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Projekt

Entwicklung und Validierung verbesserter Teil-Modelle für transiente Sprays mit Verbrennung

Autor und Koautoren	OURANIA-NEKTARIA MARGARI
beauftragte Institution	Laboratorium fur Aerothermochemie und Verbrennungssysteme
Adresse	Clausiussstasse 33, ETH Zentrum CH-8092 Zurich
Telefon, E-mail, Internetadresse	01 6327785, margari@lav.mavt.ethz.ch, www.lav.ethz.ch
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ZUSAMMENFASSUNG

Die vorliegende experimentelle Arbeit befasst sich mit Emissionen von direkt einspritzenden Dieselmotoren. In diesem Zusammenhang ist ein gutes Verständnis der Russbildung und –oxidation wesentlich; diese Vorgänge werden in der vorliegenden Arbeit mit optischen Methoden untersucht. Für diese Arbeiten wird die Hochtemperatur-/Hochdruckzelle (HZTDZ) des Laboratoriums für Aerothermochemie und Verbrennungssysteme verwendet, wobei bildgebende (2D) optische Methoden zur Untersuchung der Vorgänge der Russbildung und –oxidation eingesetzt werden. Die Ergebnisse dienen auch zur Validierung von Modellrechnungen, welche die Voraussage von Russemissionen erlauben.

Die Experimente zur Untersuchung der Bildung von PM-Emissionen (***P***articulate ***M***atter) wurden unter konstantem Zustand (Druck und Temperatur) des Versuchsträgers durchgeführt, wobei unter konstanten Einspritzzeiten der Einspritzdruck der Common - Rail – Einspritzung variiert wurde. Es gelangten zwei verschiedene optische Methoden zum Einsatz, ein auf einer Zweifarbenpyrometrie beruhendes 2D-Verfahren zur Bestimmung der Russtemperatur und des KL-Faktors (ein Mass für den Russ-Volumenanteil) sowie ein Laseroptisches Verfahren (Gesamtstaub Laser BDL) zur Bestimmung des Russ-Volumenanteils. Ferner wurden durch Auswerten von gemessenen Verbrennungsdrücken und optischen Signalen der Zündverzug bestimmt.

Messungen bei 40 bar Zellendruck, 790 K Zellentemperatur und 3 ms Einspritzzeit zeigen mit steigendem Einspritzdruck (500 bar, 1000 bar, 1300 bar) einen abnehmenden Zündverzug und abnehmenden KL-Faktor wobei die Russtemperatur zunimmt. Dies ist darauf zurückzuführen, dass bei steigendem Einspritzdruck der Brennstoff besser zerstäubt und schneller und intensiver mit Luft vermischt wird, was sich auch durch einen höheren Anteil der vorgemischten Verbrennung zeigt.

Im Vergleich ergibt das BDL-Verfahren einen höheren Russ-Volumen-Anteil als der pyrometrisch bestimmte KL-Faktor. Dies ist dadurch zu erklären, dass mit der Pyrometrie nur der heisse leuchtende Anteil des Russes erfasst wird, während mit dem BDL-Verfahren auch kältere nicht leuchtende Anteile einbezogen werden.

Zweifarben Pyrometer und Gesamtstaub Laser (BDL) sollen auch für die geplanten Versuche zur Untersuchung des Einflusses des Brennstoffs auf die Verbrennung eingesetzt werden. Es sind Untersuchungen an Diesel/Butylal Gemischen mit 25% und 50% Masseanteile Butylal, sowie Diesel/Wasser-Emulsionen mit 13% und 25% Wasseranteil geplant. Zur Bestimmung des Zündverzugs sollen zusätzlich eine Chemolumineszenz - Methode zur Detektion der OH und CH - Bildung eingesetzt werden. Es sind Messungen am Einhubtriebwerk geplant.

Aim of the Project

One of the main goals of this project is to acquire a large data set for a detailed study of the ignition delay and its location as and the emission levels that are produced by the direct injection Diesel engines, so that currently available or future simulation models can be validated. In order to meet future emission regulations, both on-road and off-road heavy-duty diesel engines will require minimized cylinder-out emissions and the use of exhaust after treatment technologies. In-cylinder emission control technologies, as e.g. fuel injection system optimization, use of exhaust gas recirculation, and modification of fuel composition are investigated in detail at our laboratory. A good analysis of the combustion processes will lead to the comprehension of these phenomena and the reduction of the emission levels, without impairing the engine performance and efficiency. In order to achieve this goal an experimental work is performed in *LAV/*ETH in a High temperature-high pressure cell (Figure 1) and in a Rapid Compression Machine (RCM) (Figure 2).

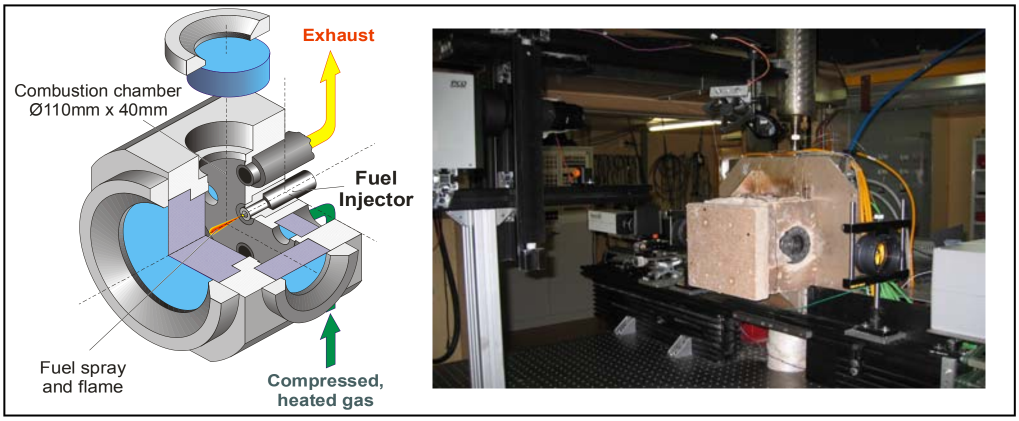

Figure 1*:* High temperature-high pressure cell

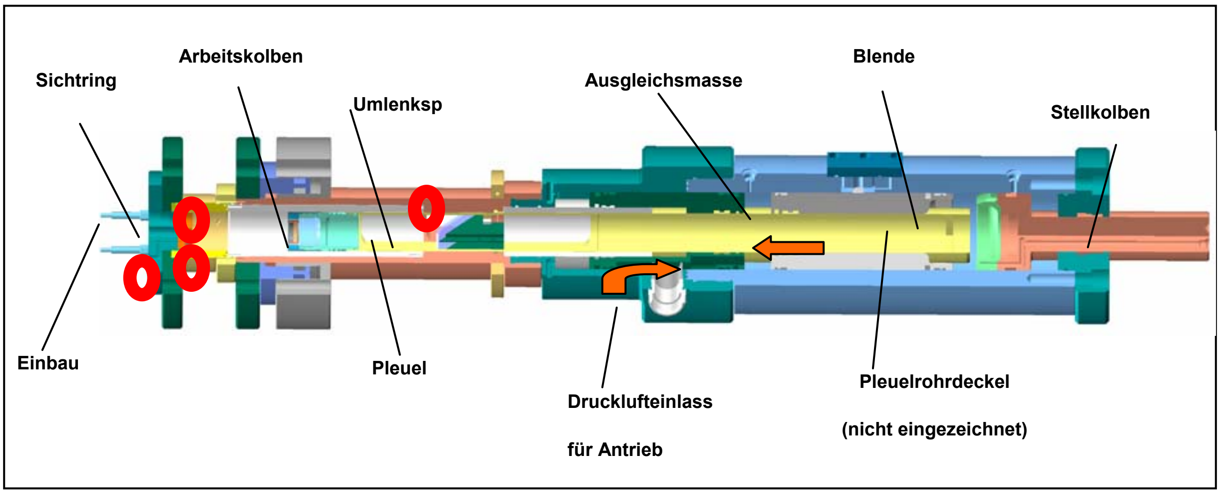

Figure 2*:* Rapid compression machine

The advantage of a combustion cell is its ability to simulate a wide range of conditions, including those found in the real Diesel engines. The benefit of the rapid compression machine is the excellent and flexible optical access, the counter driving pistons that guarantee a nearly vibration free operation, and the various measurement techniques that can be applied on parallel.

Achieved work and Results

The major part of Diesel combustion involves diffusion flames. One of the characteristics of this type of combustion is its high luminosity caused by the thermal radiation of soot particles at high temperatures. Two techniques, the two-color pyrometry and the back diffused laser technique (BDL) will be presented and results will be discussed. Since it is difficult to get enough optical access inside a running Diesel engine the constant volume high-pressure-high-temperature cell (HTDZ) is used. This facility has full optical access and can deliver answers to the basics of soot formation and oxidation during the combustion process.

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Measurement techniques

Back Diffused Laser (BDL) Technique

Figure 3 shows a schematic of the optical setup for the BDL measurements. The Nd:YAG laser shots a laser beam at a wavelength of 532 nm in the direction of the first high energy mirror, which is mounted at an angle of 45 degrees. This mirror has a reflectivity of more than 99% at an angle of 45° and a wavelength of 532 nm. Most of the light is reflected and passes then through two lenses, being diffused. By the use of diffused light, the Shadowgraph effect caused by the change in the refractive index of the mixture is suppressed. Dark areas are therefore only caused by extinction.

A second high energy mirror deflects the diffused light at 45 degrees, which passes afterwards a white screen to make the soot visible. Then, the light goes through the high-temperature high-pressure cell, where its intensity is reduced because of the soot in the flame. Then, it passes through a line band pass filter (532 nm) to suppress the influence of flame radiation on the measured intensities and the objective (focal length 33 mm) of the camera. Finally, the CCD camera records the image of the flame (figure 3) [1].

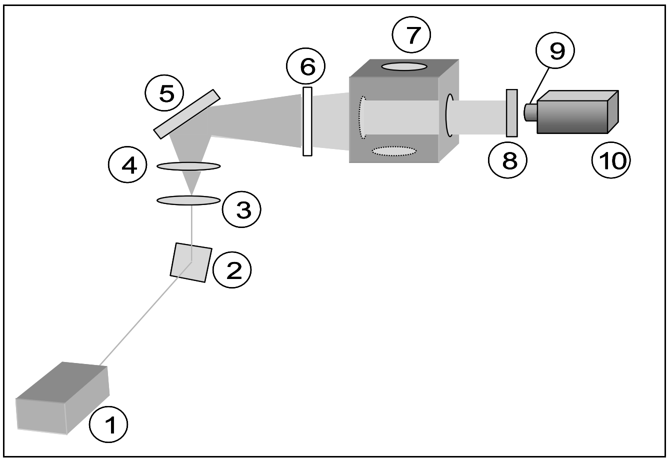

Figure 3: Schematic of the BDL setup

[1]	Nd:YAG laser	[6]	White screen
[2]	High energy mirror	[7]	High-temperature high-pressure cell
[3]	First lens to diffuse the laser beam	[8]	Line band pass filter
[4]	Second lens to diffuse the laser beam	[9]	Objective
[5]	High energy mirror	[10]	CCD camera

When light of the intensity I_0 passes a cloud of particles, the detected intensity I will be smaller. The presence of the particles has resulted in the extinction of the incident light, which has been absorbed and scattered by the particles. This circumstance is used to evaluate the soot volume fraction f_V or the optical thickness KL (KL-factor).

Theoretical fundamentals

The attenuated intensity of the light, which has passed a cloud of particles, is described by Lambert-Beer's law [3,4]:

$$I = I_0 \cdot \exp\left(-\int_0^L K_{ext} \cdot dx\right) \tag{1}$$

Here, I_0 is the incident light intensity. The extinction coefficient K_{ext} for a cloud of particles depends on the number, size and properties of each particle. The following relation from light scattering theory shows this dependence [3,4]:

$$K_{ext} = \frac{\Pi}{4} \cdot C_n \int_0^\infty Q_{ext} \cdot N(D) \cdot D^2 \cdot dD \tag{2}$$

Q_{ext} is a complex function of the particle size and the refractive index of the particle. A theory, which describes the problem of absorption and scattering by small particles for a sphere of arbitrary radius and refractive index well, is the so-called Mie theory. There are many approximations to its solution. According to the very common Rayleigh scattering approximation, the extinction efficiency Q_{ext} can be expressed as the sum of an absorption efficiency and a scattering efficiency. Because soot is highly absorbing, the absorption efficiency component is dominant and Q_{ext} can be written as follows [3,4]:

$$Q_{ext} = Q_{abs} = 4 \cdot X \cdot \mathrm{Im}\left\{\frac{\tilde{m}^2 - 1}{\tilde{m}^2 + 2}\right\} \tag{3}$$

Im is the imaginary part of the expression in the cambered parentheses and $\tilde{m}$ is the complex refractive index of soot. The volumetric density of particles (in the case of this thesis the soot volume fraction) is proportional to the number density and can be obtained from the extinction measurement as follows (for detailed derivation of this relation see [3,4]):

$$f_V = -\frac{\lambda}{6 \cdot \Pi \cdot L \cdot \mathrm{Im}\left\{\frac{\tilde{m}^2 - 1}{\tilde{m}^2 + 2}\right\}} \cdot \ln\left(\frac{I}{I_0}\right) \tag{4}$$

In equation (4), λ is the laser wavelength and L is the geometrical path length through the soot, respectively. With the assumption that the extinction coefficient is constant over the geometrical path of the light through the cloud of particles, the optical thickness can be calculated as follows according to Lambert-Beer's law [3,4]:

$$K \cdot L = -\ln\left(\frac{I}{I_0}\right) \tag{5}$$

To get a KL-factor on the order of 10^{-8} the following relation has to be used (Schubiger R.A. [5]):

$$K \cdot L_m = \frac{K \cdot L_{\mu m}}{2.19 \cdot 10^8} \tag{6}$$

$K \cdot L_m$ is the resulting KL-factor if $[m]$ is used as unit length and $K \cdot L_{\mu m}$ if $[\mu m]$ is used, respectively. Thus, $K \cdot L_m$ is on the order of 10^{-8} and $K \cdot L_{\mu m}$ on the order of 10^0.

Pyrometer

In figure 4, the optical setup of the pyrometer is presented, as it was used for the experiments.

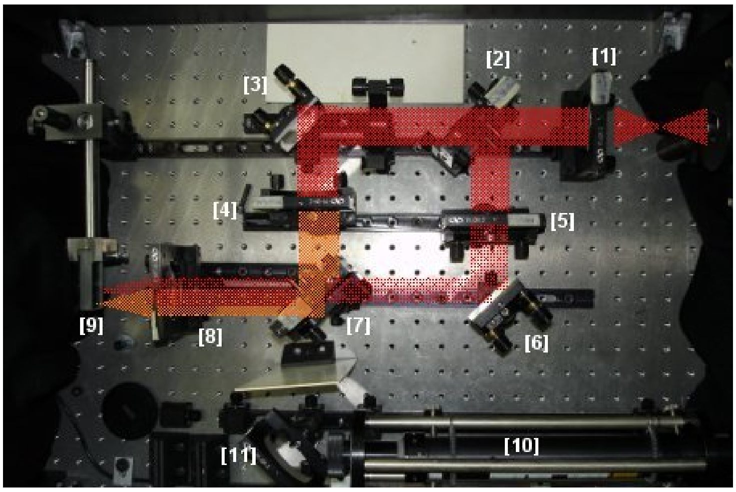

Figure 4: Optical setup two-colour pyrometry

[1]	First lens (f = 127 mm)	[7]	Dichroic beam splitter (“cold mirror”)
[2]	Dichroic beam splitter (“hot mirror”)	[8]	Second lens (f = 127 mm)
[3]	Adjustable mirror	[9]	Optical prism
[4]	Band-pass-filter (640 nm)	[10]	HeNe-laser
[5]	Band-pass-filter (740 nm)	[11]	Fix mirror
[6]	Adjustable mirror		

The light, which is reflected by the flame or rather by the soot, is caught by a zoom objective and focused. Normally, there is a film or a CCD-chip of a camera arranged at the focal point. In this case, the beam of rays diverges and is defocused by a first lens (focal point at infinity). This quasi-parallel beam of rays impinges on a dichroic beam splitter (“hot mirror”) which reflects the light above 700 nm and transmits the rest. Compared to a normal beam splitter which has a nearly wavelength-independent transmittance- and reflectance-characteristic, respectively, these dichroic beam splitters take as much advantage as possible of the present light intensity. After the “hot mirror” the two beams are filtered by a band-pass-filter of 640 nm (visible) and 740 nm (infrared), respectively. Adjustable precision mirrors change the direction of the beams by 90 degrees. To project both images of the flame simultaneously and preferably distortion-free onto the ICCD-chip of the camera, a second dichroic beam splitter (“cold mirror”) merges the two paths of rays. These impinge then on a second lens and are finally focused on the ICCD-chip. Because for the used non-achromatic lenses the focal length changes with the wavelength of the passing light, it is not possible to obtain sharp images for both wavelengths. Therefore, an optical prism is placed between the second lens and the camera The theoretical background of the pyrometer technique is given in the following references [3, 4, 5, 6].

Results

Several image sequences for different conditions have been acquired using pyrometer and BDL technique (Table 1).

Fuel	p_{cell}	T_{cell}	p_{inj}	$t_{inj,}$
[-]	[bar]	[K]	[bar]	[ms]
Diesel	40	790	500	3.0
Diesel	40	790	1000	3.0
Diesel	40	790	1300	3.0

Table 1: Parameters for pyrometer measurements

The initial parameters applied to the HTDZ were: cell temperature 790K, cell pressure 40bar, injection duration 3ms and injection pressure 500bar. In figure 5 the complete soot formation and oxidation period is presented as well as the soot temperature evolution as a function of the time after the start of injection. Each picture is resulted by the average of 10 instantaneous images acquired under the same conditions. In this case the ignition delay is 2.5ms after start of injection (ASOI) and it is located on the cell wall. The images (a) to (e) represent the soot temperature, while the contours (f) to (j) correspond to the KL factor in the volume of the flame. The soot formation and oxidation period lasts about 1.3ms.

Repeating the same experiments, keeping all the initial parameters constant except the injection pressure that changes from 500bar to 1000bar and 1300bar (Table 5), similar behavior of the combustion is occurred. In all cases the ignition is located on the cell wall. At injection pressure 1000bar the ignition delay is 2.1ms while at 1300bar it is 1.9 ms, based on the pressure traces recorded during combustion. The soot formation and oxidation period at these two cases lasts 2.3ms and 1.3ms respectively (Figure 6).

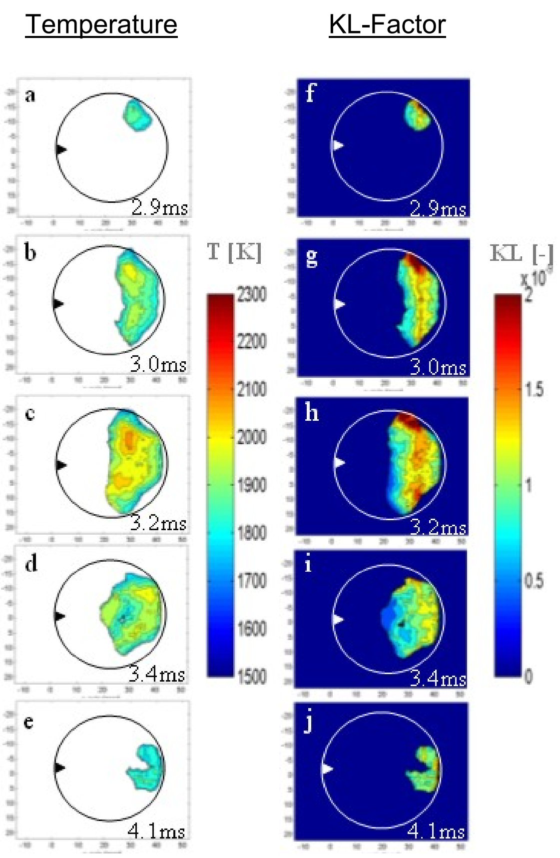

Figure 5: Evolution of the soot temperature and KL-factor at cell temperature 790 K, cell pressure 40 bar, injection duration 3ms and injection pressure 500 bar

In figure 6 the summed KL-factor of the flame cross section is plotted for all three different injection pressures, 500bar, 1000bar and 1300bar, versus the time ASOI. It is observed that at injection pressure 1000bar the quantity of KL-factor is higher than in the other two cases 500bar and 1300bar. At injection pressure 1300bar it is observed a decrease to the total KL-factor. From figure 6 where the arrows show the ignition delays for each case, it can be seen that at injection pressure 1300bar the premixed face of combustion is longer that in the other two cases. This explains the lower values of KL-factor. Increasing the injection pressure the atomization is better, the fuel drop size decreases, the evaporation rate increases, the mixing between air and diesel fuel is better and so the ignition delay is shorter [2]. Moreover, in figure 6 it can be seen that in all cases the sum of the KL-factor appears two peak values. Similar behavior has been observed in diesel engines using a single fiber pyrometer.

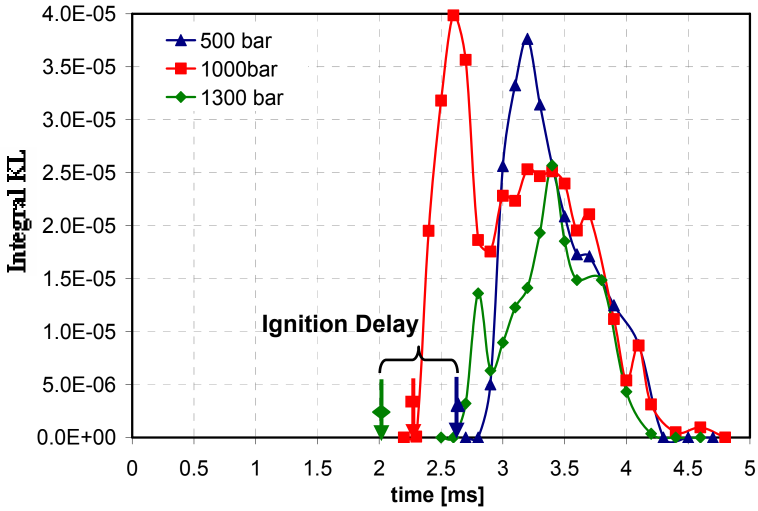

Figure 6: Development of the integral of the KL-factor through the flame cross section over time at cell temperature 790 K, cell pressure 40 bar, injection duration 3ms and at three different injection pressures: 500 bar, 1000 bar, 1300 bar

Figure 7 presents the soot temperature at the above conditions, as function of the time ASOI. It is observed higher soot temperature at higher injection pressure. Comparing the results for the ΣKL and the temperature at the same conditions, it is observed that at high temperatures (injection pressure 1300bar) the ΣKL has lower values than at the cases with low temperatures (injection pressure 500 and 1000bar).

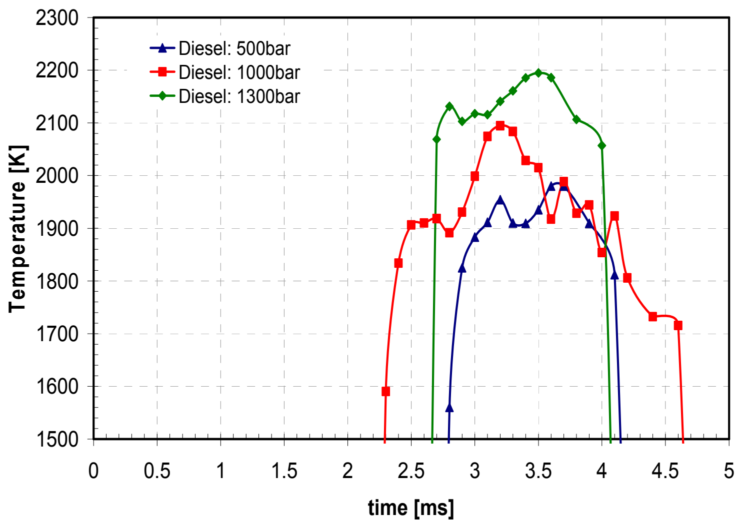

Figure 7: Temperature profile at cell temperature 790 K, cell pressure 40 bar, injection duration 3ms and at three different injection pressures: 500 bar, 1000 bar, 1300 bar

A comparison between the results of pyrometer and back diffusion laser technique is presented in figure 8. The integral value of the KL-factor, calculated by both techniques, is presented versus the time after start of injection, at cell temperature 790K, cell pressure 40 bar, injection duration 3ms and injection pressure 1300 bar. The comparison between the two techniques shows that the trend of the ΣKL evolution over time is similar. An interesting point is the high values of ΣKL evaluated by BDL technique compared to the one estimated by pyrometer. As was mentioned above, pyrometer is a technique based on the recording of the emitted light coming from the glowing soot ('hot' particulate matter) at high temperatures, while the BDL technique records both 'cold' and 'hot' soot.

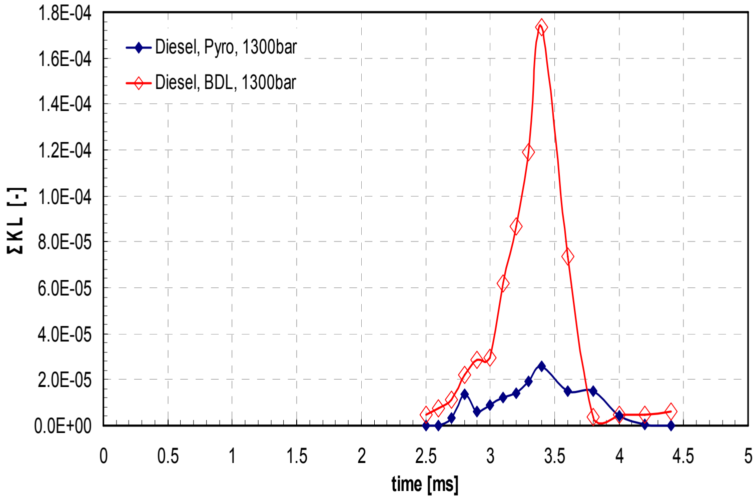

Figure 8: Comparison between pyrometer and BDL technique: the sum KL-factor through the flame cross section over time at cell temperature 790 K, cell pressure 40 bar, injection duration 3ms and injection pressures 1300 bar

Observing the raw images taken by BDL and pyrometer technique (figure 9), at the same conditions (cell temperature 790K, cell pressure 40 bar, injection pressure 1300 bar and injection time 3 ms), the BDL technique gives additional information (as it was mentioned before) than the pyrometer about the formation of the soot cloud, but it cannot give any information on the temperature. In figure 9 the first set of images show the mean BDL image (over 10 pictures) taken at 2.9 and 3.3ms after start of injection

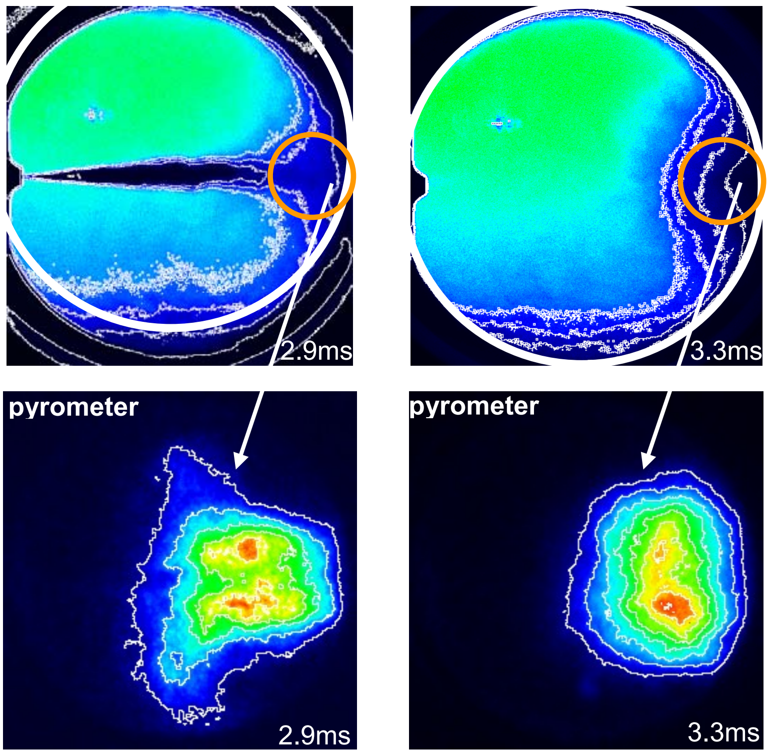

Figure 9: Comparison between pyrometer and BDL technique: Mean Raw images at 2.9 and 3.3ms after star of injection, at cell temperature 790 K, cell pressure 40 bar, injection duration 3ms and injection pressures 1300 bar. The scale between the BDL picture and pyrometer is different.

The second set presents the mean pyrometer pictures at the same timing. The pyrometer picture shows a zoom of the region of where the soot appears, as it is indicated in figure 9. In all pictures the contour of the light intensity is presented.

National Collaboration

We have an intensive and fruitful collaboration with the Reaction analysis Group (Dr. T. Dreier et.al.) of the Paul Scherrer Institute (PSI) on spray combustion research using both identical facilities (HTDZ) of the two institutions.

International Collaboration

Collaboration on “Spray data base” proposed by ETH and PSI in the frame of the IEA implementing agreement “Energy conservation and emissions reduction in combustion” on the occasion of the 2003 Task Leaders meeting.

Evaluation 2005 and Outlook 2006

Pyrometry is a technique that helps to understand soot formation and oxidation during combustion. Moreover, BDL technique is an important tool for wider investigation of the soot formation and oxidation evolution. It can be used as well as the shadowgraph technique, giving qualitative information for the liquid phase of the diesel spray. The difference between these two techniques is their sensitivity. Pyrometer is recording light that comes by the glowing, ‘hot’ soot particles while BDL technique records both ‘cold’ and ‘hot’ particulate matter. Therefore, the results of the comparison of these measurement methods show higher soot concentration by BDL instead of by pyrometer.

These two optical measurement techniques are going to be used for further investigation of the diesel combustion. More fuels, in form of blends Diesel-Butylal 25% and 50% in mass, as well as Water-Diesel emulsions of 13 and 25% in mass are planed to be used. Measurements of the ignition delay, applying the chemiluminescence technique [7] at different wavelengths recording OH, CH species will be taken at the Rapid Compression Machine (RCM). Moreover, a new high speed camera is going to be used for pyrometer measurements. In this case a sequence of injection, ignition and further combustion will be recorded simultaneously, showing the complete phenomenon of one cycle.

Publications based on the material of this year are prepared and it is expected to be available in 2006.

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