

Time and Spatially Resolved Temperature Measurements of a Combusting Diesel Spray Impinging on a Wall

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ABSTRACT

The interaction between a combusting diesel spray and a wall was studied by measuring the spray flame temperature time and spatially resolved. The influence of injection sequences, injection pressure and gas conditions on the heat transfer between the combusting spray and the wall was investigated by measuring the flame temperature during the complete injection event.

The flame temperature was measured by an emission based optical method and determined by comparing the relative emission intensities from the soot in the flame at two wavelength intervals. The measurements were done by employing a monochromatic and non intensified high speed camera, an array of mirrors, interference filters and a beam splitter. The studies were carried out in the Chalmers High Pressure High Temperature (HP/HT) spray rig at conditions similar to those prevailing in a direct injected diesel engine prior to the injection of fuel. Fuel was injected into the combustion chamber by a common rail system using an injector with a single hole nozzle. The combusting spray impinged on a wall whose temperature was similar to the combustion chamber gas temperature.

Results of these experiments show variations in the flame temperature as a consequence of the interaction between the combusting spray and the wall. There is a reduction in the flame temperature after impingement followed by a temperature rise as the wall is heated up by the flame. The effects caused by injection pressure, injection sequences and gas temperature lead to differences in the heat flux between the combusting spray and the wall.

INTRODUCTION

Spray combustion is an intricate phenomenon vital for direct injected (DI) diesel engines involving complex stages ranging from spray development to fuel oxidation. These stages, whether part of spray development or fuel oxidation, are utterly affected when the spray impinges on the combustion chamber surface, having repercussions on the development and characteristics of the spray, flame evolution and formation of pollutants. Moreover, it affects the flame temperature and the operating temperature of the combustion chamber itself [1, 2].

The interaction between spray and combustion chamber surfaces can occur under two scenarios: the combustion chamber is impinged by the fuel plume prior to ignition, or impinged by the combusting spray after combustion commences.

In general, at cold starting procedures the former scenario occurs and fuel is adhered to the chamber surfaces after the fuel plume impacts on the chamber walls forming a film surrounded by sparsely adhered deposits [3]. The thickness and extent of these films are influenced by the combustion chamber geometry, operational parameters and injection conditions [4]. Furthermore, axial and radial velocities of the spray near to the wall are affected by surface roughness and by the inclination relative to the spray axis [5, 6], meanwhile the evaporation process and heat transfer to the wall are associated to the spray characteristics prior to the impingement [7, 8].

For the latter case regarding combusting sprays impinging on the combustion chamber, i.e. the spray initiates to be combusted prior of reaching the combustion chamber surface, the results of this interaction are alterations in flame temperature and variations in the heat flux to the wall. The reduction in flame temperature itself, leads to numerous consequences related to the efficient oxidation of fuel and production of pollutants. Additionally, it has been observed that the heat flux to the wall by diffusion governed flames is larger than for premixed stoichiometric flames [9, 10]. Even though combustion is mostly governed by diffusion for DI diesel engines, premixed combustion also occurs.

The aforementioned interactions have prominent repercussions on combustion efficiency, formation of pollutants and heat release rate [2, 11–14]. Nevertheless of the advances to characterise the interaction between combusting sprays and combustion chamber surfaces, further research is needed to clarify the influence that this interaction has on flame temperature and in the oxidation and production of soot. Moreover the specific role and consequences that combustion chamber conditions and injection parameters have on them.

Flame temperature measurements offer a possibility to study the affection caused to the combusting spray by the collision against the chamber walls. Flame temperature, among other factors, is an important variable related to the rate of heat release, chemical kinetics and the production and oxidation of soot, consequently, it is important to be acquainted with the flame tempera-

ture of the combusting spray and its variations as a result of this interaction time and spatially resolved.

Temperature measurements conducted by emission based optical methods are considered to be relatively uncomplicated and capable to offer a reasonable degree of accuracy [15–17], having good ability to acquire information in hostile environments maintaining low intrusiveness.

Flame temperature measurements for multiphase flows, like combusting and sooting DI diesel sprays, can be carried out by measuring the temperature of the immersed particles by assuming that particles and flame are in thermal equilibrium. Several studies have been carried out on a wide variety of applications: from combusting particles [18–20] up to DI diesel spray combustion [1, 2, 21], where soot particles are being present inside most of diesel flames. On these studies flame temperature was measured by the two-colour method, which basically consists on comparing the electromagnetic emission from soot particles at two wavelength intervals and treating particles as black body radiators [22].

In this work, the interaction between combustion chamber surfaces and the combusting spray is imitated and studied by measuring the flame temperature of a spray impinging on a wall. Temperature was measured time and spatially resolved by an emission based optical method using an array of mirrors, lenses, interference filters, and a monochromatic, non intensified high speed camera. The influence that different evaluation algorithms have on the estimation of the flame temperature were investigated. By the aim of this technique, it is possible to measure the flame temperature evolution and local variations caused by the interaction with the wall. Several combustion chamber conditions and injection strategies were studied.

THEORY

Due to the fact that most of DI diesel sprays produce soot while being combusted, in addition that soot particles inside flames are very small ($D_p \lesssim 100 \text{ nm}$) [23–25], it can be safely assumed that soot particles and flame are on thermal equilibrium on a time scale smaller than the time resolution of most of the non-intensified CCD detectors. Even though Planck stated that his theory about heat radiation from black bodies should be employed for objects bigger than the detection wavelength [26, 27], which is not the case of soot particles in DI diesel flames, it is still possible to quantify the radiation from incandescent soot. Radiation from soot can be treated either by the two-colour approach, which is employed by commercial pyrometers [2, 21, 22], or by a correction developed for particles whose size is smaller than the wavelength [28–34]. The latter approach is employed for flame temperature calculations in this work.

Flame temperature measurements are habitually done by employing a colour CCD detector and a filter to remove IR and UV light, nonetheless, it is possible to do these kind of measurements by the aid of a monochromatic CCD detector and an optical arrangement of lenses, mirrors, filters and beam splitters. Certain assets of the employment of monochromatic CCD detectors, compared to colour CCD detectors, are the increased

dynamic range, the possibility of the employment of image intensifiers leading to shorter exposure times, and broader flexibility as a consequence of the liberty of interchange filters on demand. The latter aspect is specially useful to avoid erroneous measurements on cases where two-colour pyrometry can be confounded by the presence of water vapour, carbon dioxide and carbon monoxide radiation peaks in the near infrared emission spectrum and by flame chemiluminescence in the blue and ultra violet region.

The connection between the spectral radiation from soot and flame temperature measurements, together with the differences among commonly employed approaches, are described in this section.

SPECTRAL RADIATION FROM SOOT

The total spectral radiation from a spherical body D_p of emissivity ϵ_λ , comprehended in the wavelength interval between λ_i and λ_f , can be calculated according to Planck [26] by Equation 1.

$$Q_{rad\lambda_i-\lambda_f} = \int_{\lambda_i}^{\lambda_f} \pi D_p^2 \cdot \epsilon_\lambda \cdot \frac{2\pi hc^2}{\lambda^5} \cdot \frac{1}{e^{\frac{hc}{k_b T_p \lambda}} - 1} \cdot d\lambda \quad (1)$$

Commercial pyrometers commonly estimate the emissivity ϵ_λ , for the case of flames containing incandescent particles, according to Hottel and Broughton (H&B) [22] by Equation 2, where k is an absorption coefficient related to the amount of soot, s is the geometric thickness of the flame along the detection path and α is a specific coefficient dependant on wavelength, particle size and flame structure. Nevertheless, variations of α in the visible region are small, therefore these variations are oftentimes neglected and α is consider as constant [2, 21, 35–38].

$$\epsilon_\lambda^{(a)} = 1 - e^{\left(\frac{-ks}{\lambda^\alpha}\right)} \quad (2)$$

The combination of (1) and (2) leads to (3), with which the radiation from a single particle between λ_i and λ_f , can be estimated.

$$Q_{rad\lambda_i-\lambda_f}^{(a)} = \int_{\lambda_i}^{\lambda_f} \pi D_p^2 \cdot \left(1 - e^{\left(\frac{-ks}{\lambda^\alpha}\right)}\right) \cdot \frac{2\pi hc^2}{\lambda^5} \cdot \frac{1}{e^{\frac{hc}{k_b T_p \lambda}} - 1} \cdot d\lambda \quad (3)$$

Alternatively and probably more correctly, the emissivity ϵ_λ of a single particle which is small compared to the radiation wavelength, can be calculated on the basis of the Mie theory described by the Rayleigh approximation as it is shown in Equation 4, being m the complex refractive index of soot.

$$\epsilon_{(\lambda,m)}^{(b)} = 4\pi \cdot \left(\frac{D_p}{\lambda}\right) \cdot E(m) \quad (4)$$

where

$$E(m) = \frac{n^2 - 1}{n^2 + 2} \quad (5)$$

Hence, by combining (1) with (4) and (5) conducts to (6).

$$Q_{rad\lambda_i-\lambda_f}^{(b)} = \int_{\lambda_i}^{\lambda_f} \pi^2 D_p^3 \cdot \text{Im} \left[\frac{m^2 - 1}{m^2 + 2} \right] \cdot \frac{2\pi h c^2}{\lambda^6} \cdot \frac{1}{e^{\frac{hc}{k_b T_p \lambda}} - 1} \cdot d\lambda \quad (6)$$

The use of Equation 6 for estimating the radiation from particles which are small compared to the radiation wavelength has shown to be in a close agreement to experimental data among different scenarios and conditions, ranging from LII to interplanetary dust studies [27–34]. Even though there is a wide variety of complex refractive indices of soot (m) reported in the literature it is worth to highlight that the relative wavelength dependence of $E(m)$ is small, which is shown by modest differences in the values reported among publications [39–43].

TEMPERATURE CALCULATIONS

Flame temperature is calculated by comparing the electromagnetic emission intensities at two frequency intervals. This approach is based on the supposition that soot has a defined and finite temperature, consequently it emits electromagnetic radiation continuously and its intensity depends on flame temperature and on the frequency at which is being emitted. The ratio between emission amplitudes at these two frequency intervals corresponds to a given temperature. By calculating the relation between electromagnetic radiation at two frequency intervals against temperature leads to establish the mean temperature of the particles whose radiation is captured by a determinate section of the detector. By using this approach, temperature calculations are independent of particle size, particle concentration, and frailty affected by window contamination by deposits. The ratio between emission at two frequency intervals can be written as in Equation 7, where the detector efficiency ($D_{eff}(\lambda)$), optical elements transmissivity and reflectivity ($I_{eff}(\lambda)$) are considered.

$$R(T, \lambda, m) = \frac{Q_{rad\lambda_{a_i}-\lambda_{a_f}}}{Q_{rad\lambda_{b_i}-\lambda_{b_f}}} \cdot \frac{I_{effa}(\lambda)}{I_{effb}(\lambda)} \cdot \frac{D_{effa}(\lambda)}{D_{effb}(\lambda)} \quad (7)$$

The correlation between particle temperature and emission ratio at two arbitrary frequency intervals calculated by Equation 3 and by Equation 6 with a wavelength-independent complex refractive index and Equation 6 with a wavelength-dependant refractive index are plotted in Figure 1.

Figure 1 shows the differences in flame temperature calculations as a consequence of the approaches used for treating the emissivity of soot particles. Differences among approaches are relatively small for low temperatures, nevertheless these differences increase for higher temperatures. The Hottel and Broughton (H&B) approach and a wavelength-dependant refractive index show the highest and lowest temperature respectively for the same intensity ratio. The differences between a constant and a wavelength-dependant complex refractive indices are relatively small for temperatures close to the adiabatic flame temperature of a DI diesel flame ($T \lesssim 2700$ K). However, this difference

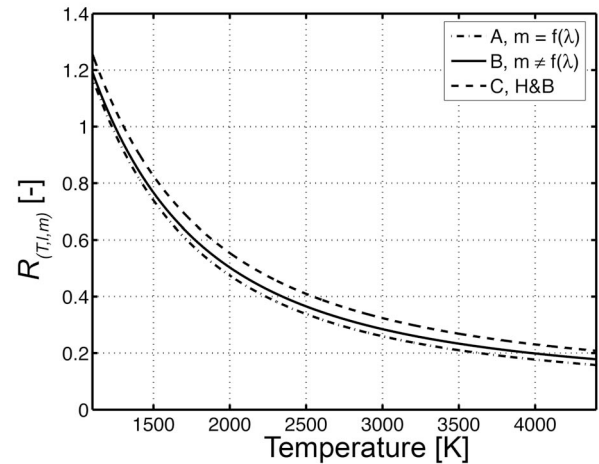


Figure 1: Correlation between particle temperature and the ratio between emission at two different frequency intervals for three different approaches. (A) Eq. 6 with a wavelength-dependant complex refractive index ($m = f(\lambda)$), (B) Eq. 6 with a wavelength-independent complex refractive index ($m \neq f(\lambda)$), and (C) Eq. 3 for an optically thick flame ($ks \gg 1$).

increases for high temperatures close to the temperatures of interest for LII studies ($T \lesssim 4500$ K).

It has also been stated, that using a wavelength independent complex refractive index overestimates the flame temperature compared to the Spectrum-Line Reversal Method by (15 K) on normal flame temperature ranges, and by (40 K) on temperatures of interest for LII studies [27, 43–45]. The marked difference on the relation among temperature and radiation ratios, between Equation 3 (H&B) and Equation 6 approaches, has to do with the fact that the former approach (H&B) is based on uncorrected black body radiation. In the case of soot, which particle size is notably smaller than the wavelength, leads to profound differences. It has been reported [27, 36, 43] that using the (H&B) approach, it conducts in some cases, to overestimate the flame temperature to values above the adiabatic flame temperature. Differences between the above mentioned approaches becomes more evident when measurements are performed on wide separated wavelength intervals.

In this work flame temperature is calculated by using Equation 6 and Equation 7 employing a wavelength-independent complex refractive index supposing that soot particles are small compared to the wavelength. By employing wavelength-independent complex refractive indices, temperature measurements are independent of their value.

EXPERIMENTAL RIG

OPTICAL ARRANGEMENT

Temperature measurements of combusting sprays impinging on a wall were done by an optical method using an array of mirrors, interference filters, and a monochromator.

high speed camera with a 12-bit dynamic range detector, obtaining time and spatially resolved temperature measurements of the spray projected on a plane perpendicular to the axis of the detector. Images were captured at a rate of 7,200 frames per second (fps). The interference filters employed have a transmittance centred at 532 nm, and 450 nm with a FWHM of 40 nm respectively.

The camera recorded a projected image of the combusting spray on each of the two half sections of the detector, each half of the detector captured a set of images spectrally filtered by the respective interference filter. The images were digitally processed afterwards. The temperature was determined by comparing the emission amplitude of these images. The temperature of the spray was measured from the moment at which combustion commences (SOC) until the moment at which combustion terminates (EOC).

The optical arrangement was calibrated by measuring the spectral transmittance and reflection of the optical components ($D_{eff}(\lambda)$) and ($I_{eff}(\lambda)$) by the aid of a commercial spectrometer at spectral ranges of interest for these measurements. The spectral response of the camera detector was obtained from the fabricant. A sketch of the experimental set-up for flame temperature measurements is depicted in Figure 2.

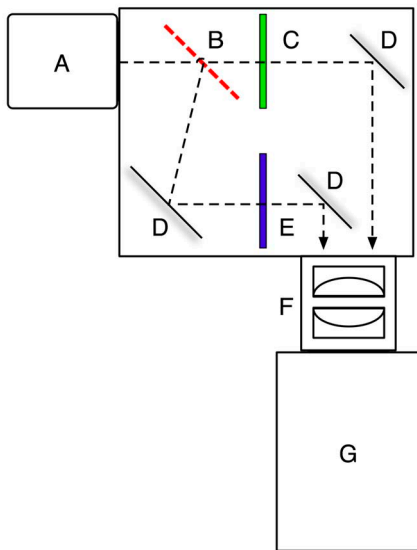


Figure 2: Experimental set up for flame temperature measurements. A: F-mount 105 mm–1/1.8 objective, B: Beam splitter, D: Aluminium protected mirrors, C: Interference filter centred at 532 nm with a FWHM of 40nm, E: Interference filter centred at 450 nm with a FWHM of 40nm, F: Achromatic planar relay optics, G: Monochromatic non-intensified High Speed Camera.

SPRAY RIG AND EXPERIMENTAL CONDITIONS

The experiments were conducted in the Chalmers High Pressure High Temperature (HP/HT) spray rig. The Chalmers HP/HT spray rig is an optically accessed combustion chamber with a volume of two litres, each combustion event is considered isobaric. Pressurised and preheated air flow through the combus-

tion chamber at a constant velocity (0.1 m/s), therefore the conditions before each injection can be considered quiescent. Fuel was injected using a common rail injection system with a single hole, vertically aligned injector nozzle ($\phi = 0.15 \text{ mm}$). An outline of the Chalmers HP/HT spray rig is presented in Figure 3.

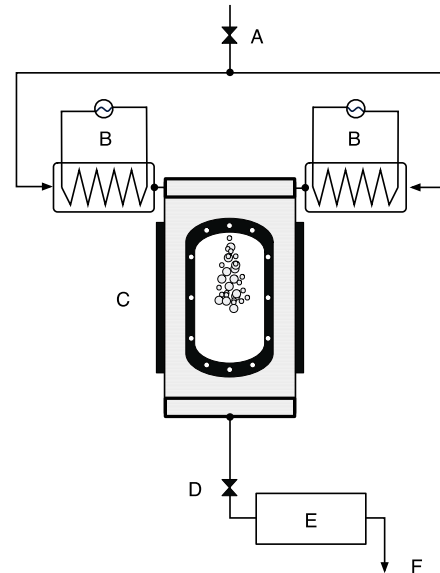


Figure 3: Sketch of the Chalmers HP/HT spray rig showing an outline of the configuration employed for these measurements. A: Pressurised air inlet regulator, B: Air electrical heaters, C: Optically accessed test section, D: Air flow controller, E: Exhaust gas heat exchanger, F: Gas exit.

The conditions inside the combustion chamber were controlled in order to achieve operational conditions similar to those in an internal combustion engine before injection, the combustion chamber gas pressure was $P_g = 70 \text{ bar}$, and the gas temperature ranged from $T_g = 520 \text{ }^\circ\text{C}$ to $T_g = 560 \text{ }^\circ\text{C}$. Fuel injection pressure was set between $P_i = 800 \text{ bar}$ and $P_i = 1200 \text{ bar}$. Two air qualities were studied: normal air, i.e. atmospheric air, and air with combustion residuals. The normal air condition had a period between injections long enough to evacuate the combustion chamber completely before fuel was injected again, meanwhile the air with combustion residuals condition had a very reduced time between injections assuring that a remanent of the combustion products from the previous injection were present prior to the injection of fuel. No measurement of the air quality was done.

A wall was set in the combustion chamber in the path of the spray and perpendicular to the injection axis. The wall temperature was similar to the gas temperature prior to every injection. The wall was set at a distance of 60 mm from the injector nozzle tip, the diagram of the wall and injector inside the Chalmers HP/HT spray rig is presented in Figure 4.

Swedish environmental class I diesel fuel was employed, selected properties are presented in Table 1. Two injection strategies were investigated, single and split injection. For the single injection case, the injection duration was 4 ms , meanwhile for the split injection case the first and pulses had a duration of 2.5 ms and 1 ms respectively with a dwell duration of 5 ms .

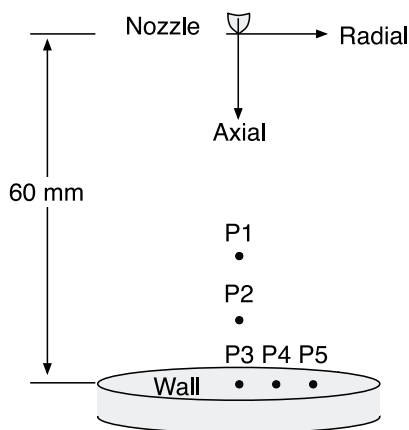


Figure 4: Sketch of the experimental configuration employed for these measurements where a wall was set perpendicular to the injection axis. The coordinates for the points (P1-P5) shown on the sketch are: P1(46,0), P2(53,0), P3(60,0), P4(60,3) and P5(60,6).

DATA ANALYSIS AND ERROR DISCUSSION

Temperature is thus calculated, by correlating the intensity ratio between every pixel pair of the detector sections, i.e. images are pondered against each other, versus the relation between electromagnetic radiation ratio and temperature. The total emission is calculated according to Equation 6 and Equation 7 using a wavelength-independent complex refractive index, by supposing that soot particles are small compared to the wavelength. By employing wavelength-independent complex refractive indices, temperature measurements are independent of the value of them.

Images between the two detector sections were digitally processed by the aid of a morphological algorithm in order to correlate pixel to pixel, thereafter the ratio between corresponding pixels was calculated. Even though the complete dynamic range of the CCD detector would be desirable to be employed, an upper safety margin must be set when acquiring data due to the fact that saturation must be avoided. Neutral density filters were employed for some cases. Exposure parameters were set to have a captured value no larger of (95/100) of the maximum value of the detector.

Table 1: Properties of Swedish diesel fuel Environmental Class 1 (MK1)

Property	Value
Density (at 15°C)	835.4 $\frac{kg}{m^3}$
Viscosity (at 40°C)	3.31 $\frac{mm^2}{s}$
Sulphur content	55 $\frac{mg}{kg}$
Cetane number	53.1
Net heat of combustion	42.93 $\frac{MJ}{kg}$
Flash point	79 °C
Dist: IBP	193.5 °C
Dist: FBP	358.0 °C

Due to the high thermal conductivity of carbon-dominant particles, such as soot, it can be assumed that particles are on thermal equilibrium with the gas, at least on time scales where non-intensified cameras operate and are able to capture an image; nevertheless particle temperature may differ from gas temperature when particles are oxidising.

On account that at normal flame temperatures soot radiation is mainly situated in the infrared region, it is appealing to do measurements in this region of the spectra; notwithstanding, there are radiation and absorption peaks caused by the presence of water vapour, carbon dioxide and carbon monoxide; these absorption and emission bands can contribute to errors when doing temperature measurements by this method. Moreover, visible light sensitive detectors are more common than detectors able to measure infrared or ultraviolet radiation. Altogether draws special attention to the spectral regions where radiation is measured in accordance to avoid anomalous flame temperature measurements.

RESULTS AND DISCUSSION

GENERAL DESCRIPTION

Temperature measurements of combusting sprays are shown in sequences of consecutive frames for different fuel injection and combustion chamber conditions. Table 2 presents the experimental conditions corresponding to each case and relates them to combustion chamber conditions, fuel injection pressure, air quality, injection strategies, i.e. single or split, and to the associated figures.

Temperature versus time plots for a set of points described in Figure 4 are depicted for every condition together with a plot of the arithmetic mean, maximum temperature and temperature at a point on the wall surface aligned to the injection axis (P3) versus time.

Each sequence of frames show flame temperature measurements from the start of combustion (SOC) until the end of combustion (EOC). However, the first frame (top left) of all frame sequences corresponds to the fifteenth (15th) frame after the logical pulse, i.e. 1.48 ms after the start of injection (ASOI), meanwhile the last frame (bottom right) corresponds to the fiftyninth (59th) frame after the logical pulse, 7.73 ms ASOI. The time difference between consecutive frames is 138 μs.

In brief terms, fuel is injected at a high velocity into the combustion chamber, then it is atomised, vaporised and blended with air; eventually the mixture ignites either before or after impinging the wall. At the moment when the spray reaches the wall it spreads on the radial direction with eddies whose direction is towards the spray axis, meanwhile fuel continues being injected. Figure 5 shows an schematic of the phenomena of the spray impinging on a wall.