\kappa\) is the ratio of specific heats \((c_p/c_v)\). An appropriate range of \(\kappa\) for CI engine is 1.3+1.35 [5]. For the presented analysis the equation given by [4] was used \((\kappa=1.4-7.1810^{-5}T)\).

In-cylinder pressure measurements and net heat release analysis are illustrated in figs. 2-4 (three values of the mass of fuel injected, corresponding to various engine loads). The results reveal that combustion process in insulated engine is characterized by shorter ignition delay and lower heat release during premixed combustion than the standard engine. Figures show also that the pressure lines during compression “go” lower for uninsulated engine (compare fig.1, illustrating pressure measurements in motored engine). The pressure lines coincide during diffusion phase of combustion, when the radiation heat transfer reaches the maximum. The significant differences in injection process (peak injection pressure was ca. 23 MPa) were not observed.
The results of the experiments can be commented as follows:
- PSZ coatings are effective as heat barrier during compression and premixed burning period i.e. during this part of engine operating cycle when convective heat transfer is dominant;
- low heat rejection during compression causes an advance in heat release beginning (premixed spike);
- during diffusion combustion phase, growing soot concentration in flame [2] promotes radiation heat transfer;
- the heat absorbed by surface deposits of combustion chamber is reradiated through the translucent ceramic coating and increases the temperature at ceramic/metal interface but can not be radiated back because of limited translucency window [19, 20]. It enhances overall heat transfer and generates a fuel economy loss (fig. 5, [9]).

Fig. 1. Compression pressure in motored standard and insulated diesel engine (motored)

This phenomenon may be referred as greenhouse effect (illustrated in fig. 6), because the transmission of radiant energy through the ceramic barrier and subsequent “trapping” by the ceramic insulation coating assist in keeping a TBC/metal interface at elevated temperature (compared to uninsulated surface). It explains the poor performance of thermally insulated diesel engine. In diesel engines, radiation contribution is evaluated for about 1/6 [2] ÷ 1/3 [5] of the total surface heat transfer (in spark-ignited engines a portion of heat transferred by radiation is estimated to be small in comparison to the total value of heat transfer [5]). That is why the ceramic coatings capabilities as heat barriers are severely reduced especially in diesel engines.
Fig. 2. Cylinder pressure ($p_{cyl}$), injection line pressure ($p_{inj}$) and net heat release rate ($dq$) in standard (thin lines) and insulated (thick lines) diesel engine at $\lambda=3.4$

Fig. 3. Cylinder pressure ($p_{cyl}$), injection line pressure ($p_{inj}$) and net heat release rate ($dq$) in standard (thin lines) and insulated (thick lines) diesel engine at $\lambda=1.7$
Fig. 4. Cylinder pressure ($p_{cyl}$), injection line pressure ($p_{ini}$) and net heat release rate ($dq$) in standard (thin lines) and insulated (thick lines) diesel engine at $\lambda \approx 1.7$.

Fig. 5. Comparison of indicated specific fuel consumption of insulated and uninsulated diesel engine (constant speed).
Fig. 6. Spectral emissive power for flame and surface temperature

4. Conclusions

The conclusions from the above-presented measurements are that (from the thermodynamic point of view) thin PSZ coatings for engine combustion chamber can not be recommendable for a diesel engine. Thin PSZ coatings are partially transparent to the thermal radiation and when the ceramic is translucent, its capabilities as heat barrier material are severely reduced especially in highly radiating environment of diesel flame. Results of experiments on direct-injection diesel engine suggest that application of PSZ TBC to diesel engine combustion chamber could not be a useful way for improving the fuel economy. The radiation from soot particles in the diesel engine flame is about five times the radiation from gaseous product and that is why the PSZ coatings may rather suitable for SI engine (preferably gas-fuelled). To insure the optimum thermal barrier performance for either clean or heavily sooted combustion chamber surfaces, an opaque ceramic material should be considered.
References