INVESTIGATION OF FUEL WALL FILMS USING LASER – INDUCED – FLUORESCENCE

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ABSTRACT
Modern gasoline engines use the principle of direct injection. During the warm-up and for early injections the spray droplets contact the piston surface. As a result of the spray-wall interaction a wall film occurs. The liquid film as a fuel rich zone is one important reason of high soot emissions. Therefore it is necessary to carry out investigations on wall film forming and evaporation. It is aimed to reduce the wall film mass. The method of Laser-Induced-Fluorescence is able to quantitatively visualize wall films. Using this technique it is possible to study the effects of spray shape, orientation, operating pressure, injection quantity as well as distance from the wall.
The boundary conditions of the test section are close to those of an emission test engine. As a simplified approach the LIF measurements are taken under normal ambient conditions. The applied injector is a common high-pressure six hole nozzle controlled by a magnetic system. Two parameters were varied: the injection pressure and the distance between nozzle and wall. As a result the spatial and time resolved wall film thicknesses were found.
The first aim was to design a sensitive setup without using intensifiers. This resulted in a very fine-resolution gray scale and height information. Subsequently the analysis of the measuring system and the calibration were conducted.

INTRODUCTION

The first known investigations of water films were performed by Hopf in 1910. The method using a micrometer screw to measure the film thickness was used by scientists until 1963. In the meantime new methods were developed. Dunkler and Berglin (1952) measured capacity differences and Jackson (1955) was the pioneer using a radioactive tracer in the fluid. In 1964 Hewitt et al. were conducting the first fluorescence based film measurements followed by Hiby in 1968.

So the idea of applying fluorescence to wall films is known since 60 years. But with the development of intense and precise excitation sources the method became more applicable. Le Cos et al. (1994) were one of the first using a laser for inducing the fluorescence in liquid films. At the beginning point wise measurements were performed, eg. Meingast et al. 2000 or Lindgren et al. 2002. For many applications selective height information are sufficient. So Cheng et al. and Lida et al. published local LIF wall film measurements in 2009. Due to further developments in laser and camera hardware recently the first spatial resolved wall film thickness experiments have been carried out. Alonso et al. (2009) were interested in gasoline films and Magnusson et al. 2010 were investigating diesel films.

The method is based on findings of Bouger (1729) and Lambert (1760) who described the phenomena of light absorption. Later Beer (1852) found that the transmittance of light depends on the absorband concentration. For the Laser-Induced-Fluorescence the tracer represents the absorband and so the LIF-signal is proportional to the absorbed light. In this sense the Beer-Lambert-Law can be written as follows:

$$I_f = \phi \cdot I_0 \cdot \left(1 - \exp\left(-\epsilon \cdot C \cdot h\right)\right) \qquad (1)$$

The dependency on the wavelength does not emerge from the equation. So the fluorescence signal intensity I_f is directly proportional to the intensity of the excitation radiation I_0 and to the quantum efficiency ϕ. From special interest is the logarithmic correlation between the LIF-signal and the length of the light path h (e.g. film thickness). The molar absorption coefficient ϵ and the molar concentration of the absorband C (e.g. tracer) have the same behaviour. The experiments described in this paper are based on this correlation.

EXPERIMENTAL METHOD

This study focuses on the LIF investigations of spray-wall interaction and fuel films. As a first approach the injection process of the real homogeneous charged Otto engine is replaced by the experimental setup illustrated in figure 1. The fuel is ejected onto a flat $50 \times 50\text{mm}$ quartz surface by a symmetric six hole gasoline nozzle for central position. Only one of the six spray jets is used for the evaluation.
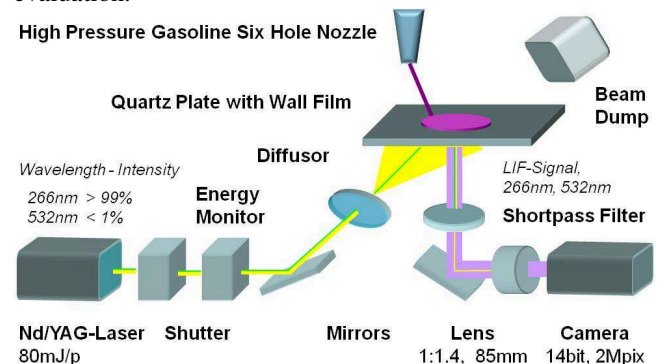

Figure 1: Schematic experimental setup

Both the Nd/YAG-Laser which excites the fuel and the camera which represents the LIF-signal detector are located underneath the quartz plate. In this arrangement, the interruption effect of the spray is minimized in the visualization. Decoupling the forth harmonic wavelength of 266nm the Spectra-Physics Quanta Ray LAB-170-10 Nd/YAG-Laser provides pulse energy up to 120mJ/pulse at a frequency of 10Hz for a pulse duration of only 4ns.

The high energy of one pulse will immediately start to evaporate the liquid film, which causes a bubble formation. Therefore it is necessary to expand and homogenize the laser profile and to reduce the laser power. By setting laser power to 80mJ/pulse and adjusting the beam profile the maximum fluorescence signal can be archived. Contrary to previous experiments using continuous lasers the film-images have a high sharpness of movement resulting from the short pulse duration.
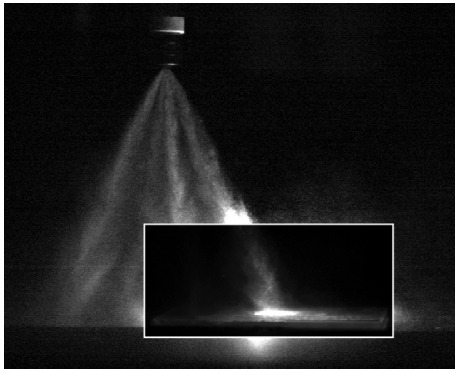

Figure 2: Side view of the injection onto a quartz plate

Two more components are important for working with a pulse laser. The laser shutter which is placed directly behind the laser blocks the beam. For safety reasons the radiation passes the shutter only during the recording. Behind the shutter the energy monitor is located. Because the laser exhibits a pulse to pulse energy fluctuation the energy monitor detects the individual pulse energy. Later the signal is used for correction purposes.

properties	iso-octane	3-pentanon
boiling point [°C]	99	101
density [g/cm^3]	0.69	0.81
molar mass [g/mol]	114.2	86.1
vapor pressure at 20°C [hPa]	51	37.6
heat of vaporisation [kJ/mol]	38.5	35.1

Table 1: Properties of iso-octane and 3-pentanone

In the early phase of the experiments it was found that most surfaces in the lab and also the mirrors and lenses are sensitive –in form of fluorescence– to the laser radiation which caused significant background noise. Therefore it is necessary to minimize the number of laser optics and to avoid light scattering by a precise alignment of the optical laser path. Also the beam dump is indispensable. In this context the beam expander with its lenses was substituted by one 5° UV diffuser optic to achieve a homogeneous laser profile. The width of the homogenized laser profile is

set by adjusting the distance between diffuser and quartz surface.

The LIF Signal is detected by an Imager pro X 2M camera combined with the trigger controlling from LaVision. The 14-bit CCD camera, with 16,000 gray levels, has a resolution of 1,600 × 1,200 pixels. In combination with the 85mm Zeiss lens with a set f-number of 1.4 the maximum of light can be captured. This composition enables a very fine gray-scale and height resolution. In addition a 20mm extension tube was mounted between camera and lens. Because the area of interest has an extension of only 50 × 50mm this is necessary to obtain a maximum spatial resolution. According to this, the area of 1 × 1mm is represented by 1024 pixels. This is much more than required for a good image. But for the post processing it is useful in order to smooth sensor noise without losing spatial information.
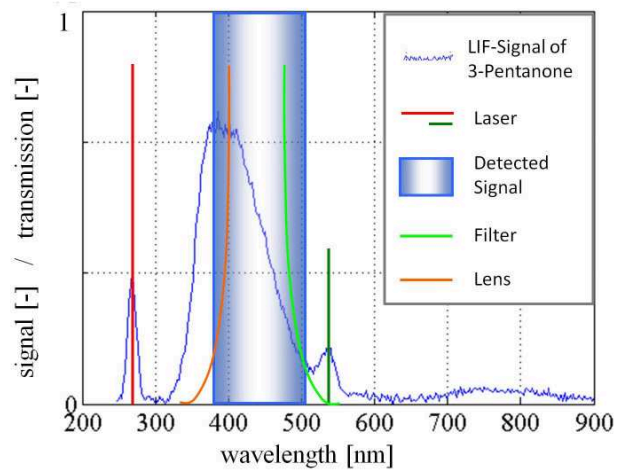

Figure 3: Wavelengths and signal location

The injected liquid can be considered as a component of the experimental setup. It influences the signal intensity and the wavelength of the LIF signal and therefore the other components of the setup. For instance, if the signal wavelength is only found in the UV region, an intensifier with UV lens has to be used. In the present study the binary mixture of 5% vol. 3-pentanone in iso-octane was chosen as fuel substitute. Iso-octane is the basis and non-fluorescing. The LIF-signal producing tracer is 3-pentanone. Compared to other tracers, like toluene, 3-pentanone produces only a very low response signal (Fujikawa et al. 1997, Wieland et al. 2005). But the physical and chemical properties match best with those of iso-octane (table 1). That is why in combustion systems research the combination of iso-octane and 3-pentanone is commonly used as a substitute of gasoline. Another important issue is that 3-Pentanone is most sensitive to an excitation wavelength of 266nm.

For LIF measurements one of the most important issues is the selection of the signal wavelength. Since the LIF-signal of 3-pentanone is really low it is necessary to avoid the detection of signals which do not have their origin within the wall film. Therefore the spectral response of 3-pentanone in iso-octane was measured in a fluorescence spectrometer (RF-5301PC). The response signal of 3-pentanone excited with 266nm is plotted in figure 3. To

capture only the wall film signal the 532nm laser radiation is cut off with the help of a 500nm (FWHM of 10nm) short-pass filter. Signals below 360nm are absorbed by the lens. Radiation noise within the sensitive detection field is deleted in the post processing.

CALIBRATION

To be able to derive a height information from the LIF-signal a precise height calibration is necessary. Therefore three different calibration methods were tested. First the most common thickness calibration, second the concentration calibration and third the droplet calibration were carried out. All three methods are supposed to give the desired LIF-signal intensity for a known film height. This correlation can be applied for the following film height measurements.
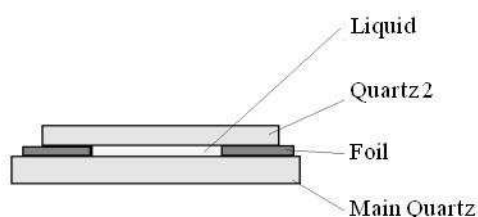

Figure 4: Film height calibration setup

Figure 4 illustrates the setup for the thickness calibration. By positioning a foil between the main quartz plate and second quartz plate a defined distance inside the plates is generated. Both quartz glasses have a very smooth surface with a corrugation less than 150nm. Two foils were used, one with a thickness of 40µm and another with 80µm. So that it was possible to adjust eight film thicknesses between 40 and 320 µm. Of course eight steps would not be necessary if a linear correlation between the LIF-signal intensity and the film height is assumed – like it is usually done for thin layers. But this assumption and the reproducibility of the calibration should be proven for the setup. The 3-pentanone / iso-octane mixture was injected with a syringe und drawn into the gap by capillary force. In order to avoid buoying upward of the upper quartz the plates were clamped together.
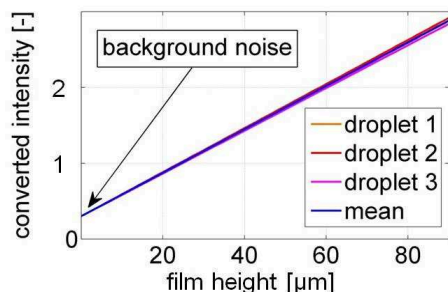

Figure 5: Results from droplet calibration

The same setup is used for the second method, the concentration calibration (Cheng et al. 2010). This calibration was executed in combination with the thickness calibration just by varying the concentration of 3-pentanone between 1.25% and 15% (vol.). The idea of this calibration is that there is the same correlation between the LIF-signal

and concentration like it is between the LIF-signal and film thickness. This results from the Beer-Lambert-Law. Using this relationship it is sufficient to set one defined film height and change the concentration of 3-pentanone.

For the droplet calibration as the third method a droplet with a defined volume is placed onto the main quartz plate. Although using a micro syringe it is difficult to obtain the desired volume. This is due to the adhering liquid on the syringe and evaporation. Therefore a series of droplets was balanced on a high resolution balance, in order to get a mean droplet size. This is about 10% below the adjusted syringe volume. For the later experiments the LIF-signal / height correlations of at least three droplets were averaged. But figure 5 demonstrates that the calibration curves match really close.

There are different approaches to receive the LIF-signal / height correlation out of the droplet images e.g. the refractive index matching imaging introduced by Drake et al. (2002) for a rough surface. Because of the thin films as a first approximation a linear correlation was used. With the help of the LIF-Signal / volume correlation,

$$\frac{I_{f,pixel}}{\sum_{ij} I_{f,ij}} = \frac{h_{pixel}}{\sum_{ij} h_{ij}} = \frac{h_{pixel}}{V_{drop}/A_{pixel}} \qquad (2)$$

a height for each pixel is calculated. This leads to a slight overestimation of the film thicknesses. The estimation will soon be substituted through the Beer-Lambert-Law, which leads to a nonlinear system of equations.
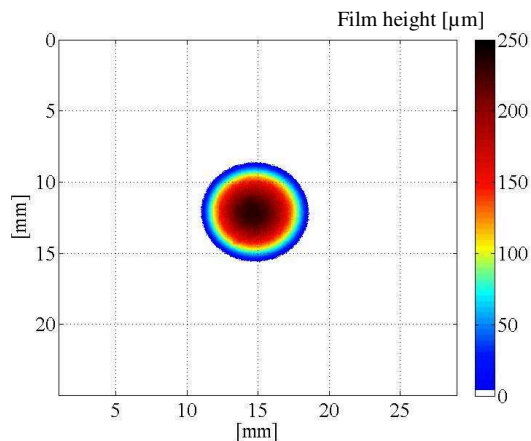

Figure 6: Droplet height

The experimental results show that the concentration method is the most sensitive method. It is very difficult to create a mixture with an error less than 5% (vol.). Therefore the results scatter. The measurements of the fist method are very reproducible. It was found that the LIF-signal behaves linear up to certain thicknesses, for instance for 5% (vol.) of 3-pentanone up to 160µm or for 10% (vol.) of 3-pentanone up to 80µm. Beyond this height the logarithmic trend starts to get visible. For both calibrations – the first and the second method – an additional quartz was used to adjust a defined height. But it became evident that this quartz influences the measuring system. Especially, due to light scattering at the edges of the quartz the background noise and the LIF-signal rises. The resulting

signal is not accurately comparable to the LIF-signals of wall films measured without the second quartz plate. That is why the droplet calibration was chosen for further investigations. A droplet image derived from a 5.4μl droplet is presented in figure 6.

IMAGE PROCESSING

Quantitative Laser-Induced-Fluorescence measurements always require a detailed post-processing. For this reason it is necessary to prepare the experiments before starting the measurements. Therefore the adjustment of the laser power was carried out first with a Coherent power meter, FieldMaxII-TOP. In this step the sensitivity range of the energy monitor was attuned to the laser power.
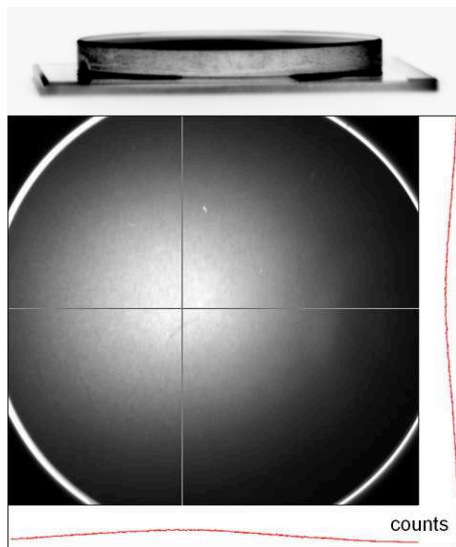
Figure 7: Laser profile image (bottom), side view negative (top)

The first record is a dark image to smooth the sensor signal. This is necessary because of a different sensitivity of the MOS capacitors. A background image can help to erase the noise which occurs between the fuel film and the camera, e.g. on the mirror in front of the camera.
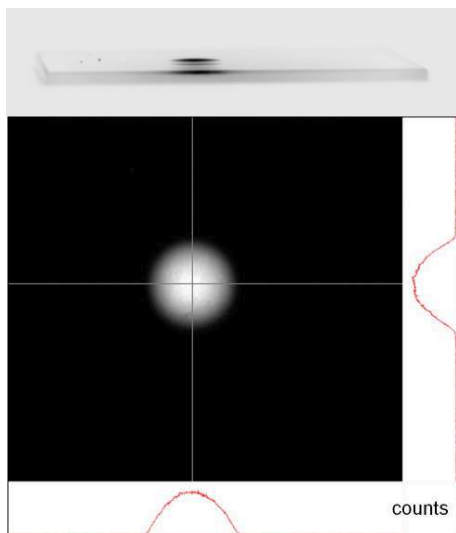
Figure 8: Droplet image (bottom), side view negative (top)

The second step is to take a laser profile image (figure 7), because the spatial distribution of the excitation energy must be considered in the calculation. To get the laser profile the same setup as in figure 4 was used. At last droplet images like figure 8 are recorded. After this procedure the wall film experiments were executed.
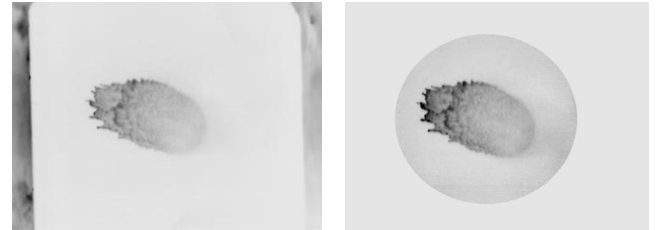
Figure 9: Wall film raw image (left), Wall film image energy and profile corrected (right)

In the post processing procedure all images are energy corrected, first. Here the pulse energies of the images recorded by the energy monitor are set into a relationship and the overall image intensities are adapted. This is followed by the profile correction. The intensities of areas with lower laser power are adapted to the maximum value. Figure 9 contrasts the raw image of a wall film with the energy and profile corrected image. This is also done for the droplet images. With the help of these images the LIF-signal / height correlation (figure 5) is calculated. Applying the film height function to the processed wall film intensity fields, the film thickness information is obtained. As an example in figure 10, the film thickness image of figure 9 is plotted.
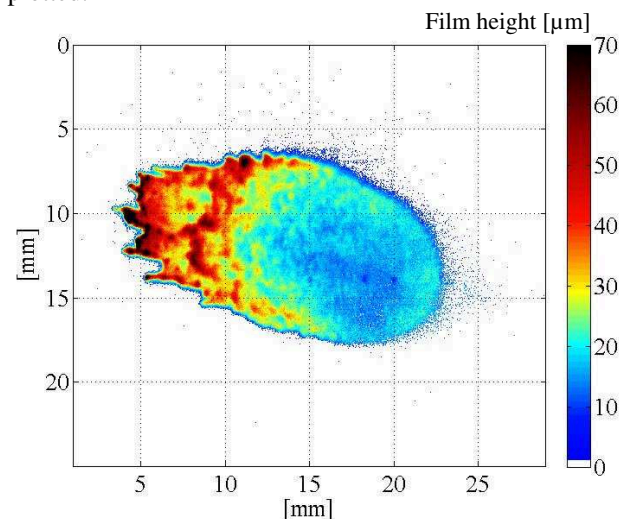
Figure 10: Wall film height image

CONCLUSION

This report highlights the opportunities to study fuel wall films with the use of Laser – Induced – Fluorescence. Compared with previous studies, the use of modern hardware allows much better information about the fuel distribution and the wall film heights. However, this requires a detailed calibration of the measurement system. For the intensity calibration different methods were tested.

The drop calibration provided the most accurat reproducible calibration results.

Following the post-processing, it is possible to compare the resulting wall films. Thereby, the influences of the boundary conditions can be determined and quantified. Interesting parameters are the maximum wall film height, the film area and the deposited fuel mass. The implementation of parametric studies is planned. Singe images of preliminary investigations are presented in figure 11. The images are taken 10ms after start of injection and the injected fuel mass is constant.
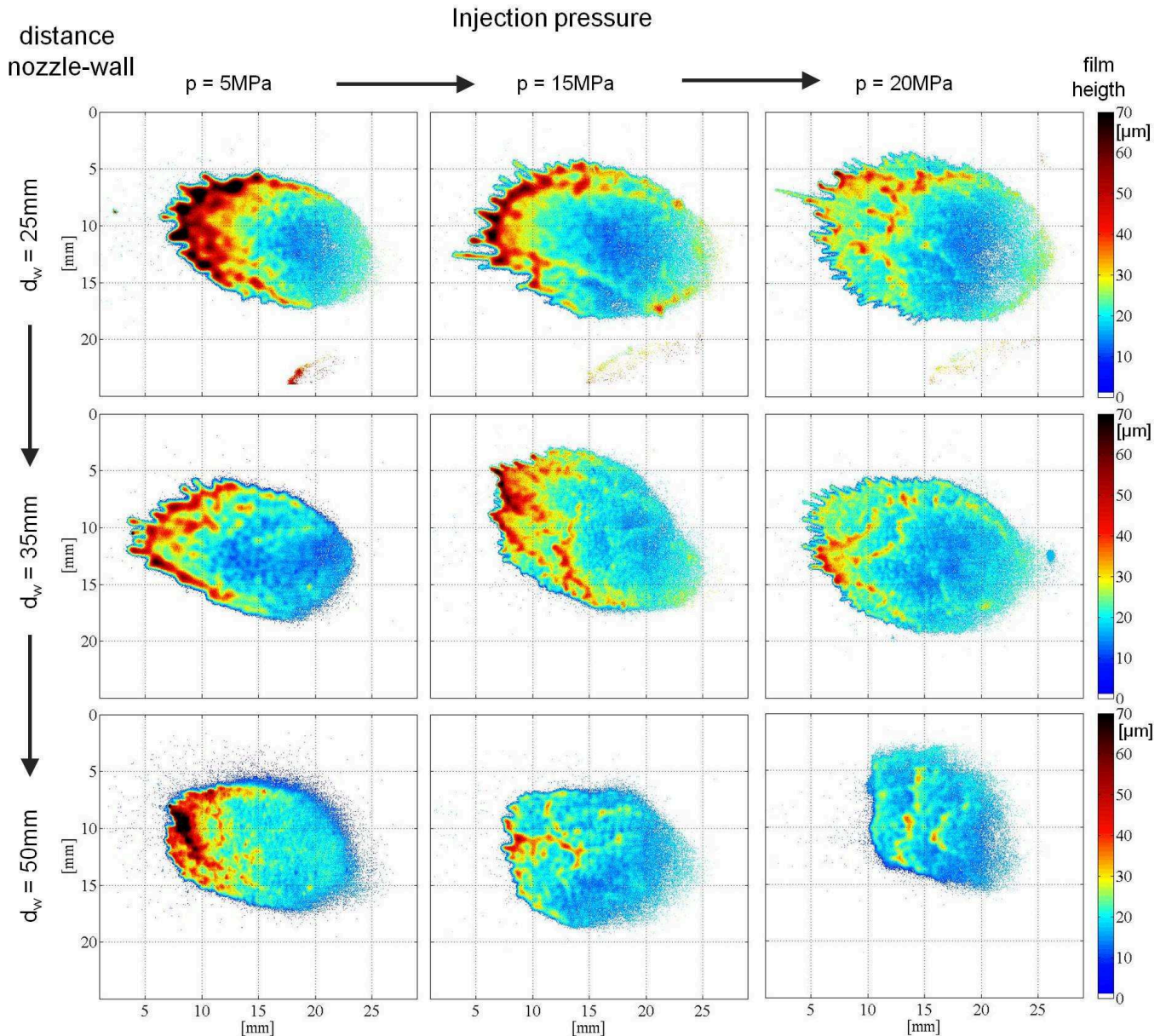
Figure 11: Film thickness images for different boundary conditions

REFERENCES

[1] Alonso M., Kay P. J., Bowen P. J., Gilchrist R., Sapsford S., *A laser induced fluorescence technique for quantifying transient liquid fuel films utilising total internal reflection*, Exp Fluids 48 (1) 2010, S. 133–142.

[2] Beer A., *Bestimmung der Absorption des rothen Lichts in farbigen Flüssigkeiten*, Annalen der Physik und Chemie. 86, 1852.

[3] Bouguer P., *Essai d'optique, Sur la gradation de la lumière*, Claude Jombert, Paris 1729.

[4] Cheng Y., Deng K., Li T., *Measurement and simulation of wall-wetted fuel film thickness*, International Journal of Thermal Sciences 49 (4) 2010, S. 733–739.

[5] Cho H., Min K. *Measurement of liquid fuel film distribution on the cylinder liner of a spark ignition engine using the laser-induced fluorescence technique*, Measurement Science and Technology 14 2003, S. 975–982.

[6] Drake M. C., Fansler T. D., Rosalik M. E., *Quantitative High-Speed Imaging of Piston Fuel Films in Direct-Injection Engines using a Refractive-Index-Matching Technique*, ILASS Americas, Madison,WI, 2002, S. 58–62.

[7] Dukler A.E., Berglin O.P., *Characteristics of flow in falling liquid films*, Chem. Engng. Progr., 48, 557/563, 1952.

[8] Fujikawa T., Hattori Y., Aklhama K., *Quantitative 2-D fuel distribution measurements in an SI engine using laserinduced fluorescence with suitable combination of fluorescence tracer and excitation wavelength*, SAE technical paper series 972944; 1997.

[9] Hewitt G.F., Lovergrove P.C., Nichols B., *Film thickness measurement using fluorescence technique*, Pt. 1. Description of the method; AERE-R 4478, 1964.

[10] Hiby J.W., Eine Fluoreszenzmethode zur Untersuchung des Transportmechanismus bei der Gasadsorption im Rieselfilm, Wärme- und Stoffübertragung, 105/116, 1968.

[11] Hopf L., *Turbulenz bei einem Flusse*, Ann. Phys., 777/808, 1910.

[12] Jackson M.L., *Liquid films in viscous flow*, AIChE J., 231/240, 1955.

[13] Lambert J. H., *Photometria, sive de mensura et gradibus luminis, colorum et umbrae*, Sumptibus Vidae Eberhardi Klett, 1760.

[14] Meingast U., Staudt M., Reichelt L., Renz U., Sommerhoff F.-A., *Analysis of Spray/Wall Interaction under Diesel Engine Conditions*, SAE Technical Paper (2000-01-0272), Detroit 2000.

[15] Le Coz J.F., Catalano C., Baritaud T., *Application of laser induced fluorescence for measuring the thickness of liquid films on transparent walls*, Proc. 7th Int. Symp. On Applications of Laser Techniques to Fluid Dynamics, ed. Adrian RJ, Lisbon, Portugal, 1994, pp.29.3.1-29.3.8.

[16] Lida M., Yoshikawa K., Arcoumanis W., *Fuel Film Behavior Analysis Using Simulated Intake Port*, SAE Technical Paper, 2009

[17] Lindgren R., Block R., Denbratt I., *Development of a Wall Film Thickness Measurement Device*, Proceedings of the 1st International Conference on Optical and Laser Diagnostics, London, 2002.

[18] Magnusson A., Begliatti M., Hervás F.B., Andersson M., *Characterization of Wall Film Formation from Impinging Diesel Fuel Sprays using LIF*, 23rd Annual Conference on Liquid Atomization and Spray Systems. Brno, ILASS – Europe 2010, S. 1–10.

[19] Park S., Ghandhi J.B., *Fuel Film Temperature and Thickness Measurements on the Piston Crown of a Direct-Injection Spark-Ignition Engine*. Warrendale, SAE International 2005.

[20] Wieland K., *Photophysical characterization of toluene and 3-pentanone for quantitative imaging of fuel/air ratio and temperature in combustion systems*, PhD Thesis, University of Heidelberg, 2005.