

Experimental Investigation of Multi-In-Cylinder Pyrometer Measurements and Exhaust Soot Emissions Under Steady and Transient Operation of a Heavy-Duty Diesel Engine

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ABSTRACT

Future engine emission legislation regulates soot from Diesel engines strictly and requires improvements in engine calibration, fast response sensor equipment and exhaust gas aftertreatment systems. The in-cylinder phenomena of soot formation and oxidation can be analysed using a pyrometer with optical access to the combustion chamber. The pyrometer collects the radiation of soot particles during diffusion combustion, and allows the calculation of soot temperature and a proportional value for the in-cylinder soot density (KL).

A four-cylinder heavy-duty Diesel engine was equipped in all cylinders with prototype pyrometers and state of the art pressure transducers. The cylinder specific data was recorded crank angle-resolved for a set of steady-state and transient operating conditions, as well as exhaust gas recirculation (EGR) addition and over a wide range of soot emissions. A continuously operating gas sampling photo acoustic soot sensor was used for measuring the exhaust gas soot concentration.

A correlation of cylinder specific pyrometer measurements and corresponding tail pipe soot concentrations for a set of operating conditions was developed including variability of start of injection, engine load and speed, injection pressure and EGR. The correlation matches the in-cylinder soot concentration at the end of the combustion well with exhaust pipe soot emissions. In transient operation, the predicted soot emissions showed immediate response on changing engine load, speed and their combination whereas the soot concentration sampled in the exhaust stream was delayed due to gas mixing. The agreement between the two measurement methods was good. Furthermore a qualitative analogy between soot temperature and cylinder specific EGR rate was found.

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INTRODUCTION

The large variety of Diesel engine applications on-road and off-road, faces more and more strict legislations regarding their harmful pollutant emissions such as soot and NO_x [1]. In this challenging context, development in terms of engine control and exhaust gas aftertreatment systems are required and ask on their part for improved understanding of Diesel engine particulate synthesis [2, 3]. For this purpose, advanced engine testing and measurement equipment are fundamental tools. The well-known optical measurement principle called two-colour pyrometry, characterises soot formation and oxidation right at the point of occurrence inside the cylinder by gathering the emitted light from solid

luminous soot particles during diffusion combustion. The premixed phase of Diesel combustion shows typically no significant soot formation and radiation from particles.

The connection between the luminous flame radiation and the related density was first proposed by H. C. Hottel and F. P. Broughton in 1932 [4], whereas the focus laid on optical estimation of the flame temperature. The by-product of this approach was a parameter called KL , representing the soot cloud density as the absorption coefficient times the characteristic length. An application oriented description of the two-colour pyrometry method for temperature and soot characterisation in Diesel engines can be found in [5]. Pyrometry is either performed two dimensionally using a fast sampling camera [6, 7], or zero dimensionally based on a

collecting lens and an optical fibre in combination with a photo diode [8]. The latter principle is mostly applied in production engine experiments where access to the combustion chamber is often highly limited. The recorded signal represents the spatially integrated information of a three dimensional phenomena which is characterised by spatial inhomogeneities in mixture formation, evaporated fuel, reaction zones, absorption coefficients, soot particle density and last but not least temperature. High temperature zones contribute dominantly to the gathered radiation due to 4-5 orders of magnitude stronger emission than chemiluminescence [9]. Colder zones are generally neglected by this method due to the exponential dependency of radiation on temperature. The errors implicated by these circumstances along the line of sight are reported to reach up to 100 - 200 K in soot temperature and 50 % for soot volume fraction calculation [7]. However, without strong temperature gradients along the line of sight due to mixture formation, the soot temperature and density can be measured more accurately [10].

In previous studies the connection of in-cylinder soot concentration estimated with *KL* and tailpipe emissions was investigated for steady-state Diesel engine operation. The error in soot temperature was calculated to be 57 K and 30 % in soot volume fraction, and the aromatic content of the fuel was found to play a significant role in soot formation [11]. Supporting results were reported by P. Kirchen et al. [12], analysing the *KL* evolution during the combustion of two different fuels with and without pre-injection. Furthermore, the *KL* value at the end of the analysable signal range was seen to correlate well with Filter Smoke Number (FSN) exhaust soot measurements (linear regression with $R^2 = 0.89$). Another study on Diesel-water-emulsion and its influence on the soot oxidation phase showed a *KL* plateau towards the end of combustion [13]. Within this range a stabilised soot concentration was presumed and a good correlation with exhaust gas measurements was found (exponential regression $R^2 = 0.90$). In addition the calculated soot temperature was compared with engine out NO_x emissions, where an exponential dependency could be discovered. The pyrometry approach has been applied to study the influence of post-injection timing on soot oxidation and the corresponding exhaust emissions [14].

Transient engine operation was also studied using the presented measurement method [15]. The engine cycle resolved information is advantageous in terms of response time compared to exhaust gas sampling. The in-cylinder gas temperature was measured with laser-induced phosphorescence thermography and compared with engine out NO_x concentration. Simultaneously, a two-colour pyrometer was used for *KL* calculation. However, a correlation of the *KL* evolution over time and the corresponding exhaust soot concentration was not found.

In this study the application of a multi-in-cylinder two-colour pyrometer is demonstrated over wide range of soot

emissions in steady-state and transient engine operation. The measurement principle is tested with respect to its predictive capabilities of exhaust soot concentration in view of providing a new input signal for engine control purposes. Cylinder-to-cylinder differences in terms of injection and EGR are investigated. Pyrometry and exhaust gas elementary carbon measurements are converted to engine cycle-resolved soot mass. The steady-state calibration of the optical sensor is followed by exhaust soot prediction in transient engine operation. Some preliminary findings and guidance to the measurement principle complement the study.

EXPERIMENTAL SETUP

Test Rig

A modified Liebherr D924 heavy-duty Diesel engine is used for the experiments which has been successfully applied in previous studies [13, 16] (specifications table 1). A Common Rail injection system replaces the standard conventional injection in order to allow flexible control of injection parameters. The suction throttled Common Rail pump is an ETH Zurich development and the injectors feature 6 holes with 0.21 mm nozzle diameter (Ganser CRS AG). The engine control unit (MALI Bodensee Steuergeraete) offers a detailed injector map for only one cylinder. Additional injectors are controlled with a rough deviation map, leading to differences in fuel mass between cylinders. The engine was coupled to an eddy-current brake (Schenk W450).

Table 1. Engine specifications Liebherr D924Ti-E A4

Displaced volume	6.64 l
Number of cylinders	4
Bore	122 mm
Stroke	142 mm
Compression ratio	17.2
Number of valves	2
Rated power	183 kW at 2100 rpm
Max. torque	1060 Nm at 1540 rpm
Max. BMEP, max. p_{cyl}	20 bar, 160 bar
Turbocharger	K27.2 (KKK) +intake air-cooling

The engine had originally no EGR system. Thus, the turbocharger provides a higher intake pressure compared to the outlet pressure for all operating conditions. High pressure EGR is fed from the exhaust manifold upstream the turbine to the intake manifold. The EGR path is further equipped with an intercooler and a dynamically controlled EGR valve close to the intake manifold. The required change in pressure difference from outlet to inlet was set by a slow acting exhaust throttle after the turbine, which limited the range of possible for steady-state, but in particular for transient operating points.

The 2-valve cylinder head offers sufficient installation space for a pressure sensor and a pyrometer with access to the

same cylinder. Two holes were drilled through each cylinder head ending inside the piston bowl area.

Instrumentation

The in-cylinder soot radiation measurements were performed with an optical light probe (OLP, Kistler Instruments), which is a multi-colour pyrometer and as a prototype still in development. All four cylinders were equipped with an OLP prototype and the corresponding amplifier.

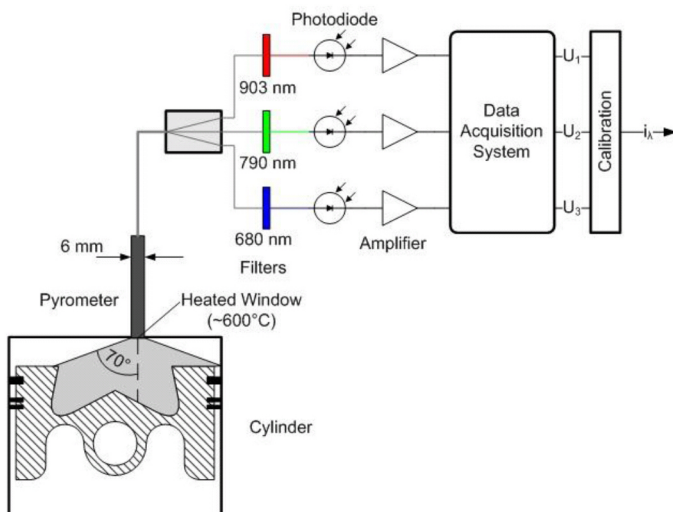


Figure 1. Schematic design of the three-colour pyrometer measurement chain (adopted from [12])

Due to the miniaturisation of the sensor, a later application even in car engines is possible. A sapphire lens at the tip of the OLP captures light from the combustion chamber at a view angle of 140° , and is heated to 600°C by an enclosing and electrical heating system (Figure 1). Previous tests showed reduced intensity while measuring without heating. Further, the lens was clear after in-cylinder measurements and oxidation of artificially created soot deposits occurred with enabled heating. Hence, the lens should be prevented from soot deposits and the transmission is kept constant during a measurement campaign. The gathered soot radiation is conducted through an optical fibre and split to three filters at wavelengths of 680, 790 and 903 nm. At the selected wavelengths, significant emissions from reaction species is avoided [5]. Photodiodes convert the intensity to a voltage signal. The respective narrow filter full width-half maximums are 15, 13 and 11 nm, minimising post-processing errors [17]. The signals from the photodiodes are amplified and recorded every 0.2°CA . The OLP raw signals and the absolute light intensities are linked by a calibration of the whole measurement chain, using a halogen lamp mounted to an integrating sphere which provides a homogeneously illuminated surrounding. A previous spectrum analysis of this apparatus allows the OLP calibration at all filter wavelengths [5, 12, 18]. It was found that a calibration

with a heated lens is required due to thermal expansion of the OLP tip, and its influence on the distance between lens and optical fibre.

The exhaust gas soot mass concentration (elementary carbon per volume) was measured with a photo acoustic soot sensor PASS (AVL 483) including a diluter (AVL) [19]. Due to the continuous sampling and quick response time of less than 1 s, the device is suitable for steady-state and transient measurements. The PASS signal of transient engine measurements was only corrected for the initial transport delay at the start of the transient. Signal smoothing effects through longitudinal exhaust gas mixing from the cylinder head through the turbine and inside the diluter/PASS combination were not modelled, since little influence can be seen in [18]. During transient experiments, the NO_x concentration was measured additionally with a fast sampling chemiluminescence detector (Cambustion CLD500).

The cylinder individual EGR rate during steady-state operation was determined cylinder individually by the ratio of the CO₂ concentration between the intake runner and exhaust manifold branch. Thus, the air-fuel ratio can be calculated as well. A NDIR analyser (Fisher-Rosemount Binos 1001) was used for exhaust gas sampling and a fast mass spectrometer (V&F Airsense) in the intake, respectively. Due to the large volume of the EGR path, significant transport delays of several seconds occur in transient cases. Thus a wide band lambda sensor (ETAS ES630 with Bosch LSU 4.9) was installed upstream of the EGR valve to measure the CO₂ concentration of the EGR gas fed to the intake. Each cylinder is equipped with a pressure transducer (Kistler Instruments 6041AS32) and was operated with the corresponding amplifier regarding a thermodynamic analysis. The air mass flow was measured in steady-state operation with a Venturi tube, whereas in transient operation a hot-film air-mass meter (Bosch HFM7-105) was used. The latter was calibrated with the Venturi tube at steady-state engine operation before and after the transient. In steady-state engine operation, generally all cylinders were investigated. However, during transient operation only reference cylinder #4 was equipped with an OLP and EGR measurement.

METHODOLOGY

Two-Colour Pyrometry Algorithm

The OLP calibration data (offset and proportional factor) converts the raw signals directly to radiation intensities. Hence, an apparent black body temperature (T_{abb}) can be calculated for each wavelength according to Planck's radiation law and the Wien approximation for black bodies (Planck constants $C_1 = 3.7418 \times 10^{-16} \text{ Wm}^2$, $C_2 = 1.4388 \times 10^{-2} \text{ mK}$) [5]:

$$i_{b,\lambda}(T_{abb}) = \frac{2C_1}{\lambda^5 \left(e^{\left(\frac{C_2}{\lambda T_{abb}} \right)} - 1 \right)} \quad (1)$$

At the apparent temperature a black body emits the same radiation intensity as any non-black body at a higher temperature:

$$i_{b,\lambda}(\lambda, T_{abb}) = i_{\lambda}(\lambda, T) \quad (2)$$

The emissivity of an arbitrary body is defined by the ratio of its emission intensity to the emission intensity of a black body with the same temperature:

$$\varepsilon_{\lambda}(\lambda, T) = \frac{i_{\lambda}(\lambda, T)}{i_{b,\lambda}(\lambda, T)} \quad (3)$$

Here the radiating body is represented by the observed soot cloud with a chromatic (wavelength dependent) emissivity smaller than 1. Thus the actual soot temperature must be higher compared to the calculated black body temperature in order to emit the same intensity. The combination of (2) and (3) leads to a new expression for the emissivity by applying Planck's law (1):

$$\varepsilon_{\lambda}(\lambda, T) = \frac{i_{b,\lambda}(\lambda, T_{abb})}{i_{b,\lambda}(\lambda, T)} = \frac{\left(e^{\left(\frac{C_2}{\lambda T} \right)} - 1 \right)}{\left(e^{\left(\frac{C_2}{\lambda T_{abb}} \right)} - 1 \right)} \quad (4)$$

Hottel & Broughton suggested the following empirical correlation in order to model the emissivity of the soot cloud using the absorption law [4]:

$$\varepsilon_{\lambda} = 1 - e^{\left(\frac{-KL}{\lambda^{\alpha}} \right)} \quad (5)$$

KL can be seen as an optical thickness represented by the product of an absorption coefficient and a length along the line of sight through a continuous flame. Furthermore, KL is a factor proportional to soot volume fraction which is useful in Diesel combustion research. The constant α describes the influence of wavelength on emission potential and was found to be 1.39 for Diesel diffusion flames in [4] and 1.38 in [20]. The latter made a re-examination of the algorithm considering scattering where the tolerance for KL is within 1 %. Combining equations (4) and (5) leads to an expression which can be solved for KL :

$$KL = -\lambda^{\alpha} \ln \left(1 - \frac{e^{\left(\frac{C_2}{\lambda T} \right)} - 1}{e^{\left(\frac{C_2}{\lambda T_{abb}} \right)} - 1} \right) \quad (6)$$

Equation (6) can be formulated for two different wavelengths (indices 1 and 2), and the two expressions can be equalised (KL of the observed soot cloud or flame respectively must be the same). The soot cloud temperature T is the remaining unknown dimension:

$$\left(1 - \frac{e^{\left(\frac{C_2}{\lambda_1 T} \right)} - 1}{e^{\left(\frac{C_2}{\lambda_1 T_{abb,1}} \right)} - 1} \right)^{\lambda_1^{\alpha}} = \left(1 - \frac{e^{\left(\frac{C_2}{\lambda_2 T} \right)} - 1}{e^{\left(\frac{C_2}{\lambda_2 T_{abb,2}} \right)} - 1} \right)^{\lambda_2^{\alpha}} \quad (7)$$

Hence, in the experimental case two filtered signals are required defining $T_{abb,1,2}$. T is calculated numerically using Newton's method [21]. KL is then given by equation (6). T and KL are mainly influenced by the relation of two intensities at different wavelengths rather than a direct result of the absolutely recorded intensity.

In the next step, the connection between KL and the soot concentration is drawn. In this context a relation with the volumetric density of particles C_v was proposed by H. Zhao & N. Ladommatos [5]:

$$C_v = \frac{1}{6\pi L_{ls} \operatorname{Im} \left\{ \frac{r^2 - 1}{r^2 + 2} \right\}} \cdot \frac{KL}{\lambda^{\alpha}} \quad (8)$$

The complex refractive index of soot particles r is a wavelength dependent value. If the soot density is known, the gravimetric soot concentration can be calculated in principle using (8). Since the in-cylinder values of r and soot density can hardly be defined in a practical OLP application, it is reasonable to assume them as constant. Thus, the in-cylinder soot mass can be written as a relation featuring KL , the cylinder volume V_{cyl} and a mean length along the line of sight L_{ls} (9). L_{ls} is approximated with the distance between the OLP lens and the centre of the piston bowl. The latter position is crank angle dependent.

$$m_{s,pyro} \sim KL \cdot \frac{V_{cyl}}{L_{ls}} \quad (9)$$

Correlation of In-Cylinder Soot and Exhaust Gas Concentration

The three colour pyrometry provides three wavelength pairings to calculate three different soot temperatures and KL .