SIMULTANE ANWENDUNG VON PLIF UND MIXPIV: QUANTIFIZIERUNG DER MESSGENAUIGKEIT

SIMULTANEOUS APPLICATION OF PLIF AND MIXPIV: QUANTIFICATION OF THE MEASUREMENT PRECISION

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PLIF, MixPIV, Probability Density Functions of concentrations

Abstract

In new generation gas turbines auto-ignition driven combustion processes are used to improve part load behaviour. To control mixing, ignition and burn-out in the second stage of the combustor, shielding air is injected with the fuel into the combustion chamber. In order to optimize self-ignition combustors with respect to pollutant emissions, it is important to have in-depth knowledge of mixing history. This information can be provided by Probability Density Functions (PDF) of mixture fraction at selected points.
As fuel, shielding air and primary combustor exhaust gas flow form a three stream mixing problem, a technique is needed to simultaneously acquire such PDF to understand the mixing mechanisms of this injection system.
We present a two tracer application using Uranin for classical PLIF (Planar Laser Induced Fluorescence) and PIV (Particle Image Velocimetry) particles analyzed with MixPIV excited by a continuous wave laser. PLIF is a well understood method to obtain mean quantities and mixing statistics and we use it here as the reference method to evaluate the MixPIV technique.
MixPIV derives mixture fraction PDF from flows seeded with PIV Particles. This method deconvolves numerically the mixture fraction PDF from the measured light intensity PDF using the simultaneously acquired light intensity PDF at a reference location. MixPIV has been demonstrated for a free air jet and could be validated with literature data (Pernpeintner et al. 2011). The set-up used here for in depth validation consists of an enclosed confined jet in co-flow, which is seeded simultaneously with uranin and polyamide particles. As working fluid water is applied.
The results show that the separation of both signals is possible. Data are compared for mean quantities and mixture fraction PDF's. Finally the quality of the MixPIV signals are compared to the LIF results and literature data.

Experimental Set-Up

Fig. 1 shows the set-up for the benchmark test case. The continuous wave laser forms a horizontal light sheet with a maximum thickness of 1 mm. The observed area is 50mmx200mm. The cameras are placed on opposite sides and are viewing the others mirror image. With this set-up errors like mass flow fluctuations, leakage effects and asymmetries

are recorded simultaneously and therefore don't compromise the data comparison. The MixPIV signal is acquired with a Photron SA5. It is used as the master camera and synchronises the LIF camera, a Photron APX Ultima, with a non intensified camera head.
An Argon Ion Laser operated at 4 W used with light sheet optics illuminates the meridional cross section through the jet. In this set-up, we dope the jet flow with uranin and pump it through the seeding generator, where polyamide particles are added. A delta wing vortex generator then homogeneously mixes the uranin with the particles.

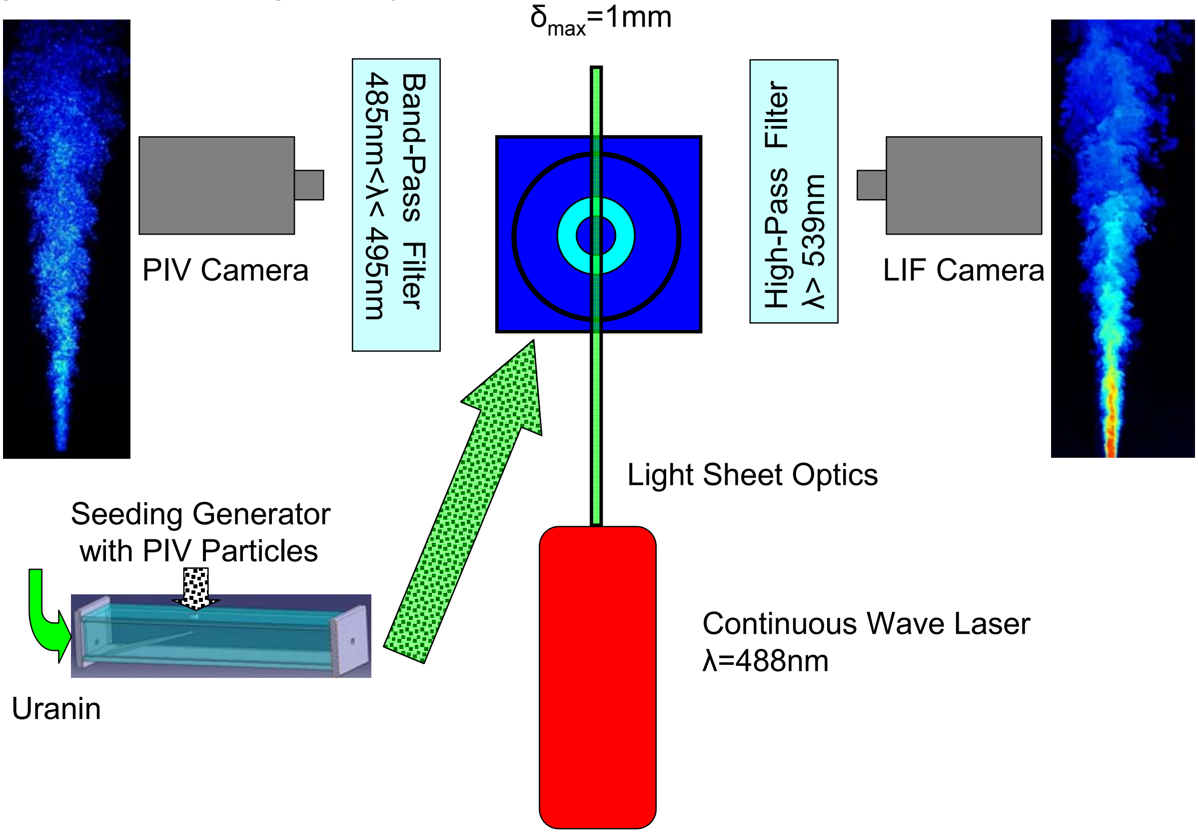

Fig. 1: Set-up for simultaneous application LIF and MIXPIV

Uranin has its absorption maximum at 500 nm and fluorescence maximum at 560nm (Brackmann 2000). A Semrock high-pass filter, opening at 539nm is used to separate the uranin fluorescence from the 488nm scattered light of the PIV particles. The uranin tracer is used in a concentration range, in which the recorded light intensity is proportional to the Uranin concentration, which gives the following relation with the mixture fraction f:

$$f = \frac{Intensity_{x,r}}{Intensity_{x_0 r_0}} \qquad (1)$$

In this formulation x_0 and r_0 indicate the reference position, where f=1, i.e. the jet nozzle exit. Using the DaVIS® software a background und laser light sheet correction of the raw LIF data are applied. Laser fluctuations are later corrected based on the reference location intensity using Matlab.

Polyamide particles with an average diameter of 20 µm are used as the second tracer. As they scatter light from the Laser only, a band pass filter (491nm +/-9.7) is used to separate the signal from the LIF. In comparison to the LIF Signal, the detected light intensity is not directly proportional to the mixture fraction. The data analysis is based on the following relation:

$$\Theta = \rho \cdot f \quad (2)$$

Where Θ is the normalized light intensity, ρ the normalized particle density (Pernpeintner et al. 2011) and f is the mixture fraction. Pernpeintner et al. show for the PDF's of the local light intensity PDF_Θ, that of particle density PDF_ρ and of mixture fraction PDF_f are related by the following convolution integral:

$$PDF_\Theta(\Theta) = \int_0^1 PDF_\rho\left(\tfrac{\Theta}{f}\right) \cdot \frac{1}{f} \cdot PDF_f(f) \cdot df \quad (3)$$

At the nozzle exit, where $f = 1$ and $PDF_f = \delta(f - 1)$, equation 3 shows that the particle density distribution is equal to the light intensity distribution: $PDF_\rho = PDF_\Theta$. With equation (3) and the normalized particle density PDF_ω the mixture fraction PDF_f can be derived from the local intensity PDF through a numerical deconvolution of the signal. As the equation system is badly conditioned the inversion is done by a Thikonov regularization. In this Thikonov regularization the parameter α is a stability parameter, which improves the numerical inversion of the problem. α should have values between 0.02 and 0.3 to achieve stable solutions, a value of zero means that the original solution of the system is used. Detailed discussions on this topic can be found in Pernpeintner et al. 2011. As well as LIF, MixPIV needs a light sheet correction using a homogenous concentration image. We found that a correction with the homogenous uranin instead of a homogenous particle image improved the quality of the sheet correction.

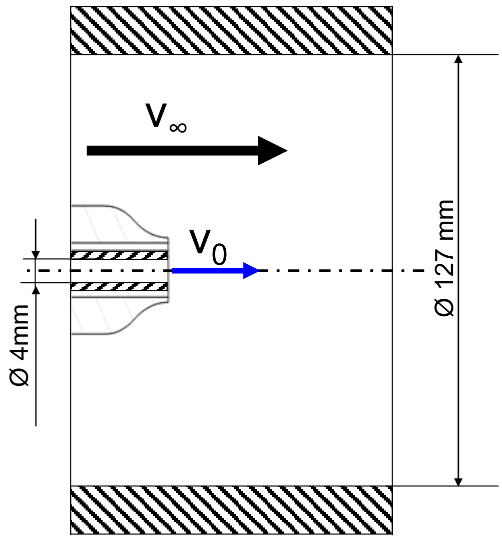

Fig. 2: Sketch of the injection system

Fig. 2 shows a sketch of the confined co-flow injector. The round cylindrical jet nozzle diameter is 4mm; the surrounding round duct has a diameter of 127mm. The main flow Reynolds' number based on duct diameter and bulk velocity is 46920. That of the injector nozzle based on jet velocity and diameter is 46720. Both flows are fully turbulent. The momentum flux ratio between jet and co-flow,

$$J = \frac{\rho_w u_0^2}{\rho_w u_\infty^2} \tag{4}$$

is equal to 1000. As densities are identical, J reduces to the velocity ratio between injection and main flow. The mixing section has a length of 500mm. A camera speed of 2000fps was used. For statistical independence we used 10000 frames for the MixPIV analysis and 4000 for the LIF. The LIF frames have a resolution of 6 pixels per mm and the MixPIV data of 4 pixels per mm. For stable solutions of MixPIV we chose a region of 4x4 Pixels and for LIF 8x8 pixel regions in the analysis. For direct comparison the PDF of both signals were created with 256 bins.

Results and discussion of Simultaneous LIF and MixPIV

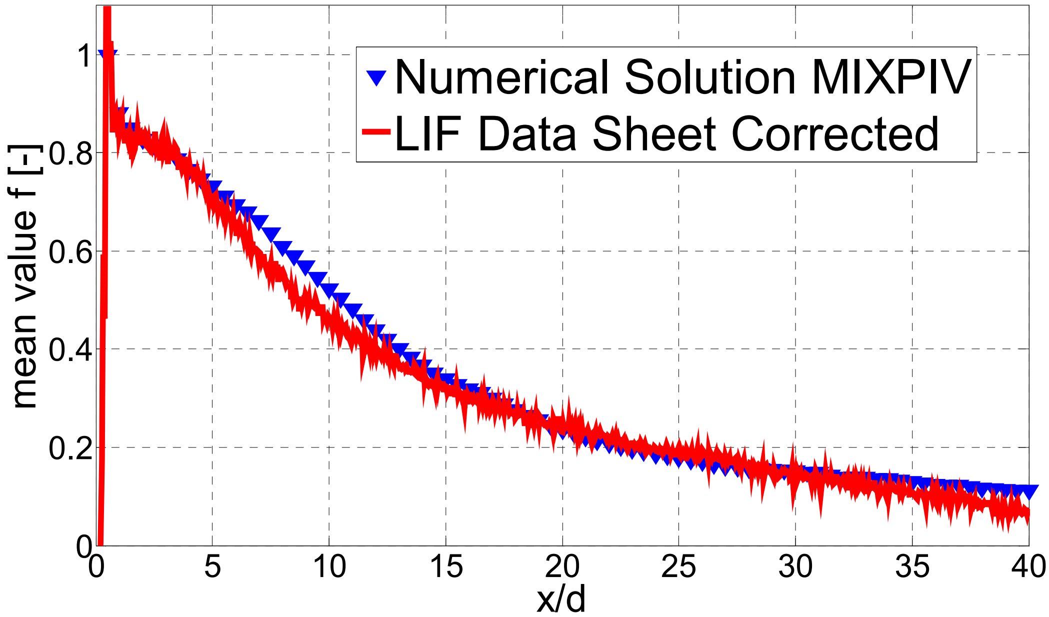

Fig. 3: Comparison of axial profiles from LIF and MixPIV

Fig. 3 shows the axial centreline profiles of the mixture fraction from both methods. In general both data sets match very well. Between x=5d and 15d a slight deviation of about 10% is observed. From x=15d to 30d the values match perfectly. Then the LIF signal indicates a further decrease. Comparison of raw measurement data showed that after 30d the signal gets weaker due to a combination of poor light sheet quality and low Uranin concentration. The MixPIV data seem to be unaffected by the poor light sheet quality.

In Fig. 4 six radial profiles of the mean concentration until x=25d are compared from both methods. Right at the nozzle the profile of the LIF data is a little narrower than the MixPIV data. This effect has vanished on x=5d and also in the far field both profiles match each other. For the so called self similar region, mentioned by Thring and Newby 1953, starting at x=5d, a correlation for confined co-flowing systems can be found. This correlation was introduced by Tieszen et al. 1996 in the following form:

$$f = \alpha_C \left(\frac{\rho_j}{\rho_\infty}\right)^{1/2} \left(\frac{r_j}{x}\right) \exp\left(-\beta_C \left(\frac{r}{x}\right)^2\right) \tag{3}$$

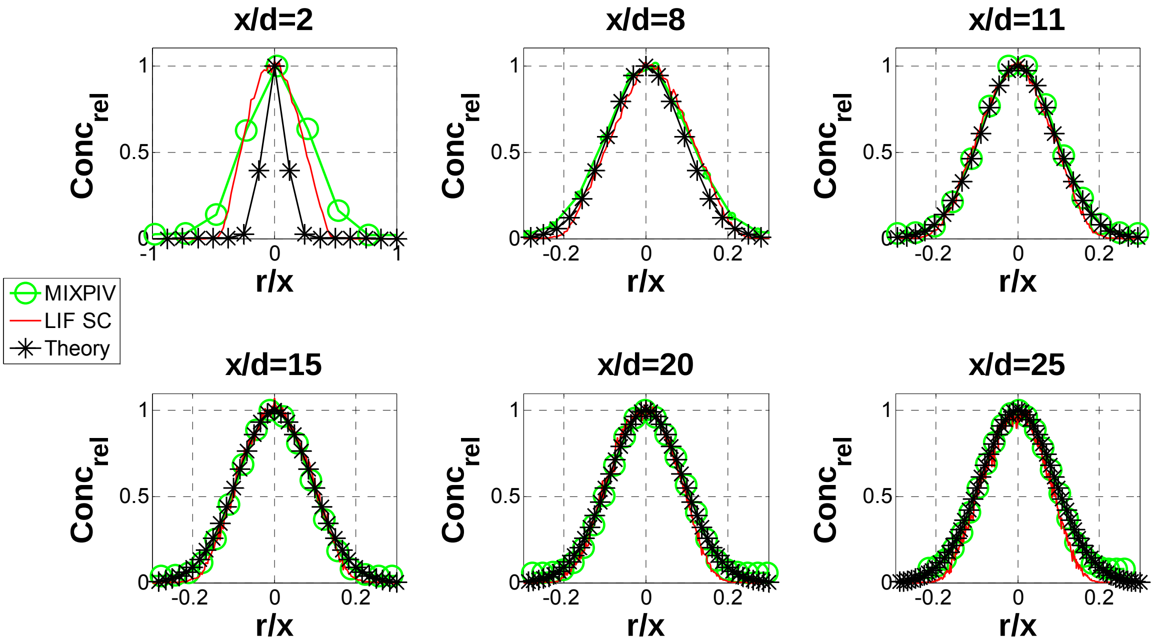

Fig. 4: Comparison of radial profiles from LIF and MixPIV

Lawn 2009 mentions values of α_C=10 and β_C=56-60. Our LIF data showed that α_C changed with r_j/x, but the product of these two quantities was always one. So this term was set to one and measurement data could be fitted with β_C=60, which is within the allowed range mentioned in literature. In the self-similar region the correlation also aligns well with the measurement data. Looking at the average data of MixPIV in the far field, it is found that the values of the radial profiles aren't exactly zero for large radii. We found that PDF's in this area are β shaped. From the raw data it can be seen that the maximum should be at f=0, but the PDF's maximum after deconvolution is at concentrations of 0.0097. It is assumed that this is a numerical error. In regions with general low intensities such as the far field this error becomes significant. It is less than 0.1% in near field regions, where the main mixing occurs and is therefore considered as negligible for substantial mixing regions.

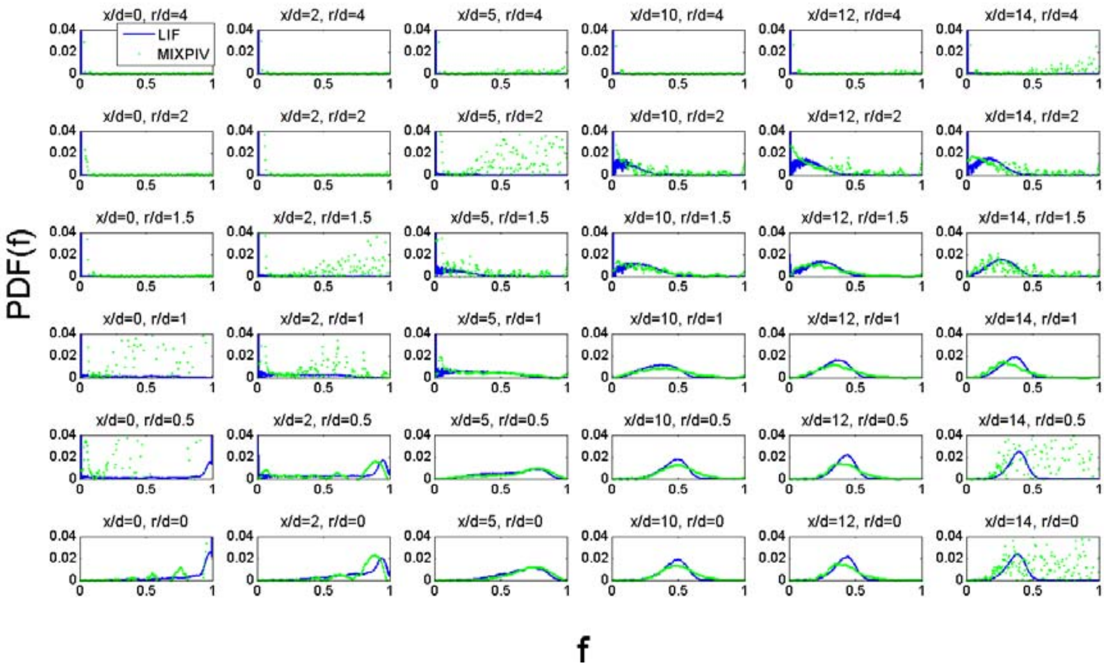

Fig. 5: Comparison of PDF's from LIF and MixPIV

In Fig. 5 the comparison of the mixture fraction PDF obtained from both methods is shown for a number of axial and radial positions, where the axial station increases from left (nozzle exit) to right and the radial location increases from bottom (centerline) to top. The LIF based PDF are plotted in blue and the MixPIV based ones are plotted in green symbols. Again, very good agreement is seen in general between the methods, validating both the MixPIV approach and the signal separation technique. In some cases the numerical system for the MixPIV deconvolution proved to be very unstable which is seen mostly in regions with high intermittency.

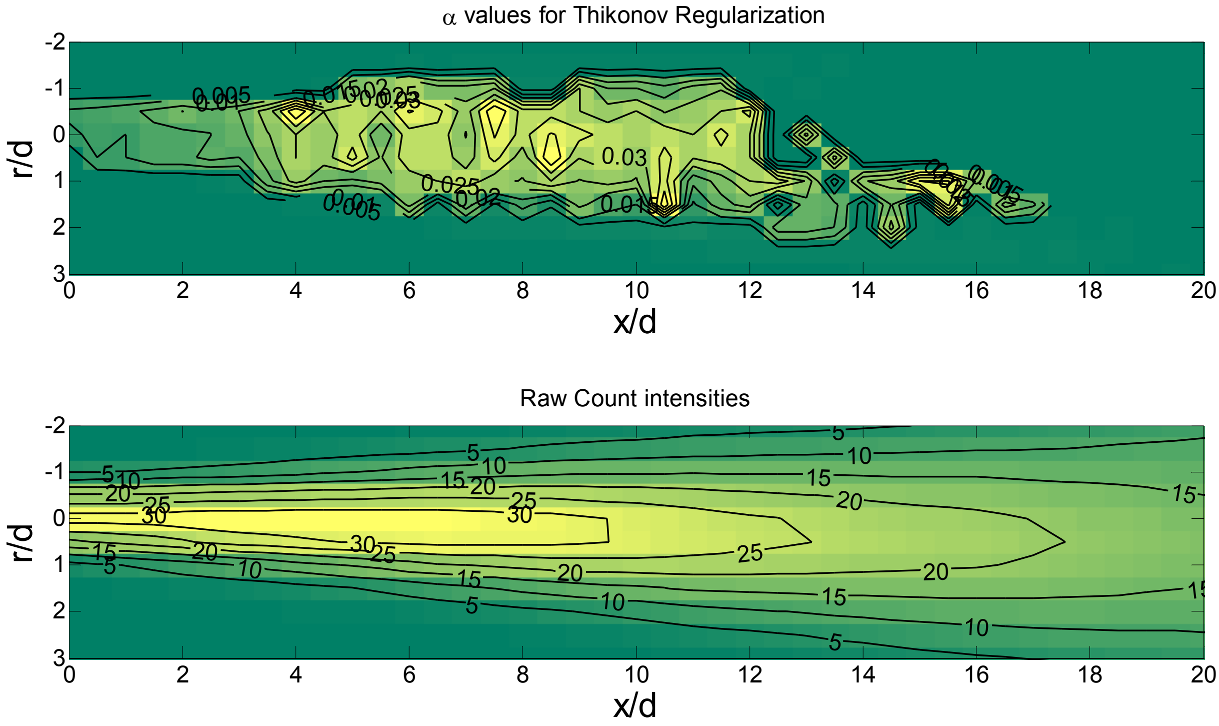

Fig. 6: Comparison of α and raw count intensity

In order to understand the stability of the code, the α value for the Thikonov Regularization was further investigated. α is the so called stability parameter of the matrix inversion used to calculate the PDF from the count signals. Ideally it would be zero, indicating a well conditioned linear system. Setting it too large produces the identity solution. A so called L-curve optimization is performed, which gives the correct α at minimal error of the equation system. From this investigation and comparing with the experimental frames it seems that there may be a connection between α and the particle density gradient. Besides the MixPIV method mixture fraction and thus mean particle density can be expressed by the mean values of the raw counts. In the top of Fig.6 a contour plot of α values used for the deconvolution is shown while below the mean count intensities are given. Comparing the contour distributions of both plots it is found that higher values of α are aligned with the 20 count isoline which is in the region of high radial gradients. This findings lead to the assumption that the sampled region has been chosen to big and creates therefore instabilities as we find big values of alpha.

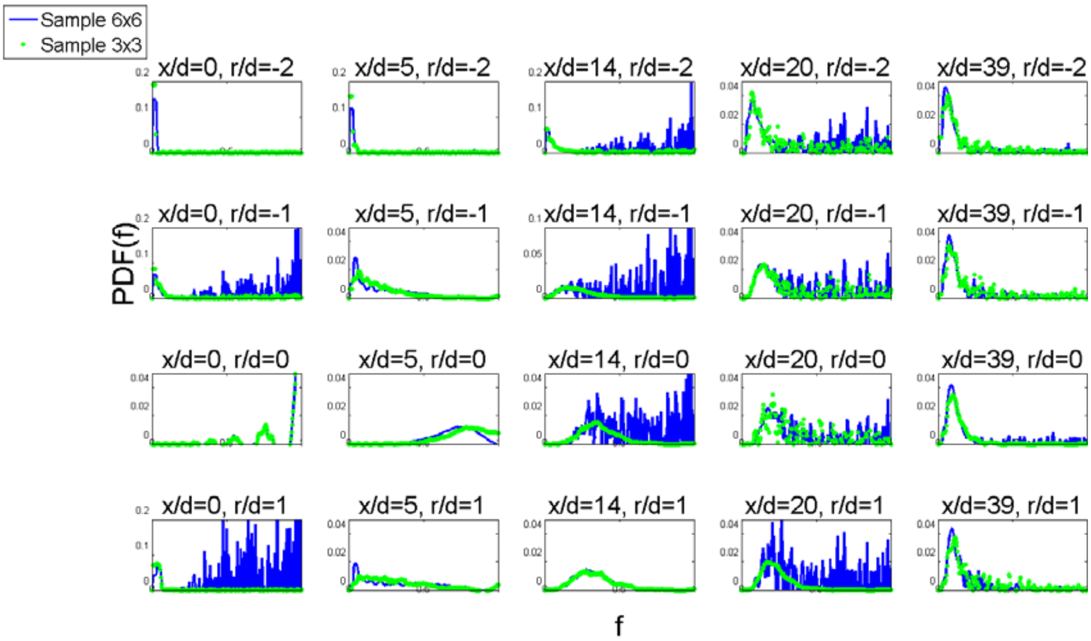

Fig. 7: MixPIV PDF's with different area sampling of surrounding pixels

To confirm this assumption, the analysis was repeated with a smaller sampling region. Fig.7 shows the same measurement PDF sampled with a varying number of pixels around the interested point. The analysis with an area of 6x6 pixels is plotted in blue, the one with the green symbols indicate a sampling of 3x3 pixels. An increased stability of the deconvolution can be achieved by decreasing the pixels around the interrogation point in areas of high gradients. The reduction of values creates an increased kurtosis of the count PDF. It seems that the algorithm is more stable for these PDF's.
This is a key finding for a successful application of the method, as it indicates that a certain contrast in values is needed for a stable deconvolution of the signals.

Summary and Conclusions

The results showed that a simultaneous application of LIF and MixPIV is possible. Mean mixture fractions can be gained from both methods equally. When it comes to Probability Density Functions, the MixPIV algorithm needs high enough contrast to work stably and give meaningful distributions. Then MixPIV is capable of achieving PDF's of quality comparable to LIF. As this set-up is a worst case scenario, the measurements are taken in two enclosed geometries of which one is a pipe; the results are promising for quantitative mixture studies of injection systems in water flows.

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Literature

Brackmann, U., 2000: “Lambdachrome® Laser Dyes“, Third Edition, pp. 146-147

Lawn, C.: “Lifted flames on fuel jets in co-flowing air”, *Progress in Energy and Combustion Science,* **2009***, 35*, pp. 1 - 30

Pernpeintner, M., Lauer, M., Hirsch, C., Sattelmayer T., 2011: “A METHOD TO OBTAIN PLANAR MIXTURE FRACTION STATISTICS IN TURBULENT FLOWS SEEDED WITH TRACER PARTICLES”, Proceedings of ASME Turbo Expo 2011 GT2011 June 6-10, 2011, Vancouver, British Columbia, Canada

Thring, M. W., Newby M. P.: “Combustion length of enclosed turbulent jet flame”, Proc. Combust. Inst. 1953, 4, pp. 789–796

Tieszen, S. R.; Stamps, D. W. & O'Hern, T. J.: “A heuristic model of turbulent mixing applied to blowout of turbulent jet diffusion flames”, *Combustion and Flame,* **1996***, 106*, pp. 442 - 466