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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 Einführung der Common-Rail Einspritztechnologie erweiterte die Möglichkeiten der Einflussnahme auf die Wärmefreisetzungsrate dramatisch. Innermotorische Massnahmen, welche im direkten Zusammenhang mit der Einspritzung stehen, sind die Optimierung des Einspritzdrucks, des Einspritzzeitpunktes, des Einspritzprofils sowie sind durch die Common-Rail-Technologie Mehrfacheinspritzungen möglich. Speziell zu erwähnen ist die Entkopplung der Drehzahl vom Einspritzdruck. In Bezug auf Emissionen sind weitere Massnahmen im Luftpfad zu nennen wie die Abgasrückführung und Ladeluftkühlung sowie eine Optimierung der Kraftstoffzusammensetzung. Es ist ein Trend absehbar, die Vorteile der Diffusionsvebrennung mit denen der Vormischverbrennung zu kombinieren und gleichzeitig die Nachteile der beiden Brennverfahren möglichst zu vermeiden.

Ein dominantes Problem bei der Diffusionsverbrennung stellt der NOx-Russ trade-off dar. Der NOx Ausstoss kann durch eine Senkung der Prozesstemperaturen vermindert werden. Für die Oxidierung von Russ sind jedoch hohe Temperaturen vorteilhaft. Die Kraftstoffkonzentration ist für die Bildung von Russ von entscheidender Bedeutung. In der Folge sind spezifische, durchgeführte und geplante Experimente dargestellt, um die Komplexität des Dieselverbrennungsprozesses besser zu verstehen.

Neben optischen, qualitativen und quantitativen Messungen für die Charakterisierung der Dieselverbrennung sind die Bestimmung von Zündverzug, Zündort, der Flammtemperatur und Russkonzentration von entscheidender Bedeutung. Im Berichtsjahr 2004 wurden Messungen mit der Schlierenmesstechnik [6], die Aufnahme der Mie-Streuung sowie die passive Aufnahme der Chemilumineszenz an der Hochdruck-Hochtemperatur Zelle der ETH Zürich erfolgreich durchgeführt. In [2, 3, 4] sind durchgeführte Arbeiten für die Russbestimmung genannt. Mittels der Pyrometrietechnik [3] konnte die Flammtemperatur sowie der KL-Faktror bestimmt werden. Diese Technik soll um die Möglichkeit einer Kalibration erweitert werden um die genaue Bestimmung der Temperatur und des KL-Faktors zu ermöglichen. Dazu sind experimentelle Arbeiten an der Hochdruck-Hochtemperatur Zelle sowie am Einhubtriebwerk mit Dieselemulsionen, sauerstoffhaltigen sowie synthetischen Kraftstoffen geplant.

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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).

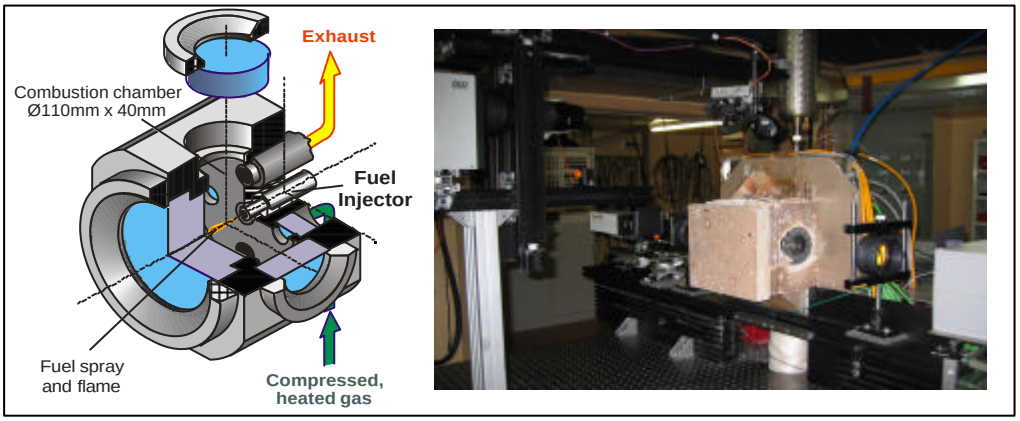


Figure 1: High temperature-high pressure cell

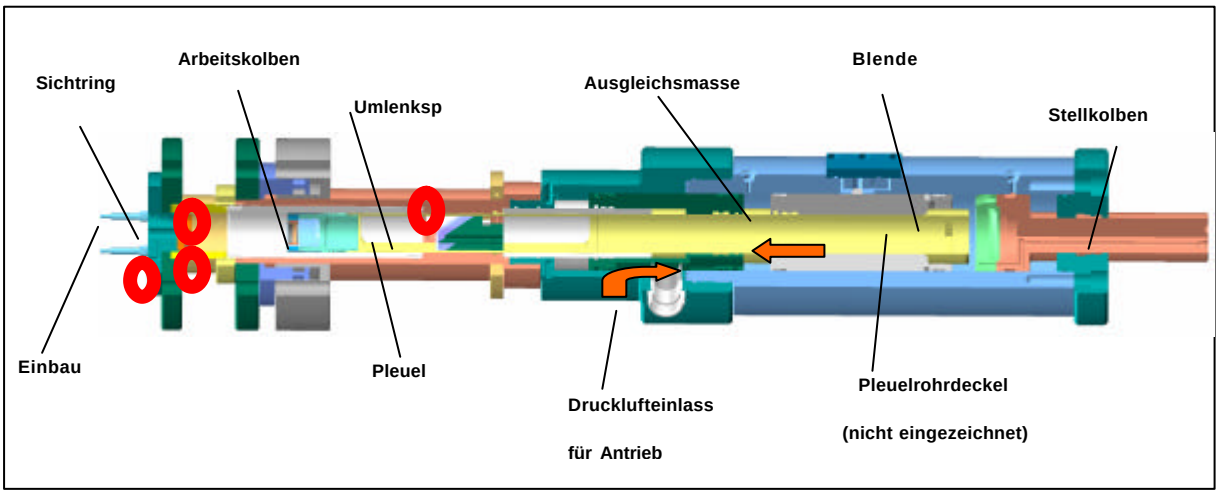


Figure 2: Rapid compression machine

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 advantage 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

By using the schlieren and the chemiluminescence technique the ignition delay and its location were defined. The pyrometer was the other equipment used to determine the soot concentration and the flame temperature.

Schlieren Technique

Schlieren technique is a backlight optical visualization technique. It is based on the optical density gradient caused by disturbances and inhomogenities of transparent media e.g. by temperature gradients or concentration changes. There are relatively small refractive indexes differences within the overall background and by definition they bend light rays in any direction other than the “normal” direction. For the Schjieren technique the light of a point light source is collimated by a lens. A second lens refocuses the beam to an image of the point source. Between the lenses the objective of interest is placed. The beam proceeds to a viewing screen where an inverted image of the test area is formed. In the focal point of the second lens a Knife-edge is placed to image the transparent Schlieren objects. Instead of a screen, a camera, can be placed behind the knife-edge to record the image [6].

Experimental set-up

The light source used to obtain the images was a Xenon lamp masked by a pinhole. A 12 bit CCD camera (PCO) is used for Schlieren images. It has a resolution of 1280x1024 pixels. The exposure time of 700ns was efficient in order to get sharp images of the fast injection process. The picture was projected on the CCD camera by a NIKKOR objective of 35mm through a round knife-edge of 0.3mm.

Chemilumunescence

In order to characterize properly the ignition start and the location, Chemiluminescence technique is used in parallel with Schlieren.

By using this technique, it is possible to detect OH and CH radicals with interference filters. Chemiluminescence is a photon-emission phenomenon that appears throughout the diesel combustion process. It rises from certain energetic chemical reactions that lead directly to the formation of atoms or molecules in an electrically excited state. Such radicals then may decay back to equilibrium energy levels by emission of photons. In hydrocarbon spray combustion systems the species contributing more prominently to the observed visible and ultraviolet chemiluminescence are CH and OH radicals. The CH and OH bands are centered at a wavelength 432nm and 510nm respectively. Using this technique, the ignition delay and its spatial location can be evaluated. Some preliminary tests without using any interference filter were carried out.

Experimental set-up

In order to accomplish simultaneous imaging of chemiluminascence and Schlieren, two cameras are used, with orthogonal lines of sight through two different cell windows. The two pictures are taken on different axis (90^0 of difference) to avoid the adoption of the beam splitter. Due to the low intensity of the chemilumunescence, a ICCD camera with a UV-objective NIKKOR 105mm are used to acquire the images. The exposure time of the camera was 7.0µs. The Schlieren experimental layout remains the same as before. For both techniques the time delay is the same and controlled by the control system of the HTDZ.

Results

Several sequences have been taken for Schlieren and Chemiluminescence. In all cases the images represent a map shot of the spray. In figure 3 an example of the measurements previously obtained is presented. The images from both techniques are merged. Captions at the right bottom of each image

represent the time after the start of injection. The initial conditions of the combustion process are listed in the table1:

Fuel	Gas	D_{nozzle}	L_{nozzle}	T_{cell}	P_{cell}	P_{inj}	T_{inj}
Diesel	Air	0.150mm	0.60mm	750K	40bar	500bar	1.9ms

Table1: initial conditions of the combustion process

According to the chemiluninescence images the combustion process starts around 3.1ms after the start of injection (Figure 3b). It evolves for 1.4 to 1.5ms and then the intensity of the light starts to reduce. It is notable that while the intensity of the light reduces a second flame side appears close to the tip of the nozzle at 4.5ms (Figure 3f). Evaluating the combustion process, taking into account both flame sides, it can be found that it lasts for 4.9ms (Figure 3s). It has to be mentioned that for the measurements none filter was used. This means that the emitted light also contains the soot spectrum. For this reason, to identify the ignition location it is necessary to capture the OH-radicals emissions only. A way to achieve this is the use of OH-filters and the emitted light as external trigger for the camera.

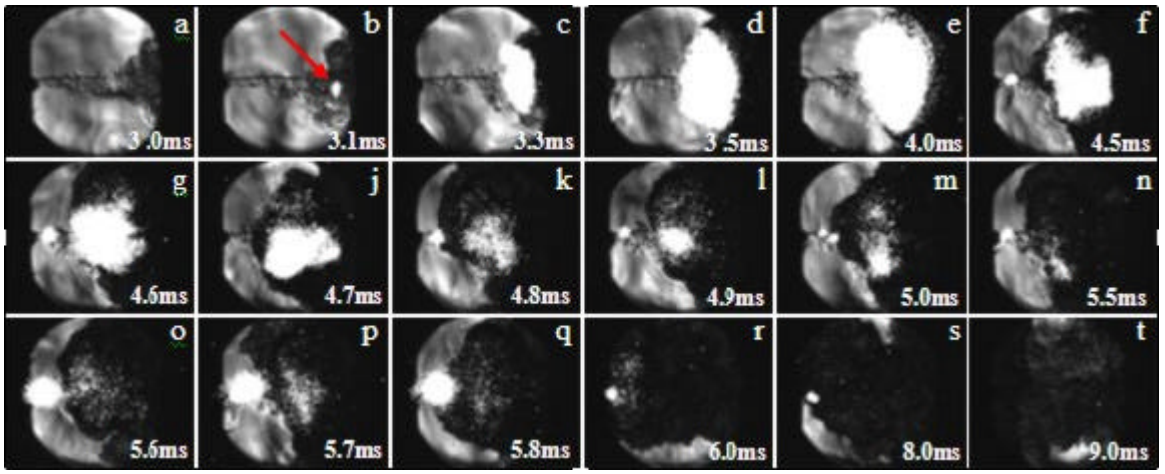


Figure 3: Injection and combustion sequence, using Schlieren and Chemiluminescence technique for T_{cell}=750K, p_{cell}=40bar, p_{inj}=500bar, t_{inj}=1.9ms

Soot Formation and Oxidation Fundamentals

Soot is a solid which consists from particles with diameter in region of nanometers. It arises from the gaseous phase of the flame. We distinguish a soot-formation stage (in which soot is formed by pyrolysis or polymerization reactions) and a soot reduction stage (in this is soot reduced or oxidized respectively). The amount of soot included in the combustion process and which will leave it finally, is controlled by the trade-off between these two mechanisms.

Soot Formation

The soot particles form primarily from the carbon in diesel fuel. Soot formation takes place in the diesel combustion environment at temperatures between about 1000 and 2800K, at pressures of 50 to 100atm and with sufficient air overall to burn fully all the fuel. The time available for the formation of solid soot particles from a fraction of the fuel is in the order of milliseconds. The resulting aerosol – dispersed solid-phase particles in a gas – can be characterized by the total amount of condensed phase (often expressed as soot volume fraction F_v – ratio of the soot volume/total volume), the number of soot particles per unit volume (N), and the size of particles (average diameter).

Soot formation rate is strongly dependent on the molecular structure of combusted fuel. In general, with rising diameter of the hydrocarbons increases the affinity to form soot as well.

The structure of molecules is also of importance – the more multiple bonds and more complex arborization occur in a hydrocarbon molecule, the more it will tend to form soot.

The soot formation mainly depends on:

- temperature and pressure
- oxygen content in the flame
- fuel properties

The two basic mechanisms for soot formation suggested in literatures are pyrolysis and pyrosynthesis. The exact route from very small hydrocarbon molecules to larger soot particles is uncertain but it can be considered in four steps (Figure 3):

1. Formation of precursor species
2. Particle inception
3. Surface growth and particle agglomeration
4. Particle oxidation

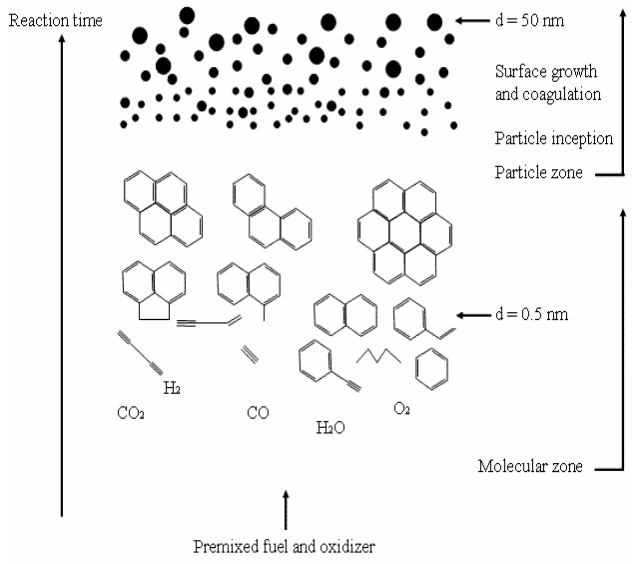


Figure 4: Schematic reaction path leading to soot formation [5]

Soot Oxidation

In the overall soot formation process, oxidation of soot at the precursor, nuclei and particle stages can occur (oxidation takes place parallel to the formation). In fact, a large fraction of the soot formed is oxidized within the cylinder before the exhaust process commences.

The rate of soot oxidation depends on the diffusion of reactants to products as well as the kinetics of the reaction. For particles smaller 1µm in diameter is the diffusion resistance minimal. Therefore, since particles sizes are smaller then this limit, the soot oxidation process in the diesel cylinder is controlled kinetically. There are many species in or near the flame that could oxidize soot – examples are: O_2, O, OH, CO_2 and H_2O.

It is quite difficult to follow the oxidation of soot aerosols in flames. Therefore at high oxygen partial pressures, soot oxidation can be correlated with pyrographite oxidation. Hereby we also assume, that the rates of oxidation of soot and of pyrographite are the same. However, this is a significant simplification of the real process. [1]

The reaction between the oxidant from the gas phase and the solid soot is mainly controlled by these processes:

- Diffusive mass transfer of the gaseous reactants from the environment to the surface of the soot
- Adsorption of the reactants onto the surface
- Reaction at the surface and formation of adsorbed products

- Products desorption
- Diffusive mass transfer of the gaseous products from the solid-surface

Theory of the Two-color Pyrometry

Flame temperature measurement

During diesel combustion, both solid soot particles and gaseous combustion products are present. However, diesel combustion is dominated by the intense radiation from the soot particles. Since the two-color method utilizes the thermal radiation from soot particles, it directly measures their temperature. The temperature of the combustion gases is not directly measured. However, the temperature difference between the two temperatures is negligible (< 1 K) when the ambient gas and soot particles have attained thermal equilibrium.

From the above discussion, it may be assumed that the soot particle and combustion gas temperatures are approximately the same [2].

Principle of two-color temperature measurement

In general, two-color pyrometry is an optical passive non-invasive method for evaluation of the temperature and soot-distribution in a flame. In the two-color method, the thermal radiation at two different wavelengths is detected and the flame temperature is then determined from their ratio by eliminating an unknown factor [3].

The intensity of radiation from a black body varies with wavelength and it also depends on the temperature of the black body. This is described mathematically by Planck's equation

$$I_l(T) = e \cdot I_{b,l}(T) = e \cdot \frac{C_1}{l^5\left(e^{(C_2/lT)} - 1\right)}$$

or rewritten for black body: $I_{b,a}(T) = \frac{C_1}{l^5\left[e^{(C_2/lT)} - 1\right]}$ (1)

where C_1 = the first Planck's constant = 3,7418 $\times$ 10^{-16} Wm^2;

C_2 = the second Planck's constant = 1,4388 $\times$ 10^{-2} m K.

The monochromatic emissivity of a non-black body is defined as

$$e_l = \frac{I_l(T)}{I_{b,l}(T)} \quad (2)$$

where $I_?(T)$ and $I_{b,?}(T)$ are the monochromatic emissive power of a non-black body and a black body respectively, at the same temperature T and wavelength ?. In other means, $e_?$ is the fraction of the black body radiation emitted by a surface at wavelength ?.

Temperature evaluation (Absolute method)

In the two-color method, an apparent temperature T_a is introduced and defined as the temperature of a black body which will emit the same radiation intensity as a non-black body at temperature T. From this definition of T_a it follows:

$$I_{b.l}(T_a) = I_l(T)$$

Combining the definition for monochromatic emissivity $e_?$ with the definition of apparent temperature T_a gives:

$$e_l = \frac{I_{b,l}(T_a)}{I_{b,l}(T)} \quad (3)$$

When combined this equation with Planck's law we obtain

$$e_\lambda = \frac{e^{C_2/\lambda T} - 1}{e^{C_2/\lambda T_a} - 1} \tag{4}$$

For practical application was e_λ estimated for soot particles by an empirical relation of *Hottel and Broughton*:

$$e_\lambda = 1 - e^{\left(-KL/\lambda^a\right)} \tag{5}$$

where K = an absorption coefficient = proportional to the number density of soot particles

L = the geometric thickness of the flame along the optical axis of the detection system.

The value of the parameter a depends on the physical and optical properties of the soot in the flame.

Combining equations (4) and (5) we obtain relation for the KL-Parameter:

$$KL = -\lambda^a \ln\left[1 - \left(\frac{e^{(C_2/\lambda T)} - 1}{e^{(C_2/\lambda T_a)} - 1}\right)\right] \tag{6}$$

Remark

In this empirical relation is the wavelength ? to be taken in µm. When this value (obtained for ? in micrometers) is to be compared with KL-values obtained by using SI-units (in m), it is necessary to multiply it by a factor $4{,}57 \times 10^{-9}$ [4].

If the product KL is taken to be independent of wavelength, it can be rewritten to following form using two specific wavelengths $?_1$ and $?_2$

$$\left[1 - \left(\frac{e^{(C_2/\lambda_1 T)} - 1}{e^{(C_2/\lambda_1 T_{a1})} - 1}\right)\right]^{\lambda_1^{a1}} = \left[1 - \left(\frac{e^{(C_2/\lambda_2 T)} - 1}{e^{(C_2/\lambda_1 T_{a2})} - 1}\right)\right]^{\lambda_2^{a2}} \tag{7}$$

The actual flame temperature T is independent of wavelength, whilst the apparent temperature T_a and (possibly) the parameter *a* vary with wavelength.

Based on the work of Kunte [4], we assume, that the parameter *a* is independent from the wavelength and takes value of 1.39.

$$a_1 = a_2 = 1.39$$

The equation (7) can be solved for the flame temperature T, provided the apparent temperature T_{a1} and T_{a2} for the flame are known at the two wavelengths $?_1$ and $?_2$. These two apparent flame temperatures can be evaluated by a two-color optical pyrometer system. Selecting the wavelengths $?_1$, $?_2$ it is important to take care of "hitting" a strong band-emissions from gaseous species.

KL-factor and Soot Concentration

Once the value of the flame temperature T, has been estimated from Eq. (7), substituting T back into Eq. (6) gives an estimate for the value of the product KL which is proportional to the soot concentration.

It is most common to obtain an estimation of the flame temperature, T and the KL factor from the two-color method. However, if some assumptions are made an estimate of the volumetric density of soot, C_v (the volume of particles in a unit of space), and soot gravimetric density, C_m (mass of soot per unit volume), can be obtained.

$$C_v = \frac{1}{6p\ L\ Im\left(\frac{m^2-1}{m^2+2}\right)} \cdot \frac{KL}{l^a}$$

where *m* is the complex refractive index of the soot particle.

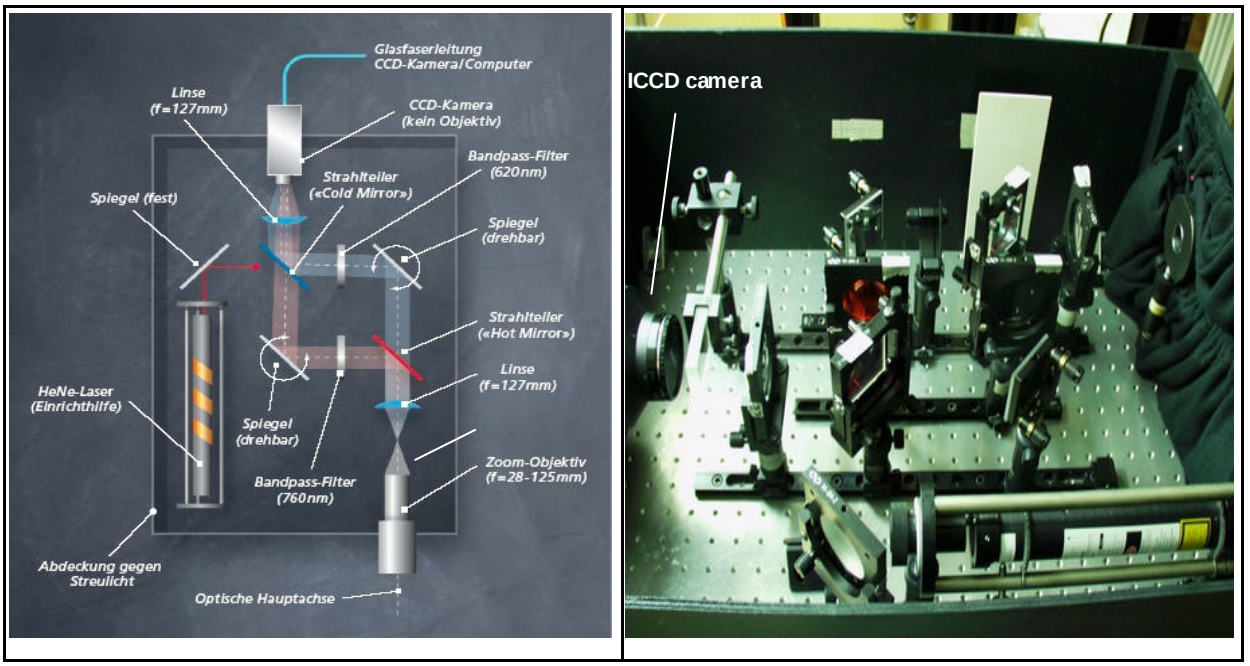
Thus, using the estimate of the KL factor it is possible to obtain an estimate of the volumetric density of soot particles.

Experiment

Measurements were done on a High-temperature high-pressure cell (HTDZ) with constant volume, which allows variation of combustion parameters in a broad region. All the measurements were performed under the following conditions and using precombustion to reach the diesel engine conditions:

Temperature T	900 K
Pressure in the cell	40 bar
Injection pressure	500 bar
$t_{inj,pilot}$	28,5 ms
$t_{inj,main}$	2,8 ms
?t (delay between 2 injections)	1 s
Used fuel	Diesel

Each set of measurements at various timings after start of injection (SOI) contained 16 images. Before going to the results it is important to present the set-up of pyrometer adapted to the high temperature high pressure cell. The following figure (Figure 5) shows the pyrometer's provision:



(a) (a)

Figure 5:(a) Schematic presentation of pyrometer, (b) picture of pyrometer set-up

Evaluated Temperature and KL factor

Evaluation of the temperature distribution and KL-factor was performed according to the scheme (Figure 6):

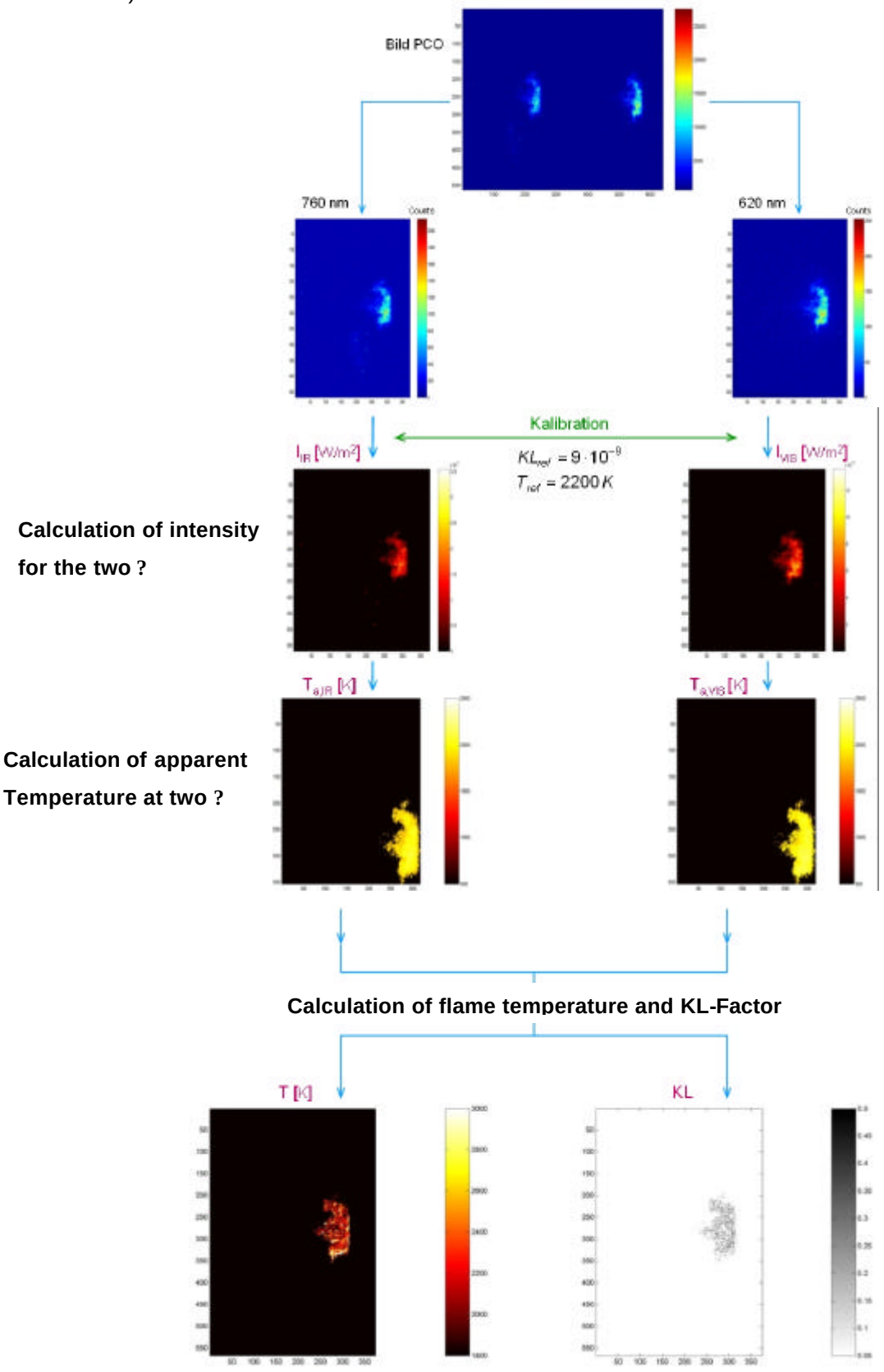


Figure 6: Procedure scheme for temperature and KL factor evaluation using the pyrometer technique

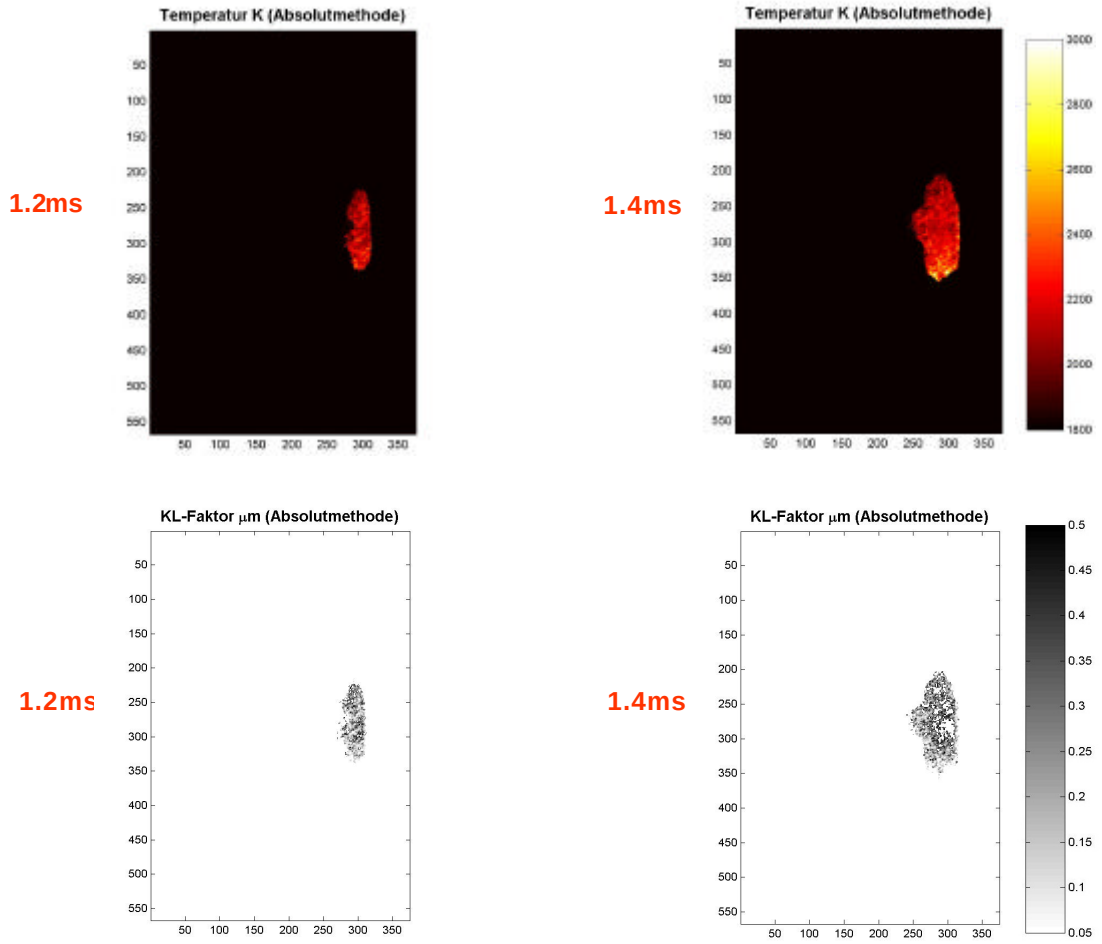
The main step is the calibration and the specification of the scaling factor $K(l_1, l_2)$ for detected voltage (number of Counts) U_1 and U_2 of the ICCD-Camera. This factor correlates desired intensity with the number of Counts.

In our case, the scaling factor was determined for the specific wavelength from the reference values for KL and temperature. This reference values were taken from a measurement a real diesel engine.

$$T_{ref} = 2200\ K$$
$$KL_{ref} = 9 \cdot 10^{-9}$$
$$K(l) = \frac{I(l)}{U(l)}$$

The value of detected voltage (=number of Counts) $U(l)$ was evaluated as the mean value of an area of pixels. It was chosen as the area of pixels with representative value of Counts for specific image. This image has been chosen from all the sets as the image with maximum mean intensity. By the selection of the representative area it is necessary to choose area, where the "peak" values are not included. The "reference" intensity $I(l)$ was determined inserting the reference values of temperature and KL-factor into the equations (1), (4) and (6).

There were taken images from start of main injection until 4.6 ms after SOI. At each timing was taken a set of 16 images. From these sets were chosen for post processing specific shots, which at best represent the entire series of images. Following results were evaluated from mean images of the set at each timing (Figure 7).



(a)

Figure 7(b): Flame temperature and KL-factor at 1.2ms and 1.4ms after the start of injection, measured with the two-color pyrometer. The initial parameters of these measurements were: T_{cell}=900K, p_{cell}=40bar, p_{inj}=500bar, t_{inj}=2.8ms (with a pilot injection)

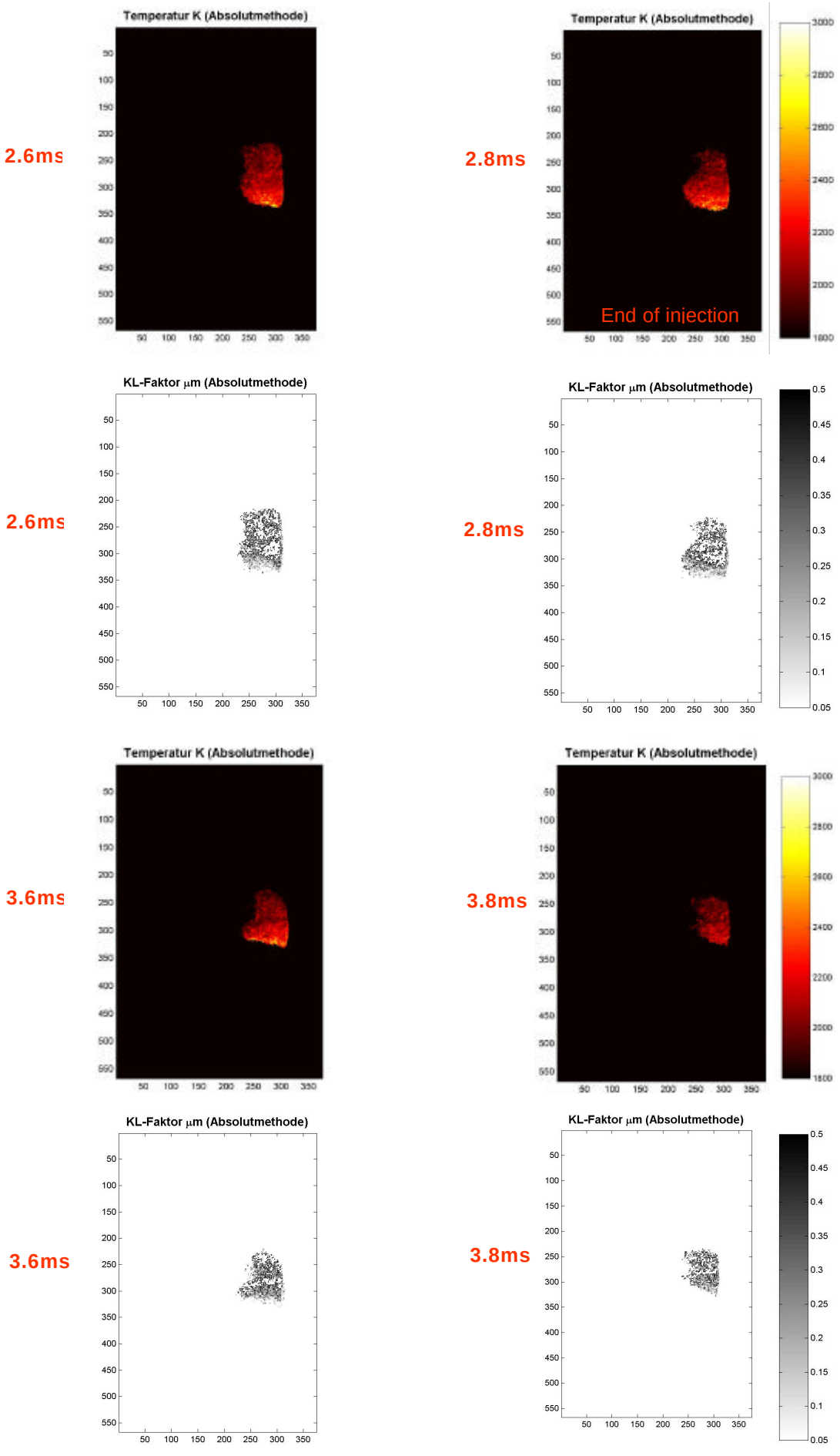


Figure 7(b): Flame temperature and KL-factor at 2.6ms, 2.8ms, 3.6ms and 3.8ms after the start of injection, measured with the two-color pyrometer. The initial parameters of these measurements were: T_{cell}=900K, p_{cell}=40bar, p_{inj}=500bar, t_{inj}=2.8ms (with a pilot injection)

National Collaboration

We have an intense and fruitful collaboration with the Reaction analysis Group 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 2004 and Outlook 2005

The Schlieren method (its principle is based on the changes of the refraction index due to the density variation) achieves satisfying pictures, providing more information than the shadowgraph technique. Using the Schlieren technique it is identifiable that the fuel starts to evaporate at the tip of the spray and then along its periphery. The cause of this phenomenon is the turbulent flow. The liquid, the vapor and the ignition location are well defined in the images. The Chemiluminescence method is suitable method to detect the beginning and the location of the combustion process. Till now this technique was applied without any filter, therefore detecting all the light from combustion. For this reason an improvement to these techniques is necessary. By using the OH-filters it will be possible to define precisely the ignition delay and its location.

Pyrometry is a technique that helps to understand soot formation and oxidation during combustion. This technique is a non-invasive routine and uses a multi-color sensor probe. It also relies on the measurement of the intensity of the light on two wavelengths. A further improve of this technique is required. To be more specific, a calibration system is important to be used to get the precise values of flame temperature and KL factor that corresponds to the soot volume fraction. Moreover, the extinction method is an important tool that will help to “calibrate” the KL factor to soot volume concentration. However, a new high speed camera is going to be used. In this case a sequence of injection, ignition and further combustion will be recorded simultaneously, showing all the phenomenon in one cycle.

As was mentioned before, the above measurements techniques are going to be applied not only on the high temperature-high pressure cell, but on the rapid compression machine (RCM) for different fuels (diesel emulsions, oxygenized fuels, synthetic fuels).

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