

An Investigation of Radiation Heat Transfer in a Light-Duty Diesel Engine

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ABSTRACT

In the last two decades engine research has been mainly focused on reducing pollutant emissions. This fact together with growing awareness about the impacts of climate change are leading to an increase in the importance of thermal efficiency over other criteria in the design of internal combustion engines (ICE). In this framework, the heat transfer to the combustion chamber walls can be considered as one of the main sources of indicated efficiency diminution. In particular, in modern direct-injection diesel engines, the radiation emission from soot particles can constitute a significant component of the efficiency losses. Thus, the main objective of the current research was to evaluate the amount of energy lost to soot radiation relative to the input fuel chemical energy during the combustion event under several representative engine loads and speeds. Moreover, the current research characterized the impact of different engine operating conditions on radiation heat transfer. For this purpose, a combination of theoretical and experimental tools were used. In particular, soot radiation was quantified with a sensor that uses two-color thermometry along with its corresponding simplified radiation model. Experiments were conducted using a 4-cylinder direct-injection light-duty diesel engine fully instrumented with thermocouples. The goal was to calculate the energy balance of the input fuel chemical energy. Results provide a characterization of radiation heat transfer for different engine loads and speeds as well as radiation trends for different engine operating conditions.

CITATION: Benajes, J., Martin, J., Garcia, A., Villalta, D. et al., "An Investigation of Radiation Heat Transfer in a Light-Duty Diesel Engine," *SAE Int. J. Engines* 8(5):2015, doi:10.4271/2015-24-2443.

INTRODUCTION

The increasing concern due to the effect of GHG emissions is pushing the researchers and manufacturers to look for more efficient engines with lower fuel consumption and CO₂ emissions. Thus, different strategies are proposed to achieve these objectives; thermal management improvement [1, 2], indicated cycle optimization [3, 4], in-cylinder heat transfer (HT) reduction [5, 6], reduction of friction and auxiliaries losses [7, 8] or engine downsizing [9] among others. In the present work, the research effort has been focused on improving knowledge of in-cylinder heat transfer.

Combustion process in Direct Injection (DI) diesel engines includes different physical and chemical processes. During the turbulent diffusion flame, an important balance between soot formation and oxidation occurs in the spray. During oxidation process, the in-cylinder soot emission is luminous and generates an important source of radiant energy [10]. Carbon dioxide and water vapor molecules also emit radiation, however it is concentrated in a narrow spectral bands and its magnitude is assumed much smaller than soot particles. Moreover, radiation may also be emitted by many intermediate species formed during the combustion process, but since their

concentration levels are small, their effect on radiation heat transfer is less important as is described in [11]. Thus, soot radiation can be considered a significant source of the efficiency losses in modern diesel engines [12]. In this sense, there are different studies in the literature which quantify the amount of fuel chemical energy lost by soot radiation [12]. Depending on soot conditions, studies provide very different results. From 0.5-1% [13] up to 5-10% [10, 14] of the total chemical energy released during combustion process can be considered as radiant losses. Not only the amount of radiant fraction is a controversy, but also the contribution of radiation to the total heat transfer varies significantly as well from 11% up to 40% [10]. The significant differences between authors are directly related with the uniqueness of the radiant emission in each combustion system considering particular engine geometry and the operating conditions tested. Therefore, it could be stated that the relationship between all these combustion and engine parameters and its radiant emission is not fully understood currently.

The two-color pyrometry method has been used to determine radiation heat transfer along with the in-cylinder temperature and the soot volume fraction (using KL factor) from diesel engine flames [13].

[16]. A detailed description of the two-color pyrometry method can be found in [17]. Thus, pyrometry can be performed by using two different strategies; two dimensionally using a fast sampling high-speed camera [18, 19] or zero dimensionally based on a collecting lens and an optical fiber in combination with a photo diode [12]. The first method provides spatial and temporal resolution of soot temperature and KL. Therefore, radiant emission can be calculated through this technique. This method is applied in particular to vessels, which can reproduce diesel engine like environment or in optical engines. The second method is applied in production engine experiments where the room for optical access to the combustion chamber is limited. The recorded signal in this case represents the spatially integrated information of a three dimensional complex phenomena which is characterized by significant gradients of spatial equivalence ratios and temperature along with the combination of reactive and non-reactive zones as well as different absorption coefficients and soot particle densities along the line of sight. [12]. Independent of the measurement technique method, there always exists some uncertainty of fouling impact from in-cylinder soot in the optical device or from occlusion of the field of view by geometric factors of the measurement system. Consequently, more research and efforts are needed in this field.

The main objective of this work was to evaluate the amount of energy to soot radiation relative to the input fuel chemical energy during the combustion event under different operating conditions in a completely controlled ambient provided by an optical engine. Under these simplified conditions, two-color method was applied by using high speed imaging pyrometer with cameras (two dimensional results) and optoelectronic pyrometer (zero dimensional results). Once a detailed comparison between both strategies was performed, a two-color thermometry sensor was used to characterize radiant energy in a fully instrumented production 4-cylinder direct-injection light-duty diesel engine under several representative engine loads and speeds. The final goal was to calculate the energy balance of the input fuel chemical energy. Results provide radiation heat transfer characterization for different engine loads and speeds as well as radiation trends.

EXPERIMENTAL SET-UP AND PROCESSING TOOLS

Experimental Test Benches

Two different test benches have been used to perform this work, an optically accessible single cylinder engine and a multi-cylinder engine.

Optically Accessible Engine

This facility is based on a 2-stroke single cylinder direct injection diesel engine (Jenbach JW 50), further information can be found in [20]. The engine has three liter displacement with 150 mm of bore and 170 mm of stroke. It is motored at low engine speed (500 rpm). Intake and exhaust are handled by ports on the liner and the cylinder head is specially designed to provide optical access to the combustion chamber. A cylindrical combustion chamber was designed to avoid

the spray wall impingement. The chamber has an upper port where the injector is mounted and four lateral accesses. One of these accesses is used for placing a pressure transducer whereas the other three are equipped with oval-shaped quartz windows, 88 mm length, 37 mm width and 28 mm thickness as it is shown in figure 1. The cylinder head and the engine temperature was controlled by means of coolant recirculation. Its temperature was set to 353 K, to guarantee a good lubricant oil performance.

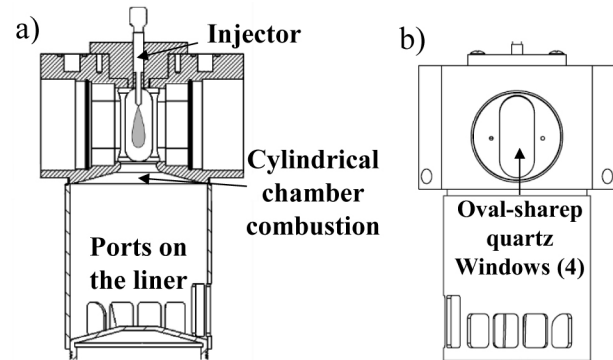


Figure 1. Scheme of the cylinder head and the liner arrangement. a) Front view, b) Side view

In order to keep in-cylinder conditions constant (pressure and temperature), the engine was operated under skip-fired mode. One injection event takes place every 30 cycles, which guarantees that in-cylinder conditions are not influenced by residual gases from previous cycle.

A common-rail Bosch injection system was used, together with a piezoelectric injector and a single-hole 140 μm outlet diameter nozzle. The injector hole was 1 mm long with conical shape (K_s factor of 1.5). The injected mass was relatively small compared to the volume of air utilized. Hence it can be assumed that the thermodynamic conditions inside the combustion chamber were barely affected by the fuel evaporation. Due to the low injection frequency used during tests, the temperature of the injected fuel can be considered constant during the tests.

Light Duty Diesel Engine

A production-type GM 1.9L Diesel engine was used for the second part of the study. The 4-cylinder engine uses a Common-Rail fuel injection system, variable geometry turbocharger (VGT), an exhaust gas recirculation system and an intake throttle valve. The engine has four valves per cylinder, centrally located injectors, and a re-entrant type combustion chamber. The swirl number is variable from 1.4 up to 2.9 and can be adjusted by a dedicated valve. All relevant engine data as well as injection system are given in [table 1](#). This engine was set up with EURO IV calibration.

The engine was directly coupled to an electric dynamometer that allows controlling the engine speed and load. The installation also included a complete instrumentation to measure different fluid temperatures and mass flows. The list of the relevant instrumentation is depicted in [table 2](#).

Table 1. Engine and injection system specifications

Engine Type	DI, 4-cylinder, charged, 4-stroke
Displaced volume	1900 cc
Stroke	90.4 mm
Bore	82 mm
Combustion Chamber	Re-entrant type
Compression ratio	17.5:1
Max. Power [kW]	110 @4000rpm
Max. Torque [Nm/min ⁻¹]	320 / 2000-2750
Injection System	Bosch Common Rail (solenoid)
Max. Rail Pressure [bar]	1600
Nozzle hole diameter [mm]	0.141
Injector Nozzle Holes	7
Hydraulic flow rate [cm ³ (30s) at 100 bar]	440

Table 2. Test cell instrumentation

Variables to measure	Sensors	Range
Temperature of liquids (coolant, oil, cooling water at exchangers...)	Thermoresistances (PT100)	-30 - 350 °C
Temperature of gases (inlet and exhaust lines, EGR...)	K-type Thermocouples	-200 - 1250 °C
Fuel mass flow	AVL 733s.18	0-41.67 g/s
Air mass flow	AVL Flowsonix Air	0-1400 kg/h
Coolant Flow	DN25 Flow meter	8.8-350 l/min
Torque	Dynamometer	0-500 Nm
In-cylinder pressure	Kistler 6125C10	0-300 bar.

A combination of thermocouples and resistance temperature detectors (PT100) was selected (taking into account the expected temperature variation) to measure liquid and gas temperatures.

The in-cylinder pressure was measured for each cylinder with Kistler 6125C10 glow-plug piezoelectric transducers and Kistler 4603B10 charge amplifiers. A crank angle increment of 0.5° was used for the in-cylinder pressure acquisition, which was performed using DRIVEN [21].

The mean variables were acquired at a low sample frequency of 100 Hz using SAMARUC, a CMT-developed test system that collects the signals of different sensors and controls the electric dynamometer [22].

Theoretical Tools

The combustion analysis was performed by means of CALMEC, a CMT-developed tool as described in [23]. Its main assumptions are the following:

- The chamber is considered an open system to account for the fuel injection and blow-by leakage.
- Combustion chamber pressure and temperature are assumed to be spatially uniform.
- Three species (air, fuel vapor and stoichiometric combustion products) are considered [24].
- Ideal gas law is used to calculate gas temperature.
- A filling and emptying model is used to calculate the trapped mass [25].
- The specific heat of the gas depends on both temperature and composition [26].
- Blow-by model is based on the evolution of the gas in an isentropic nozzle [24].
- The chamber volume deformation due to pressure and inertia is calculated by means of a simple deformation model [23].
- The heat transfer coefficient in the chamber walls is calculated with a modified Woschni-like model [27]:

$$h = CD^{-0.2}p^{0.8}T^{-0.53} \left[C_{W1}c_m + C_{W2}c_u + C_2 \frac{v_{dIVC}}{v_{IVC}p_{IVC}} (p - p_0) \right]^{0.8} \quad (1)$$

Where C and C_2 are constants whose values are 0.12 and 0.001, c_m is the mean piston speed, c_u is the instantaneous tangential velocity of the gas in the chamber that was adjusted using CFD calculations [27], p_0 is the pressure during motoring conditions assuming a polytrophic evolution, and finally C_{W1} and C_{W2} are constants, whose values are adjusted for each engine by means of a combination of experimental and modelling methodology [28].

CALMEC solves the first law of thermodynamics for an open system to obtain the RoHR [23]:

$$RoHR = mc_v \frac{dT}{d\alpha} + \frac{dQ}{d\alpha} + p \frac{dV}{d\alpha} - (h_{f,inj} - u_{f,g}) \frac{dm_{f,ev}}{d\alpha} + RT \frac{dm_{bb}}{d\alpha} \quad (2)$$

Where α is the crank angle degree, m , dT and dQ are the instantaneous mass in the chamber, gas temperature variation and instantaneous heat transfer to the chamber walls respectively, c_v is the specific heat which depends on the instantaneous temperature and composition, $dm_{f,ev}$ is the variation of injected mass, $h_{f,inj}$ and $u_{f,g}$ are the injected fuel enthalpy and internal energy of the evaporated fuel, R is the gas constant and dm_{bb} is the variation of blow-by leakage. Additionally, the heat transfer to the chamber wall Q together with a lumped conductance model allows for accurate calculation of the RoHR.

METHODOLOGY

Two Color Method

This method was applied to two different optical setups - High Speed imaging and an Optoelectronic Pyrometer. Two color pyrometry is an optical thermometry technique that makes use of the presence of radiating soot inside the flame. The intensity of radiation emitted by soot particles (I_{soot}) is proportional to the radiation emitted by a black body at the same temperature (T). This proportionality is determined by the emissivity of the particles, which can be expressed in terms of soot concentration, working wavelength (λ) and a constant parameter (α) [29]. Therefore, I_{soot} can be expressed as the following equation:

$$I_{\text{soot}}(\lambda, T, KL) = \varepsilon_{\lambda} I_{b,\lambda} = \left[1 - \exp\left(-\frac{KL_{2C}}{\lambda^{\alpha}}\right) \right] \frac{1}{\lambda^5} \frac{c_1}{\left[\exp\left(\frac{c_2}{\lambda T}\right) - 1\right]} \quad (3)$$

Where $c_1 = 1.1910439 \times 10^{-16} \text{ Wm}^2\text{sr}^{-1}$ and $c_2 = 1.4388 \times 10^{-2} \text{ mK}$. Zhao et al. [30] reported that α values are less dependent on the wavelength in the visible range than in the infrared.

In this regard, 550 and 650 nm with $\pm 10 \text{ nm}$ FWHM have been chosen when the method is used with two High-Speed CMOS cameras and 600 and 950 nm with $\pm 50 \text{ nm}$ FWHM are used when the method is applied using the Optoelectronic Pyrometer. In this study α was assumed to be 1.39, which is a commonly used for most of fuels [31]. The dependence of the emissivity on the soot amount within the optical path is usually expressed in terms of $KL_{2C} = k_{\text{soot}} L$. This variable accounts for the total contribution of the soot along the optical path, independent of the soot distribution or geometrical size.

Two high speed cameras with two CMOS sensors were employed to measure soot radiation. The signal “S” depends on the detector spectral response, the radiation itself, the area A of the sooting flame within the field of view of the detector and the solid angle Ω subtended by the detector. Several simplifications can be applied [29], and a final expression (equation (4)) is obtained for each wavelength:

$$S_{\lambda} = C_{\lambda} I_{\text{soot}}(\lambda, T, KL) \quad (4)$$

Where C_{λ} is a constant that takes into account A , Ω and λ . This parameter has to be calculated by means a radiance calibration procedure. For this purpose, calibration curves were obtained by means of a previously calibrated light source, as it is described by Payri et al. [29]. The slope of these curves is the transformation factor (C_{λ}) presented in equation (4).

Optical Set-Up

High Speed Imaging Pyrometer

The light emitted by the flame pass through a beam splitter which transmits and reflects 50% of the soot radiation to each of the two High-Speed CMOS cameras employed: a Phantom V12 for 650 nm and Photron SA5 for 550 nm. Both cameras were equipped with a 100 mm focal length and f/2 lens. In order to ensure frame-to-frame synchronization, both cameras were connected in a Master/Slave

mode. They were set to record at 15000 fps, with 5 to 8 μs exposure time for 650 nm and 8 to 12 μs for the 550 nm, depending on test conditions. A scheme of the set-up is shown in figure 2.

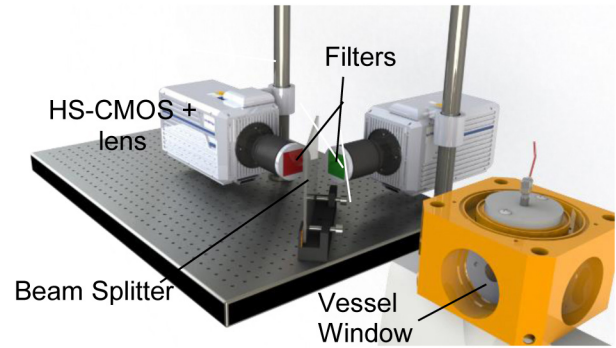


Figure 2. High Speed Imaging pyrometer Set-up

A spatial transformation is required to match both images pixel by pixel. A spatial transformation matrix is calculated, considering translation, rotation and scaling. For both images, background segmentation is also applied. A threshold value is obtained, considering a percentage of the total dynamic range of each image. The value of this percentage was set to 5% for all the tests performed, which has shown good accuracy on the flame boundary detection for all the tests. Only pixels with an intensity greater than the above mentioned 5% are considered part of the flame. Once both images are coupled, equation (3) was applied for each wavelength and KL_{2C} and temperature can be obtained for each instant with a resolution of two spatial dimensions. In figure 3, an example of the application is shown.

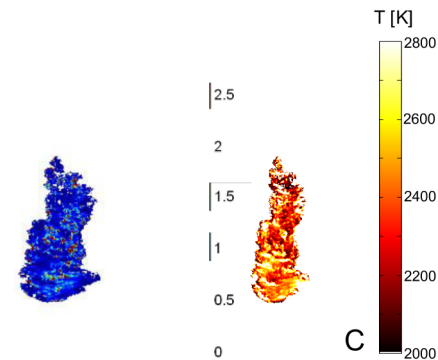


Figure 3. Composition of instantaneous soot natural luminosity at 550 and 650 nm (A) and the corresponding KL (B) and Temperature (C) distributions. Data was taken for 30% Decane –70% Hexadecane, at $\rho_c = 23.4 \text{ kg/m}^3$, $T_c = 800 \text{ K}$ and $P_{inj} = 50 \text{ MPa}$.

Optoelectronic Pyrometer

The in-cylinder soot radiation measurements were also performed with an optoelectronic signal converter with a selection of photodiodes and narrow band optical filters adapted to specific applications for combustion engine flame and radiation measurement. This light probe has been developed by AVL and is known as VisioFEM. A sapphire lens at the tip of the probe captures the light from the combustion chamber with a view angle of 90°. The soot radiation is conducted through optical fibers and split into two channels at wavelengths of 600 and 950 nm. Then, the photodiodes convert the

intensity to a voltage signal. The signals from the photodiodes are amplified and recorded every 0.5°CAD. Signal conversion and signal conditioning ensures highest possible linearity of input radiation intensity to output signal voltage. The Optoelectronic raw signals and the absolute light intensities are linked by a calibration of the whole measurement chain using a halogen lamp, which provides a homogeneously illuminated surrounding. A particular testing methodology is recommended by AVL with the aim of preventing the undesired errors in transmission due to soot deposits during a measurement campaign. [32]. A schematic of the signal path from the flame to the data acquisition device is presented in figure 4.

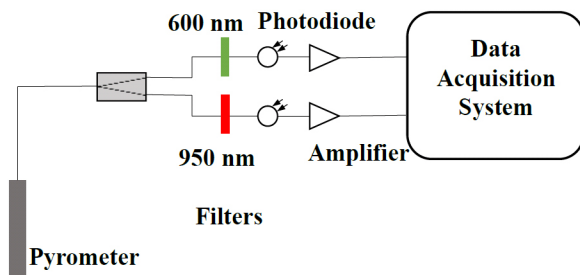


Figure 4. Signal path from flame to data acquisition device

Once both voltage signals are recorded, spectral intensity is obtained considering gain, transmission and sensitivity. Thus, once the voltage signal are converted, equation (3) is applied for each wavelength and KL_{2C} and temperature can be obtained at each instant. It is interesting to remark that with the Optoelectronic probe only temporal resolution is obtained for the soot temperature and KL results.

For the sake of clarity, figure 5 presents the optical set up when the optoelectronic pyrometer is used in both experimental engines.

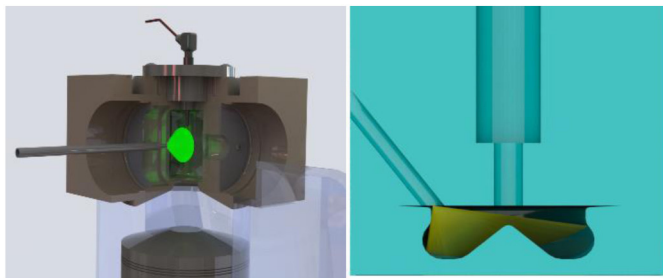


Figure 5. Optoelectronic pyrometer set up Left) Optical accessible engine configuration and Right) Light duty engine configuration

Operating Conditions

Optically Accessible Engine

The test matrix includes eight different engine operating conditions (table 3). The injected fuel mass has been obtained with an injection rate meter. To determine the intake pressures and temperatures required for the test plan, an accurate characterization of the engine has been performed, covering its full operation range. In-cylinder thermodynamic conditions have been calculated from measured pressure, using first-law thermodynamic analysis. This analysis

takes into account blow-by, heat losses and mechanical deformations. The trapped mass is estimated using intake temperature and volume at EVC. Instantaneous in-cylinder temperature evolution during the cycle is calculated using the equation of state and correcting the trapped mass with blow-by estimations. Mechanical deformations can lead to a correction on instantaneous geometric volume; however, in this specific engine they have been neglected. Figure 6 shows an example of the resulting pressure and density evolution during the injection.

Table 3. Experimental conditions optical engine

TDC Temp. [K]	TDC Density [kg/m ³]	Injection Pressure [bar]	Injected fuel mass [mg/stk]	Equivalence ratio [-]
800	23.4	500/1000 /1500	13.4/20.3 /25.4	0.05/0.07/ 0.09
	18.9	1000	20.1	0.08
900	23.4	500/1000 /1500	13.4/20.3 /25.4	0.05/0.07/ 0.09
	18.9	1000	20.1	0.08

Energizing time was set to 2ms for all conditions, which results in an approximate 4.5ms hydraulic injection duration. The injector was triggered at -6.05° aTDC (SoE) and the injection starts at -5.9° aTDC (SoI), to minimize variations of in-cylinder conditions during injection event. Each test was repeated 20 times to reduce measurement uncertainties due to engine operating variability as well as to improve signal-to-noise ratio.

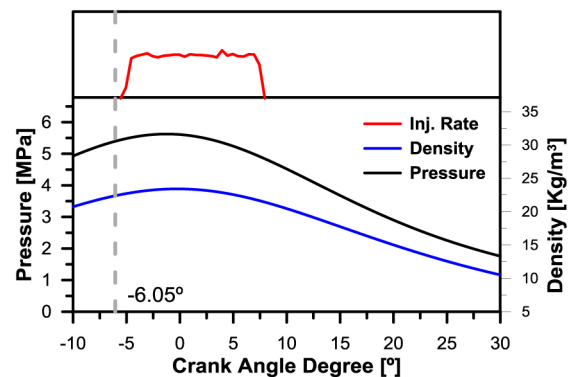


Figure 6. Thermodynamic in-cylinder conditions along engine cycle under motored conditions. Injection rate is just shown to clarify the timing and duration of the injection event.

In this work, one blend using two different fuels, n-decane and n-hexadecane, have been employed. In fact, the fuel used is a blend of both single component fuels at a 30%-70% volume fraction. They have been chosen due to their simplicity (pure fuels) and similarity with diesel fuel in terms of physical and chemical properties. Table 4 shows main fuel properties.