

Heat Loss Analysis of a Steel Piston and a YSZ Coated Piston in a Heavy-Duty Diesel Engine Using Phosphor Thermometry Measurements

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ABSTRACT

Diesel engine manufacturers strive towards further efficiency improvements. Thus, reducing in-cylinder heat losses is becoming increasingly important. Understanding how location, thermal insulation, and engine operating conditions affect the heat transfer to the combustion chamber walls is fundamental for the future reduction of in-cylinder heat losses. This study investigates the effect of a 1 mm-thick plasma-sprayed yttria-stabilized zirconia (YSZ) coating on a piston. Such a coated piston and a similar steel piston are compared to each other based on experimental data for the heat release, the heat transfer rate to the oil in the piston cooling gallery, the local instantaneous surface temperature, and the local instantaneous surface heat flux. The surface temperature was measured for different crank angle positions using phosphor thermometry. The fuel was chosen to be n-heptane to facilitate surface temperature measurements during non-skip-fire, thermally stabilized operating conditions. Assuming one-dimensional heat transfer inside each piston, the local instantaneous surface heat flux was calculated using the heat transfer rate to the oil in the piston cooling gallery and the surface temperature measurements. The results from this study show that the surface temperature variation is similar for both pistons. The instantaneous heat flux during combustion is however significantly greater for the steel piston than the coated piston. The heat release analysis also indicates that combustion is slower for the piston with the yttria-stabilized zirconia coating.

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INTRODUCTION

The heavy duty transportation sector relies greatly on diesel engines, powering more than 92% of all heavy duty vehicles worldwide [1]. To mitigate anthropogenic climate change, greenhouse gas emissions have to be reduced from all sources. Therefore, further thermal efficiency improvements are necessary in Diesel engines. Many possible ways exist to reduce losses and thus increase efficiency, e.g. friction reduction, heat loss reduction, or the reduction of exhaust losses. In-cylinder heat losses in Diesel engines have been reported to account for approximately 14-17% of the injected fuel energy [2,3]. Therefore, reducing in-cylinder heat losses has great potential for further thermal efficiency improvements. Of the total in-cylinder heat losses, approximately 50-68% is transferred to the piston [2,3]. Thus, insulating the piston is a promising approach to increase efficiency. In the past, many studies tried to investigate the possible efficiency improvement of insulating the combustion chamber with ceramic thermal barrier coatings (TBC). Of such coatings, yttria-stabilized

zirconia (YSZ) is one of the most commonly applied materials [4, 5, 6, 7]. Yet, ceramic thermal barrier coatings have not found their way into production due to inconclusive results which do not indicate a clear efficiency improvement [4,8].

To foster the further development of in-cylinder thermal barrier coatings, the current study investigates the insulation of a piston with a 1 mm thick yttria-stabilized zirconia coating. This insulated piston is compared to a standard steel piston. In the further course of this article the piston with the yttria-stabilized zirconia coating is only referred to as YSZ piston whereas the piston without a coating is referred to as steel piston. To determine whether yttria-stabilized zirconia is a good candidate for in-cylinder thermal barrier coatings, the authors examined the heat release, the piston oil cooling, the piston surface temperature and the local instantaneous heat flux at the surface. In this study, phosphor thermometry was applied to measure the piston surface temperature. This method has already been

employed in several studies to measure in-cylinder surface temperatures [9, 10, 11, 12, 13, 14, 15]. To the authors' knowledge, however, phosphor thermometry has never been applied in diesel engines under non-skip-fire, thermally stabilized operating conditions.

EXPERIMENTAL SETUP

Engine

In this study, a special cylinder head was used which accommodated a small optical access with a diameter of 21 mm (Figure 1). The optical access was obtained through the removal of one exhaust valve. With minimum effect on the combustion and in-cylinder heat transfer, the limited optical access enabled piston surface temperature measurements using phosphor thermometry. Due to geometrical constraints in the cylinder head, the optical axis was tilted by 11.7 degrees from the cylinder axis. The tilt caused the field of view to change with the reciprocating movement of the piston. Surface temperature measurements far away from top dead center were therefore not possible. The experiments were carried out on a heavy-duty, single-cylinder diesel engine equipped with four balance shafts. The low vibration level of the engine enabled precise targeting of the laser beam which is necessary for the phosphor thermometry measurements. The nine-hole XPI injector which was used during the entire measurement campaign was adjusted so that the surface temperature measurements were all taken between two sprays. Further engine specifications are listed in Table 1.

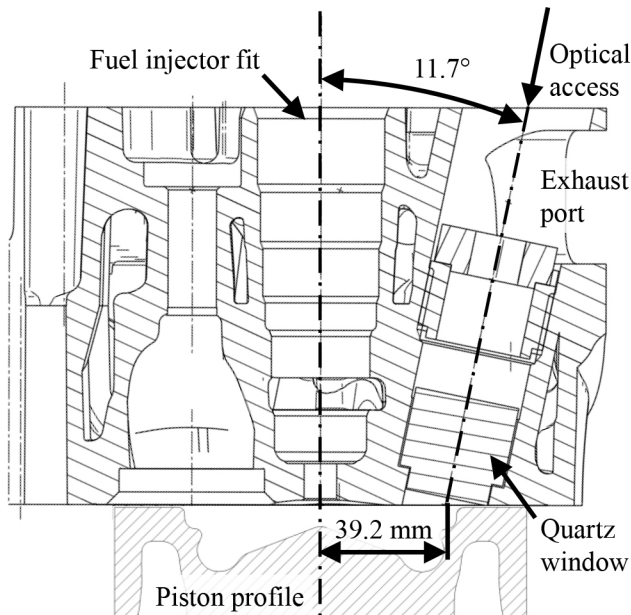


Figure 1. Cross section of the cylinder head with the optical access, together with a piston profile.

Table 1. Engine Specification

Bore, B_{cyl}	130 mm
Stroke, L	160 mm
Displacement volume	2.12 l
Compression ratio, r_c	21.16 (steel); 20.64 (YSZ)
Number of inlet valves	2
Number of exhaust valves	1
Injector	9-hole XPI
Umbrella angle	146 deg
Cup flow	275 pph

Pistons

During the experiment, two different pistons were used: a steel piston and a piston with a plasma-sprayed yttria-stabilized zirconia coating which is referred to as YSZ piston. The measured piston profile of the steel piston is shown in Figure 3. With the intention to keep the geometry and the compression ratio the same, the profile of the steel piston was used as a reference for the YSZ piston. The latter had therefore a 1 mm offset from the reference surface to accommodate the thermal barrier coating. The two layer thermal barrier coating was intended to consist of a nominally 150- μm -thick NiCrAlY bond coat (Amdry 962) and a nominally 850- μm -thick yttria stabilized zirconia layer with 8 mol-% of Y_2O_3 (HOSP Metco™ 204-XCL Yttria). Despite the efforts to make the two pistons as comparable as possible, significant manufacturing inaccuracies occurred during the coating process of the YSZ piston. Plasma spraying being a line of sight process, very little material was coated onto vertical surfaces inside the piston bowl. However, horizontal surfaces were coated with a slightly thicker layer than intended. The piston profile of the YSZ piston before and after coating are depicted in Figure 3. To highlight the differences between the steel and the YSZ piston, the outer piston profile of the steel piston is also plotted in Figure 3.

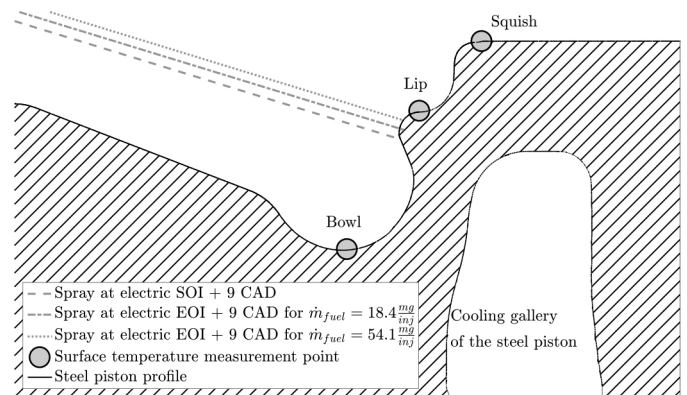


Figure 2. Profile of the steel piston including phosphor thermometry measurement points and spray axes.

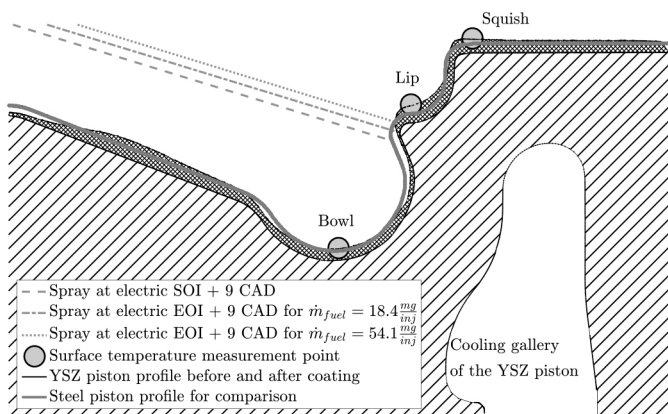


Figure 3. Profile of the YSZ piston including phosphor thermometry measurement points, spray axes and the profile of the steel piston as a reference.

In addition to the slight differences of the profiles due to the coating inaccuracies, the authors also took notice that the cooling galleries had different shapes when cutting the pistons after the experiments. The cooling galleries are also presented in Figure 2 and Figure 3

Onset of Flame Impingement

During a short preliminary test, a high-speed camera was employed to examine the onset of flame impingement onto the piston bowl surface of the steel piston. The analysis of the data from the high-speed camera showed that the flame reaches the surface at around 9 CAD after electric start of injection (SOI) as presented in Figure 4. Knowing the delay between electric SOI and the onset of flame impingement, the location of the spray impingement was calculated. Figure 2 and Figure 3 both show the spray axes at SOI + 9 CAD and at electric end of injection (EOI) + 9 CAD. Due to time constraints, the onset of flame impingement was only assessed for the steel piston. In the further course of this study, the delay until the onset of flame impingement is assumed to be similar for both pistons. It shall be noted that the spray axes intersect with the profile of the YSZ piston in a slightly different way than with the profile of the steel piston due to the mentioned coating inaccuracies.

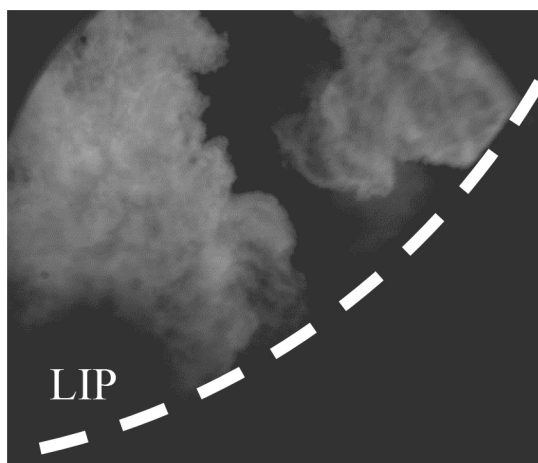


Figure 4. Flame impingement on to the wall 9 CAD after SOI, for $\dot{m}_{fuel} = 54.1$ mg/inj. The black circular areas at the upper left and the upper right corners mark the limits of the optical access. The dashed white line marks the limits of the lip of the piston.

Material Properties

The material properties which are necessary for the calculation of the local instantaneous heat flux are given in Table 2. The thermal conductivity, the specific heat capacity and density of the steel and the yttria-stabilized zirconia were obtained from the literature. The thermal effusivity, e , is the material property which is needed to calculate the instantaneous heat flux. This material property is related to the density, the specific heat capacity and the thermal conductivity as describe in equation (1).

$$e = \sqrt{kc_p\rho} \quad (1)$$

As the thermal conductivity, the density and the specific heat capacity were not measured by the authors themselves, the uncertainties of these properties are unknown. Furthermore, the values for the material properties are only given for one temperature. However, these material properties usually do exhibit a certain temperature dependency. Nevertheless, the definition of the thermal effusivity is advantageous when analyzing error propagation. Assuming that thermal conductivity, specific heat capacity and density are all afflicted by an error ε of 10%, all these errors together affect the thermal effusivity at most by 15%.

$$\varepsilon_e = \sqrt{\varepsilon_k \varepsilon_{c_p} \varepsilon_\rho} \quad (2)$$

The temperature-dependent properties of the oil were obtained from the oil supplier.

Table 2. Material properties.

k_{steel}	42.6 W/m · K	[16]
$c_{p,steel}$	470 J/kg · K	[16]
ρ_{steel}	7670 kg/m ³	[16]
e_{steel}	12392 W · s ^{0.5} /m ² · K	
k_{YSZ}	1.57 W/m · K	[17]
$c_{p,YSZ}$	454.5 J/kg · K	[18]
ρ_{YSZ}	5286 kg/m ³	[17]
e_{YSZ}	1942.2 W · s ^{0.5} /m ² · K	
$c_{p,oil}$	Temperature-dependent	[2028 J/kg · K – 2247 J/kg · K]
ρ_{oil}	Temperature-dependent	[791.5 kg/m ³ – 833.5 kg/m ³]

Phosphor Thermometry

Phosphor thermometry is a remote sensing technique that utilizes a thermographic phosphor to register the temperature of an object. Thermographic phosphors display a change in their characteristic phosphorescence emission as their temperature changes. This paper employs the changes that occur in the temporal domain of the captured luminescence to deduce the temperature. When thermographic phosphors are excited using a nanosecond pulse of ultraviolet radiation, a decaying phosphorescence is emitted. The phosphorescence decay can be approximated by a single exponential function as in [equation \(3\)](#). $I(t)$ and I_0 are the intensity of the phosphorescence at time t and at $t = 0$, respectively. τ represents the decay time and C is the signal offset.

$$I(t) = I_0 e^{-t/\tau} + C \quad (3)$$

In order to convert the measured decay time to temperature values, a calibration curve for the thermographic phosphor employed is needed. A calibration curve is obtained by simultaneously and continuously acquiring the temperature of the substrate the thermographic phosphor is sprayed on and the decay waveform. The result is a calibration polynomial that relates the measured decay time to a temperature which can later be used to deduce the temperatures experienced by the piston during the combustion cycle. In this study, the thermographic phosphor ZnS:Ag was applied due to its short decay time and the short emission wavelength. [Figure 5](#) represents the calibration curve obtained for this thermographic phosphor. To obtain the decay times out of the acquired decay waveforms, the waveforms are fitted with a single exponential function using a nonlinear least squares solver (trust-region reflective algorithm) from MATLAB. The measured decay times were then plugged into the calibration polynomial to get the piston surface temperature. A 10 Hz Nd:YAG laser at 355 nm was used as the excitation source in this study. The engine speed was maintained at $N = 1200 \text{ rpm}$ for all engine operating conditions. Thus, only one surface temperature measurement could be taken during each cycle. Surface temperatures were measured at three different locations on each piston. The three measurement positions (bowl, lip and squish) are marked in the piston profiles in [Figure 2](#) and [Figure 3](#). The laser beam diameter of 4 mm defined the size of the point measurements. The measurement location was adjusted manually before each test run.

As shown in [Figure 7](#), the measurement setup was comprised of a dichroic mirror which directed the laser beam towards the measurement location and a photomultiplier tube (PMT). The PMT acquired the luminescence decay signal from the phosphor on the piston surface.

The thin phosphor coating was manually applied using an airbrush. After the experiments the pistons were cut where the measurements had previously been taken to examine the thickness of the coating using a high resolution microscope ([Figure 6](#)). On the steel piston, the thickness of the phosphor coating was between 4 μm and 15 μm . The

YSZ piston only had a phosphor coating which was 2 μm to 9 μm thick. Due to the very small thickness of the phosphor layers, its influence on the measurement can be neglected [[9,11](#)].

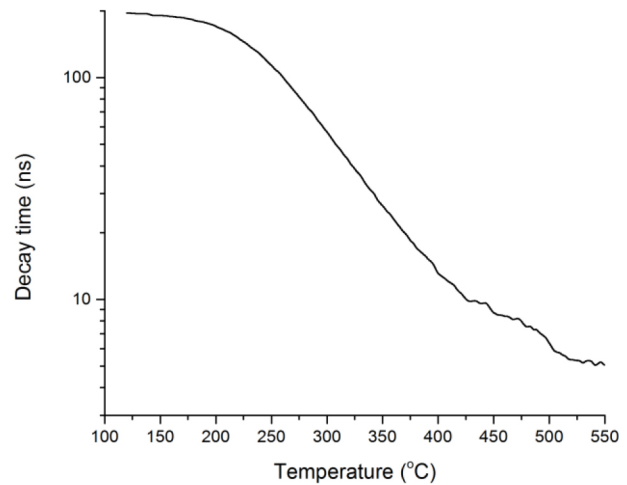


Figure 5. Calibration curve for ZnS:Ag thermographic phosphor.

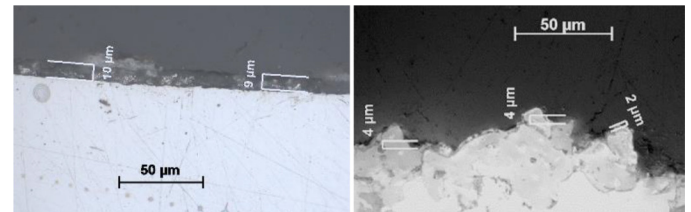


Figure 6. Measurement of the thickness of the phosphor coating for the steel piston (left) and the YSZ piston (right) using a high resolution microscope.

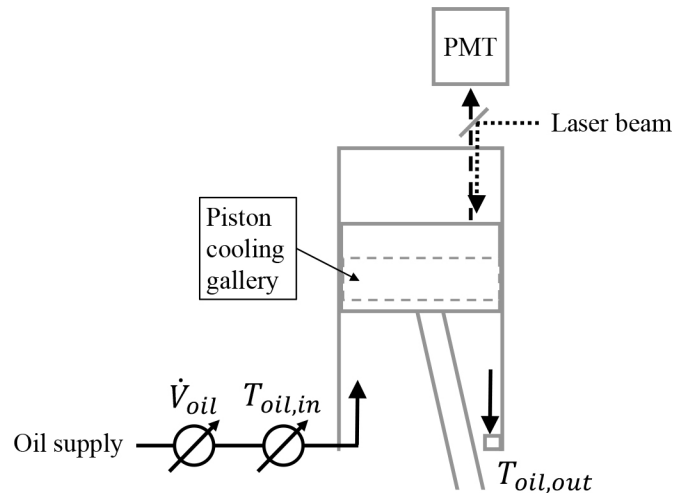


Figure 7. Sketch of the optical measurement setup and the oil cooling measurement.

Oil Temperature Measurement

The variables necessary to calculate the heat transfer rate to the oil in the piston cooling gallery, $\dot{Q}_{PC}$, are the volumetric flow rate, the temperature of the oil injected into the cooling gallery, and the

temperature of the oil exiting the cooling gallery. The volumetric flow rate and the temperature of the oil were measured shortly upstream from the oil nozzle which injects the oil into the piston cooling gallery. The temperature of the oil after the piston cooling gallery was measured with a small bucket which was mounted at the bottom of the liner. The bucket had a small hole and was equipped with a fast response thermocouple. Unfortunately the lead of the thermocouple was damaged after all surface temperature measurements at four measurement positions were completed (all three positions on the steel piston and the position in the bowl of the YSZ piston). The oil temperature after the cooling gallery could therefore not be measured when measuring the surface temperature at the squish and at the lip of the YSZ piston. Since the engine operating conditions were unchanged, the heat transfer rate to the oil during these measurements was assumed to be equal to the heat transfer rate measured when measuring the surface temperature in the bowl of the YSZ piston.

Operating Conditions

For all measurements, n-heptane, C_7H_{16} , was used as the fuel in order to reduce soot formation and thus enable measurements at non-skip-fire operations. Measurements were taken at two different engine operating conditions. The first operating condition was close to idling with an injected fuel mass of $\dot{m}_{fuel} = 18.4 \text{ mg/inj}$ and a relative air-fuel ratio of $\lambda = 9.6$. The second operating condition is at low load with an injected fuel mass of $\dot{m}_{fuel} = 54.1 \text{ mg/inj}$ and a relative air-fuel ratio of $\lambda = 3.2$. Electric start of injection (SOI) was 1 CAD before TDC for all operating conditions. This late SOI was chosen to limit the peak cylinder pressure. All measurements were taken at thermally stabilized conditions, that is to say when the heat transfer rate to the oil in the piston cooling gallery attained a constant level (Figure 8). All operating conditions are listed in Table 3.

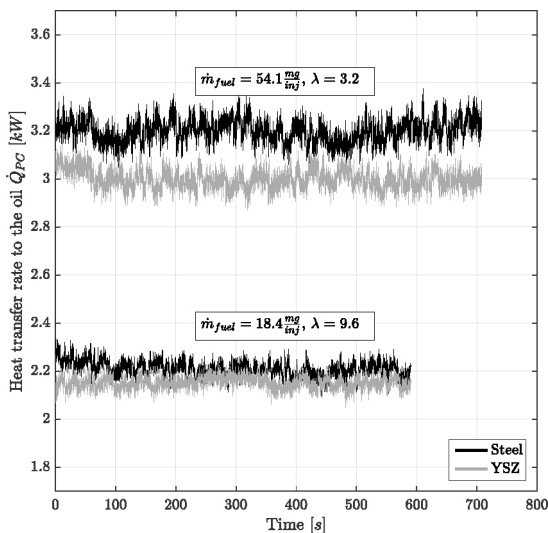


Figure 8. Measurements of the surface temperature were carried out only when the heat transfer rate to the oil in the cooling gallery had stabilized.

Table 3. Engine operating conditions

Engine operating condition I

	$\bar{x}$	s	$\bar{x}_{steel}$	$\bar{x}_{YSZ}$
$\dot{m}_{fuel} [\text{mg/inj}]$	18.4	4.3	—*	
$\lambda [-]$	9.6	2.5	—*	
$p_{inlet} [\text{bar}]$	1.174	0.028	—*	
$N [\text{rpm}]$	1199.95	0.71	1199.93	1199.97
$p_{inj} [\text{bar}]$	1447.8	21.9	1443.0	1454.7
SOI (electric)	−1 CAD ATDC			
EOI (electric)	2.3 CAD ATDC			

Engine operating condition II

	$\bar{x}$	s	$\bar{x}_{steel}$	$\bar{x}_{YSZ}$
$\dot{m}_{fuel} [\text{mg/inj}]$	54.1	6.6	—*	
$\lambda [-]$	3.2	0.4	3.20	3.24
$p_{inlet} [\text{bar}]$	1.208	0.018	—*	
$N [\text{rpm}]$	1199.89	0.98	1199.95	1199.79
$p_{inj} [\text{bar}]$	1458.8	37.3	1448.3	1475.8
SOI (electric)	−1 CAD ATDC			
EOI (electric)	4.6 CAD ATDC			

* The difference was not statistically significant for the two pistons (two-sided t-test as described in [19], significance level: $\alpha/2 = 0.025$)

Data Processing

Calculation of the Heat Transfer Rate to the Oil in the Piston Cooling Gallery

The heat transfer rate to the oil in the piston cooling gallery, $\dot{Q}_{PC}$, is calculated through equation (4), using the measured volumetric flow rate of the oil, $\dot{V}_{oil}$, the oil temperature before injection into the piston cooling gallery, $T_{oil,in}$, and the oil temperature after exiting the cooling gallery, $T_{oil,out}$:

$$\dot{Q}_{PC} = \dot{V}_{oil} \cdot \rho_{oil}(T_{oil,in}) \int_{T_{oil,in}}^{T_{oil,out}} c_{p,oil}(T) dT \quad (4)$$

The volumetric flow rate was measured before the oil nozzle; thus, the temperature-dependent density of the oil is calculated using the oil temperature before the cooling gallery. Due to the temperature dependence of the specific heat capacity of the oil, $c_{p,oil}$, the mass specific enthalpy change in the piston cooling gallery is described by