Verification and Application of Fuel-Air-Ratio-LIF

Jochen Scholz¹, Markus Röhl², Tim Wiersbinski¹, Volker Beushausen¹

¹: Laser-Laboratorium Goettingen e.V., Goettingen, Germany, Jochen.Scholz@llg.gwdg.de
²: now: Institut fuer Antriebstechnik, DLR, Berlin, Germany, Markus.Roehl@dlr.de

Abstract These investigations aim to validate the applicability of a concept for fuel-air-ratio measurements by laser-induced fluorescence (FARLIF) at elevated temperatures. For the commonly used model fuel isooctane with the fluorescence tracer toluene the FARLIF applicability was confirmed with an excitation wavelength of 266 nm for fuel-air mixtures with \( \lambda \geq 0.2 \) at pressures above 1.5 bar and temperatures at least up to 433 K.

The FARLIF-concept with 266 nm excitation was validated as well for a multi component fuel (near-standard gasoline) at \( \lambda \geq 0.1 \), pressures above 1 bar and temperatures at least up to 500 K. To the authors’ knowledge this is the first time that FARLIF could be validated for an auto-fluorescent multi-component fuel without any additional tracer.

For both fuels, the mixture temperature affects the FARLIF-intensities. Therefore, isothermal conditions are best suited for FARLIF-investigations; otherwise the temperature has to be known for signal correction.

The application of planar FARLIF-imaging is successfully demonstrated for both considered fuels. In both cases signal strengths were sufficient for quantitative single-shot fuel-air-ratio measurements in transient mixing flows under engine relevant conditions. For long excitation light paths through high fuel densities, absorption shows to affect the measurement and FARLIF-images need to be corrected. Finally, first results of double-pulse FARLIF-imaging are presented, giving insight into dynamic mixture processes. In general, the FARLIF-concept shows to be a powerful tool with multifunctional applications if used in its valid constraints and – if necessary – with appropriate corrections.

1. Introduction

Controlled and well defined mixing of gases is essential in many technical applications. In particular, the formation of ignitable hydrocarbon-air mixtures for energy generation in power plants, turbines, burners or internal combustion engines is a central point of interest for process- and industrial engineering. The performance (e.g. emission and fuel economy) of new engine concepts like spark-ignition direct-injection (SIDI) engines or homogeneous-charge-compression-ignition (HCCI) engines depends strongly on the mixture preparation and the in-cylinder fuel-air-ratio-distribution. However, new engine concepts are strongly needed to face limited fossil oil supply, rising demand and continuously increasing fuel prices. Furthermore, progressive environmental degradation results in more and more restrictive emission constraints. Therefore, many optical diagnostic techniques have been developed during the past decades with the aim to get a better understanding of the processes governing the mixture formation.

In 1994, Reboux et al. (1994) introduced a diagnostic technique to measure the fuel-air-ratio by laser-induced fluorescence (FARLIF). They used toluene as a fluorescence tracer in the model-fuel isooctane and took advantage of the strong fluorescence-quenching of oxygen. They could show that the fluorescence intensity grew linearly with the fuel-air-ratio and the intensity was pressure-independent for a fixed fuel-air-ratio at higher pressures (see section 2. FARLIF-concept). These experiments of Reboux et al. were conducted at ambient temperature and with an excitation wavelength of 248 nm. In the following, many research groups have used this technique even at elevated temperatures without testing its applicability under these conditions. Latest results of Koban et al. (2005a and 2005b) question the applicability of the FARLIF-concept at higher temperatures, but they give no temperature-limit at which the concept will fail. New measurements of Frat et al. (2004) show that for temperatures in the range of 423 K to 523 K, pressures between
0.5 and 10 bar and fuel-air-ratios between 0.2 and 2 the pressure-independency of the signal fails for 248 nm excitation of toluene-isooctane-air mixtures. The results of Schulz and Sick (2005) show, that the situation for FARLIF should be better at longer excitation wavelengths (e.g. 266 nm) but the concept should fail at elevated temperatures as well. Unfortunately they give no temperature limit either. Finally, Koch (2005) (one of the co-authors of Koban et al. (2005 a+b)) concludes from Stern-Volmer-investigations of temporal integrated toluene signals at ambient pressure that the FARLIF-concept should hold up to 500 K with this longer excitation wavelength at 266 nm. Unfortunately, he did not proof the concept directly in terms of proofing the pressure-independence or the linearity of FARLIF-signal vs. equivalence ratio. For clarification and to find the parameter range where this promising FARLIF-concept is applicable, a direct verification was necessary.

In this paper, the applicability of FARLIF with the tracer toluene in isooctane as a common used model-fuel is investigated at pressures up to 10 bar and temperatures up to 433 K with the “long wavelength” excitation at 266 nm. Following preliminary tests of the fundamental requirements, the FARLIF concept is checked directly.

After promising results, the focus was set on FARLIF-applications without any tracer – with more realistic self fluorescing fuels. Model fuels like isooctane have the disadvantage of different volatility compared to standard gasoline consisting of many hydrocarbon components with different volatilities. This means, that the mixture formation may differ. Furthermore the combustion behavior is different. So, for many applications in combustion engine development there is a demand for measurement techniques working with fuels as close to the standard as possible. Preliminary experiments show that a barely modified standard gasoline is a good candidate. Therefore, the FARLIF-concepts applicability is investigated for this almost standard fuel. Finally applications of planar FARLIF-imaging in transient mixing flows are demonstrated.

2. The FARLIF-concept

Reboux et al. (1994) proposed a measurement concept to determine the fuel-air-ratio by laser-induced fluorescence which is called FARLIF-concept in the following and is briefly explained here. In the case of linear LIF (weak excitation) the fluorescence intensity $I_f$ is given by

$$ I_f \propto E_{\text{Las}} \sigma_{\text{abs}} n_{\text{fl}} q_f $$

(1)

where $E_{\text{Las}}$ denotes the laser energy, $\sigma_{\text{abs}}$ the absorption coefficient, $n_{\text{fl}}$ the number-density of the fluorophor and $q_f$ the fluorescence quantum yield. This is dependent on the coefficient for spontaneous emission $k_{\text{rad}}$, the assembled coefficient for all intramolecular deactivation processes $k_f$ and quenching, i.e. the sum of the number-densities $n_q$ with related collisional quenching coefficient $k_q$ of collision-partner $q$ according to

$$ q_f = \frac{k_{\text{rad}}}{k_f + \sum q k_q n_q} .$$

(2)

A main issue in the FARLIF concept is that oxygen-quenching is the dominant deactivation process for the excited states. From equations 1 and 2 follows with oxygen as the dominant collision partner

$$ I_f \propto \frac{k_{\text{rad}} n_{\text{fl}}}{k_f + k_{qO_2} n_{O_2}} .$$

(3)

If the oxygen-quenching dominates the intramolecular deactivations, i.e. if $k_f<<k_{qO_2} n_{O_2}$, these deactivations $k_f$ may be neglected and the intensity gets proportional to the ratio of fluorophor and oxygen:

$$ I_f \propto \frac{k_{\text{rad}} n_{\text{fl}}}{k_{qO_2} n_{O_2}} .$$

(4)

This means, with rising pressure and therefore rising $(k_{qO_2} n_{O_2})$ the fluorescence intensity of a fixed
mixture of fluorophor and air gets pressure independent and the reached plateau-intensity is proportional to the mixture ratio \( n_{\text{flu}}/n_{\text{O}_2} \). This mixture ratio again is proportional to the equivalence ratio \( \phi = 1/\lambda \) where the \( \lambda \)-value denotes the stoichiometric air-fuel-ratio (for stoichiometric mixtures \( \lambda = 1 \), ignitable mixtures have \( 0.5 < \lambda < 1.3 \)). However, the FARLIF-signal gets pressure-independent and proportional to the equivalence ratio, i.e. inverse proportional to the \( \lambda \)-value.

3. Experimental setup and preliminary investigations

In the run-up to direct examination of the FARLIF applicability some preliminary investigations were necessary to survey the fundamental assumptions for FARLIF. A heatable pressure chamber was used to provide well controlled gas conditions from ambient temperature up to 433 K with pressures between 1 mbar and 10 bar. Pure toluene, 5% respectively 10% toluene in isooctane and their mixtures with nitrogen, oxygen and synthetic air (20% \( \text{O}_2 \), 80% \( \text{N}_2 \)) were used as test gases for the preliminary investigations. The test gases were homogeneously premixed in a heated pressure tank with a volume of approximately 3.5 l.

Two general types of experiments were conducted: a) one-dimensional time-resolved fluorescence measurements in order to get additional information about the quenching situation via fluorescence-lifetimes and b) 2d planar LIF (PLIF) in the face of the planned application. The optical setup for both is sketched in figure 1. The beam of a frequency quadrupled Nd:YAG laser (Continuum Surelite SL1-10, 266nm) is directed through the quartz-windows of the test chamber. A calibrated power meter can be inserted to measure the laser energy. In the case of PLIF measurements a light-sheet optic (a combination of cylindrical lenses) is used. At the entrance and the exit of the test chamber 6% of the laser light is led separately to an energy monitor consisting of a fluorescence screen and a CCD-camera for PLIF or two fast photodiodes in the case of time resolved measurements. This measurement of the relative energy at the entrance and exit of the test section (which can be calibrated by the power meter) is used to correct the fluorescence signals for pulse-to-pulse fluctuation of laser energy and to measure the absorption in the test chamber. The measured absorption is used to verify the correct toluene concentration of the test gas and - if

Fig 1 Optical setup for fluorescence and absorption measurements.
required – to correct fluorescence signals in terms of excitation depletion due to absorption. The laser-induced fluorescence originating from inside the chamber is detected perpendicular to the excitation using an UV objective and spectral filters for excitation-wavelength elimination (Schott WG 280 or Melles Griot 277AELP). In the case of time-resolved measurements a fast photomultiplier module (Hamamatsu H6780-04) was used as a detector and the signal was stored by a fast (2 GS) digital oscilloscope. The mono-exponential fluorescence decay was fitted to identify the fluorescence lifetime and the time-integral fluorescence intensity \( I_f \) was computed. In the case of PLIF an intensified CCD-camera (Imager 3 combined with IRO, LaVision) captured the fluorescence signal. Here, the fluorescence intensity \( I_f \) was calculated as the average of the homogenous fluorescence area excited by the light-sheet. For all preliminary investigations, signals have been averaged over 20 to 100 single measurements.

The first precondition for FARLIF is linearity of the LIF-signal with excitation energy (linear LIF). The left side of Figure 2 shows this experimental validated linearity at a temperature of 398 K in a wide range beyond the later used energy interval of 0.1 to 4 mJ/pulse. Also experiments at different temperatures and different gas compositions showed linear behavior. So, linear LIF is confirmed for the examined experimental conditions.

In order to conduct experiments under static gas conditions, thermal and photochemical stability of the tracer is necessary. For verification, a mixture of 12.5 mbar toluene, 50 mbar synthetic air and 940 mbar nitrogen was filled into the test chamber at a temperature of 398 K. The homogeneous mixture was irradiated by the laser light with 10 Hz repetition rate and 0.3 mJ pulse energy for 30 minutes. At different times during this period, the fluorescence intensity was measured. The result - normalized to the first measurement – is depicted in figure 2 on the right. The constant intensity level shows thermal and photochemical stability under these conditions.

One main precondition for FARLIF is the dominance of oxygen as collisional quencher. The quenching coefficients \( k_q \) for different collision partners were measured using Stern-Volmer-plots of the fluorescence intensity and Stern-Volmer-plots of the fluorescence lifetimes at different partial-pressures and mixtures of toluene and the collision partners oxygen, toluene itself (self-

<table>
<thead>
<tr>
<th>Collision partner</th>
<th>( k_q \times 10^{-18} \text{ m}^3/\text{s} )</th>
<th>( (k_q n_q)/(k_q n_{o2} n_{o2}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>242</td>
<td>1</td>
</tr>
<tr>
<td>Toluene self-quen.</td>
<td>16</td>
<td>2.6 \times 10^{-4}</td>
</tr>
<tr>
<td>Isooctane</td>
<td>8.5</td>
<td>2.8 \times 10^{-3}</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.73</td>
<td>1.2 \times 10^{-2}</td>
</tr>
<tr>
<td>( N_2 ) in presence of ( O_2 )</td>
<td>0.25</td>
<td>4.1 \times 10^{-3}</td>
</tr>
</tbody>
</table>

**Table 1** Quenching coefficients \( k_q \) and relative quenching strength for a stoichiometric mixture of 5% toluene in isooctane at 398 K. The dominance of oxygen-quenching is obvious.
quenching), isooctane and nitrogen. The results for a temperature of $T = 398 \text{ K}$ are listed in Table 1. To compare the quenching influence of the different collision partners at a standard mixture of 5% toluene in isooctane at a stoichiometric mixture ($\lambda = 1$) with synthetic air, the corresponding relative quenching influences $(k_{\text{q}n_2})/(k_{\text{qO}_2n_{O_2}})$ in relation to oxygen-quenching are also listed in table 1. In these investigations the unexpected but reproducible effect occurred, that nitrogen shows a weaker quenching in the presence of oxygen (see bottom of table 1). This is not yet understood and will be examined in further investigations. However, oxygen has obviously the strongest quenching coefficient and the most dominant quenching influence at relevant gas conditions. This means, also the most important requirement for FARLIF is fulfilled.

4. Direct verification of FARLIF with toluene

After these preliminary investigations the direct verification of the FARLIF-concept with toluene as a tracer in isooctane could be conducted. The experimental setup is similar to section 3 and both detection systems (time-resolved and PLIF) were used for separate verifications, delivering consistent results. Again gas mixtures at temperatures up to 433 K and pressures up to 10 bar were examined. For FARLIF-verification a certain mixture of model fuel (5% or 10% toluene in isooctane) with synthetic air was homogeneously premixed in the heated pressure tank and then its fluorescence was measured in the test chamber at different pressures. The fluorescence intensities were then corrected regarding laser intensity fluctuations and absorption effects on the laser excitation energy. For the point wise time-resolved measurements (fluorescence originating from the cell center) the corrected fluorescence intensity is given by

$$I_{f}^{\text{cor}} = I_{f} / (L_T \cdot L_R)^{0.5} ,$$

where $L_T$ denotes the measured laser transmission and $L_R$ the measured reference signal. For PLIF measurements, the corrected fluorescence intensities were calculated considering the exponential decay of the laser intensity along the excitation path in the test chamber. This procedure was performed at each constant temperature for a series of different fuel-air-ratios ($\lambda$-values, respectively).

In Figure 3 the corrected fluorescence intensities versus total pressure for different air-fuel-mixtures at $T = 398 \text{ K}$ are shown on the left. For each constant mixture ratio ($\lambda$-value) the intensity forms a plateau with increasing pressure, i.e. the pressure-independency of the signals at higher pressure is demonstrated. The plot on the right of figure 3 depicts the linear growth of the plateau intensities (taken from the left diagram) versus fuel-air-ratio (or equivalence ratio $1/\lambda$). Furthermore the

![Figure 3](image-url)

**Fig 3** FARLIF-validation at 398 K with 266nm excitation of toluene-isooctane-air mixtures

Left: Corrected LIF intensities vs. total pressure showing intensity-plateaus.
Right: Linear growth of plateau-intensities vs. equivalence ratio $1/\lambda$. 
plateau-intensities lie on a line through origin as expected from equation 4. Therefore, the FARLIF-concept is directly validated under the examined conditions, especially covering the technical important region of ignitable mixtures highlighted in the right part of figure 3. Further experiments at different temperatures up to 433 K (the limit of the used apparatus) showed similar results but different slopes in the plot FARLIF-intensity versus equivalence ratio. So, generally the results show the applicability of FARLIF at 266 nm excitation with 5%-10% toluene in isooctane for isothermal gas mixtures with a sufficient air-fraction ($\lambda \geq 0.2$) at pressures above 1.5 bar and temperatures at least up to 433 K.

This is in agreement with the predictions of Koban et al. (2005 a+b) and Schulz and Sick (2005) because they did not define at which temperature FARLIF should fail and of cause in good agreement with the prediction of Koch (2005), saying the FARLIF-concept should hold up to 500 K with toluene at 266 nm excitation. The comparison with the results of Frat et al. (2004) who found no pressure-independence between 423 K and 523 K at 248 nm excitation demonstrates that the longer excitation wavelength of 266 nm is the better choice for FARLIF with toluene. This again is in excellent agreement with the predictions of Schulz and Sick (2005). Further experiments are planned for higher temperatures up to 723 K to examine directly at which temperatures and gas conditions FARLIF with toluene will fail.

5. Direct verification of FARLIF with gasoline

After these promising results, the focus was set on FARLIF-applications without any tracer – with more realistic self fluorescing fuel. Preliminary studies showed that “colorless gasoline” (Shell...
PR 1632) is a good candidate. This is a near-standard gasoline in which only the yellow-brown bitumen components are eliminated. Again, the linearity of LIF, the photochemical stability and the dominance of oxygen-quenching were verified under similar conditions as described above. The test-chamber and the insulation were modified to expand the accessible temperature range. The direct validation of the FARLIF-concept with this gasoline was conducted analogously to the proceeding with toluene but at temperatures up to 500 K and with a wider range of fuel-air ratios. The corrected fluorescence intensities vs. density respectively total pressure are plotted in figure 4 for different air-fuel-mixtures. The mixtures near ignitable conditions are on the left, ultra lean conditions are shown on the right. Like in the case of toluene, the fluorescence intensities show pressure-independent plateaus with rising total pressure. The corresponding plateau-intensities are plotted versus equivalence ratio \( \lambda \) in figure 5. These “FARLIF-intensities” lie on a line through origin as expected for FARLIF from equation 4. To the authors’ knowledge, this is the first time that FARLIF is validated with a self-fluorescing multi-component gasoline without additional fluorescence tracer.

It is worth to be mentioned that the FARLIF-concept could be validated over a mixture range of 3 decades, as can be seen best from the double logarithmic plot on the right of figure 5. However, it is most important that FARLIF works in the ignitable mixture range as depicted in the left part of figure 5. More experiments at different temperatures show similar results but with rising slopes of the FARLIF-calibration curves (i.e. plots of the plateau-intensity vs. equivalence ratio like figure 5) for rising temperatures.

In general, the results show the applicability of the FARLIF-concept for isothermal mixtures of this colorless gasoline with air at pressures above 1.3 bar with sufficient air-fraction \( \lambda \geq 0.2 \) and temperatures at least up to 500 K. At lower temperatures the pressure and the air-fraction may be reduced to \( p \geq 1 \) bar and \( \lambda \geq 0.1 \), respectively. This effect, that at higher temperatures a higher pressure or a higher oxygen fraction – thus more oxygen collisions – are needed for FARLIF, may be explained by increasing intramolecular deactivation processes with rising temperatures. Therefore, it is expected that the FARLIF-concept will fail at some higher temperature for engine-relevant pressures and gas mixtures. Ongoing experiments will examine this higher temperature range in order to find the constraints for FARLIF with gasoline.

6. Planar FARLIF application in inhomogeneous mixtures

![Calibrated single shot FARLIF-measurement at T= 398 K, p = 3 bar with 10% toluene in iso-octane as model fuel. Mixing with air in the wake of a coaxial nozzle.](image)

After successful verification of the FARLIF-concept the application was demonstrated in terms of planar FARLIF measurements of isothermal inhomogeneous mixing situations. The setup was almost the same as described in section 3 for PLIF. Only the test chamber was modified: A two-component coaxial nozzle was inserted as the gas-inlet into the test chamber and the exit and inlet were equipped with metering valves. So it was possible to establish a controlled mixing-flow of two gas components at constant pressure between 1 and 7 bar in the test chamber. A rich fuel-air mixture was premixed in the heated pressure tank at pressures up to 10 bar serving as the reservoir for the fuel-flow. A fuel-air mixture was used instead of pure fuel.
vapor in order to have conditions valid for FARLIF even at the fuel inlet or the nozzle exit, respectively. The air for the air-inlet was preheated using a heating tube. Figure 6 shows a single shot measurement of the mixing of toluene-isooctane as the model-fuel and air in the wake of the coaxial nozzle. The laser light section is centered over the coaxial nozzle exit and the flow is directed from bottom to top. The observable diameter of the flow field is 25 mm. This image was smoothed by applying a digital Gaussian filter in order to reduce the granular structure produced by the image-intensifier at low light levels. Left and right from the central bright fuel-inlet in figure 6 the dark areas of the coaxially inserted air are clearly visible. Further outwards of the incoming air-flow the signal rises again, originating from fuel which is already mixed with air. Further downstream, the mixing of fuel and air can be seen in the center of the test chamber. Planar FARLIF-images like figure 6 can be calibrated using the calibration curve shown in figure 3 (right). Another calibration alternative is given, when the fuel-air-ratio is known in one area of the image, for example at the fuel-exit of the nozzle in figure 6. Then, the knowledge of the linearity and the pass through origin of the calibration-curve may be used to calibrate the FARLIF-image because the calibration curve is defined by the equivalence ratio of this single area.

Another demonstration of planar FARLIF-measurement is given in figure 7. In this case, the brighter fluorescing gasoline without any tracer was used. So no image smoothing was needed.

Fig. 7  Planar fuel-air ratio distributions in the wake of a cylinder in a coaxial gasoline-air flow. Left: View parallel to cylinder axis. Right: View perpendicular to cylinder axis.

Fig. 8  Visualization of areas with ignitable fuel-air-mixtures (white areas) from figure 7.
Here, a cylinder of 0.9 mm diameter was introduced at the nozzle exit as a flow-obstacle in order to increase mixing structures of the coaxial fuel-air flow. Again, the flow is directed from bottom to top and the visible diameter is 25 mm. The left image of figure 7 gives a view in direction of the cylinder axis. The laser-sheet is directed from right to the left, centered over the coaxial nozzle, so the shadow of the cylinder is visible in this image. The gas temperature was 398 K and the total pressure 5 bar. The fuel flow around the cylinder and the mixing in its wake with a certain vortex structure is clearly visible. The right image of figure 7 gives a view perpendicular to the cylinder axis where the light-sheet is placed parallelly a few millimeters in front of the cylinder. Some stray light from the cylinder behind the light-sheet is visible, showing its position. Here, the gas conditions with T = 398 K but p = 2.5 bar were slightly different. Nevertheless, the flow situation is similar showing the section through the contraction of the fuel flow oncoming to the cylinder, the flow around the cylinder and the section through the vortices in the wake of the cylinder. Again, these FARLIF-images can be calibrated using the corresponding calibration curve of figure 5. Or the calibration can be done with the knowledge of the fuel-air-ratio in one area using linearity and the pass through origin of FARLIF-calibration curves.

The difference in pressure of the two measurements depicted in figure 7 shows one drawback of this technique. At the higher pressure and therefore higher density in the left image, absorption effects become visible near the fuel exit of the nozzle. Directly at the fuel exit, a symmetric fuel distribution would be expected but the fluorescence intensity decreases from right to left along the light-path of the excitation sheet. The absorption measurement confirms absorption of nearly 30% in this region near the nozzle exit. In the case of the lower density in the right image of figure 7 with a shorter light-pass through high fuel concentrations this absorption is not visible which is again confirmed by the simultaneous absorption measurement. This means, that for measurements with long passes of the excitation light through areas with high fuel densities an absorption correction is needed for FARLIF-images. The ongoing work aims to provide a correction strategy for inhomogeneous mixture fields, using the fluorescence signal itself for a successive correction along the excitation path. However, a measurement of the actual absorption should be conducted simultaneously to FARLIF-imaging in order to rate the absorption and its effect on the fuel-air ratio error, which goes linearly with local excitation energy depletion. If the absorption through the integral excitation path can be neglected, the local error in FARLIF can be neglected as well.

Calibrated FARLIF-images like those of figure 7 (neglecting the absorption error in the left image) can be used for example for identification of ignitable mixture areas, as presented in figure 8. Here, areas with $0.5 < \lambda < 1.3$ are identified as white areas. Near the nozzle only the “contact surface” of air and fuel around the rich fuel core flow shows a small ignitable layer, as expected. Further downstream where mixing is more progressed, ignitable clouds detach from the richer fuel flow.

These and more examples of FARLIF-imaging showed the applicability of this measurement technique for quantitative single-shot experiments in isothermal transient mixing flows of air with the
model-fuel toluene-isooctane or the colorless gasoline at engine relevant pressures between 1.5 bar and 7 bar and temperatures up to 433 K. Higher pressures should be no problem for this technique as long as absorption due to high fuel density is negligible or taken into account for correction processes. Higher and more engine relevant temperatures are under examination, whereas in the case of gasoline it can be predicted from the direct validation investigation (section 5) that planar FARLIF-imaging should be applicable up to at least 500 K.

Another advanced application of FARLIF-imaging is double-pulse planar FARLIF, which is briefly described here. More details will be given at the 12th International Symposium on Flow Visualization, September 2006 in Göttingen. Similar to the common PIV-technique a double-pulse laser and a dual-frame camera are used to take two images with short temporal delay. The difference to PIV is the short excitation wavelength of 266 nm, the use of an image intensified dual-frame camera to capture the UV-fluorescence and that no particles or tracers are seeded to the flow but the self-fluorescing fuel-structures are followed. The motion of the fluorescing flow structures (like clouds etc.) are analyzed in cooperation with Paul Ruhnau from the Computer Vision Graphics and Pattern Recognition (CVGPR) group of Prof. Schnörr, University of Mannheim. They use “optical flow” algorithms for this fluorescence motion analysis (FMA) similar to those described in Ruhnau et al. (2005). Figure 9 shows the result of such a double-pulse experiment with FMA. The background shows the calibrated fuel-air-ratio field of the first image and the arrows denote the motion field of the fluorescence structures. It has to be mentioned that this is not equivalent to the velocity field of the flow but it shows where and how mixture-structures are moving. This technique may be used to follow the movement of ignitable mixture clouds in optically accessible engines for example, combining the knowledge of the fuel-air-ratio field with the fluorescence motion analysis.

7. Conclusions

The applicability of the FARLIF-concept for quantitative fuel-air-ratio measurement could be validated with the excitation wavelength of 266 nm for 5 % to 10 % toluene in isooctane as a model fuel for fuel-air mixtures with \( \lambda \geq 0.2 \) at pressures between 1.5 bar and 10 bar and temperatures at least up to 433 K. This is in good agreement to the forecasts of Koch (2005) and consistent to the predictions of Koban et al. (2005 a+b) and Schulz and Sick (2005), but it renders more precisely the temperature range where FARLIF is still valid. The comparison with the results of Frat et al., who showed that the FARLIF-concept (i.e. the pressure independency) fails above 423 K at 248 nm excitation shows that the longer wavelength excitation at 266 nm is the better choice for FARLIF with toluene-isooctane.

The FARLIF-concept with 266 nm excitation could be validated as well for a near-standard gasoline. To the authors’ knowledge this is the first time that FARLIF is validated for a self-fluorescing multi-component gasoline without any additional tracer. Here the concept holds for \( \lambda \geq 0.1, p \geq 1 \) bar and temperatures at least up to 500 K (for the higher temperatures \( \lambda \) or \( p \) has to be increased). This is a promising result for mixture formation investigations under most realistic conditions.

Unfortunately temperature effects arose for both, FARLIF with toluene-isooctane and FARLIF with gasoline. So this technique is best chosen for isothermal conditions, otherwise the temperature has to be known for signal correction. Ongoing investigations will examine higher temperatures in order to find correction terms and the constraints for FARLIF.

The application of the FARLIF-concept was demonstrated in planar FARLIF-imaging experiments for the model fuel and the (almost) standard fuel. In both cases, signal strength was sufficient for single-shot experiments in isothermal transient mixing flows, whereas the gasoline signal was the brighter in comparison. For long excitation-paths through high fuel densities the depletion of the excitation intensity influences FARLIF measurements. In these cases an absorption correction is needed for FARLIF-imaging. Investigations for an appropriate correction strategy are in progress.
Finally, first results of double-pulse FARLIF applications were presented, giving insight into dynamic mixture processes. In general, the FARLIF-concept shows to be a powerful tool with multifunctional applications if used in its valid constraints and with appropriate corrections if necessary.

8. Acknowledgement

The authors gratefully acknowledge the financial support through the Deutsche Forschungsgemeinschaft DFG in the framework of the priority program SPP 1147.

8. References


