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MISCHUNGSBESTIMMUNG EINES REAGIERENDEN JET IN HOT CROSS-FLOWS MITHILFE VON MIE STREUUNG

QUANTIFICATION OF MIXING OF A REACTING JET IN HOT CROSS FLOW USING MIE SCATTERING

M. Kolb, D. Ahrens, C. Hirsch, T. Sattelmayer
Technische Universität München, Lehrstuhl für Thermodynamik, Boltzmannstr. 15, 85748 Garching

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Abstract

A new method to obtain mixture fraction probability density functions (PDF) of turbulent mixing in planar sections of a flow field has been developed at the Institute of Thermodynamics at the Technische Universität München, Germany. The extended algorithm presented here takes different densities of mixing flows into account. Applied to reactive flows the algorithm can determine the mixture fraction before and after the flame front taking the sudden drop of the density over the flame into account. Therefore, the flow field is seeded with TiO_2 tracer particles to achieve a high spatial and temporal resolution of the mixture. This allows deep insights into the mixing patterns of the flow field. In the first part of this paper the method is validated using a nonreacting plain jet in cross flow with different densities. In the second part the method is applied to a reacting premixed plain jet in vitiated cross flow. The results show the temporal resolved detection of the flame front as well as the mixture fraction fields.

Introduction

This paper presents a MixPIV method, which allows to obtain mixture fraction probability density functions (PDF) of turbulent mixing in flow fields seeded with tracer particles. The predecessing method was validated in water channel experiments against PLIF measurements with good agreement of the results (Haner et al. 2012; Pernpeintner et al. 2011). The new algorithm can take different densities of jet and cross flow into account. The unprecedented adaptation to reactive flows with a compensation of the density drop over the flame front is the key feature of this publication.

The demand for a better understanding of the mixing patterns in reacting flow fields leads to the further development of this method. Applied to a non-reacting and reacting jet in cross flow the method gives the opportunity to get mixing fields of reacting flows. For setups with a jet in co- or cross flow the method allows to get time resolved and high spatial resolution quantitative 2-D mixture data. Additionally, the density drop across the flame front is also detectable and makes the method also useful to visualize the flame.

Description of Experiment

The presented data is obtained from the experiment shown in figure 1. The test rig consists of four modules. The first one, the plenum, houses 16 premixed swirl stabilized burners with a combined thermal power of about 1.5MW which provide the cross flow with a temperature of T_{ad}=1720K at equivalence ratio $\phi = 0.5$. The second module, the primary combustion zone, has a cross section of 500x500mm and is an impingement cooled combustion chamber which enables the 16 swirl flames to complete the combustion process before they enter the secondary combustion zone. In this third module the premixed plain jet with a diameter of 100mm and momentum ratio $J = \frac{\rho_J u_J^2}{\rho_X u_X^2} = 4 - 10$ enters the cross flow and gets ignited by the hot cross flow ($\phi_j = 0.5 - 0.77$). The secondary combustion zone has also an impingement cooled bottom plate and a water cooled steel frame with quartz windows on the top, left and right. The last module is a ceramic insulated chamber which provides the burnout of the jet flame. The primary as well as secondary combustion use natural gas as fuel. More details about the experiment can be found in Schmitt et al. 2013. For cold measurements the cross flow has a temperature of 288K and the jet of 393K which leads to different densities. For the reacting case the inlet air of the cross flow and of the jet are both preheated to 673K.

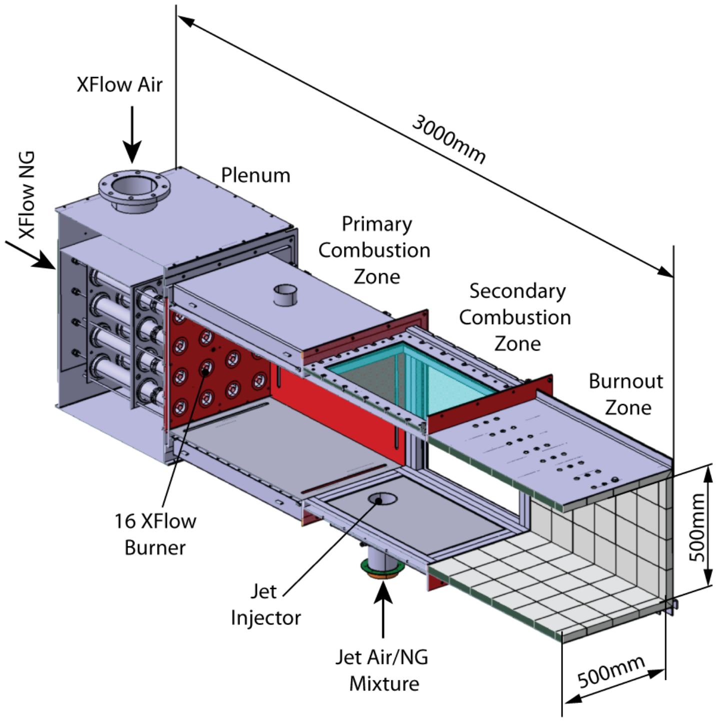

Figure 1: CAD drawing of the four modules of the test rig.

The Reynolds Number is calculated using equation 1, where u_j is the velocity of the jet at the exit, D_j the diameter of the jet and ν_j the kinematic viscosity. For the cold case the Reynolds Number is $Re_c = 42.000$ for $J = 10$, for the reacting case it is $Re_r = 59.000$ for $J = 4$.

$$Re = \frac{u_j D_j}{\nu_j} \tag{1}$$

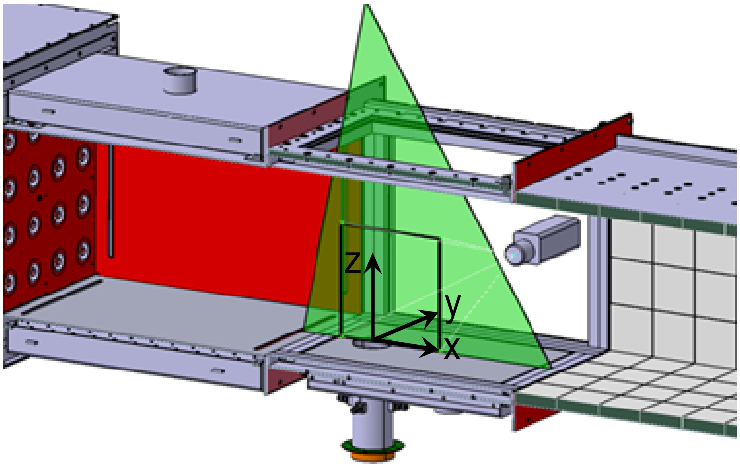

Figure 2: Scheme of the setup for MixPIV measurements.

Measurement Setup

The measurement setup for the MixPIV results is shown in figure 2. The laser sheet of a Nd:YLF pulse laser enters the measurement section from top and illuminates the center plane. The jet is seeded with TiO_2 particles with 1µm diameter. A camera with a bandpass filter (527nm +/-5) captures the scattered light. To get the cold validation data, a thermocouple is attached to a traverse and measures a three dimensional temperature field with 27.000 averaged temperatures $T(x, y, z)$. The scalar α of the temperature mixture fraction at each point can be calculated using equation 2 and is used as benchmark for the MixPIV method. The assumption made is that convective thermal and concentration mixing behave similar. The mixing through diffusion and heat conduction is different, but compared to the fast convective mixing process they are negligible. This was also shown by Roberts und Webster 2002. This method was already used by a lot of groups (Norster 1964; Kamotani und Greber 1972).

$$\alpha = \frac{T^* - T_x}{T_j - T_x} \tag{2}$$

The MixPIV Algorithm

The MixPIV algorithm uses an array of images of the seeded flow field. The following measurement errors have to be taken into account to get reliable mixture fraction results:

1. Background subtraction
2. Laser sheet correction
3. Seeding density fluctuations
4. Density correction

Equation 3 takes all those influences into account.

$$f(x, z, t) = \frac{I(x, z, t) - BG(x, z)}{I_{ref}(t)} LS(x, z) \frac{\rho(x, z, t)}{\rho_{ref}} \tag{3}$$

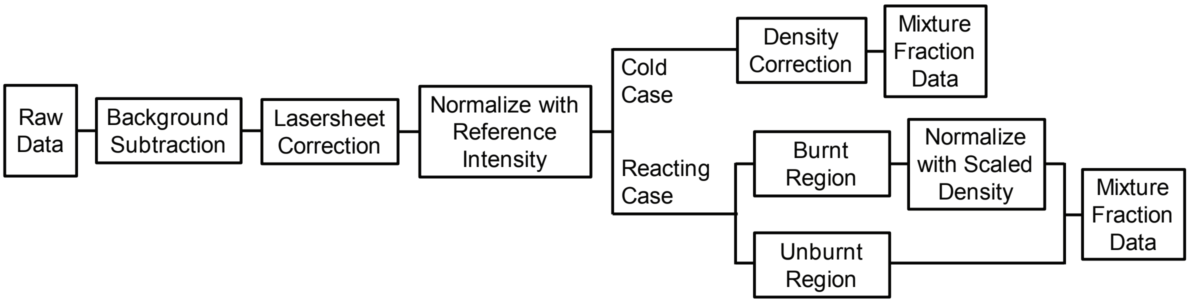

Figure 3: Scheme of the MixPIV algorithm

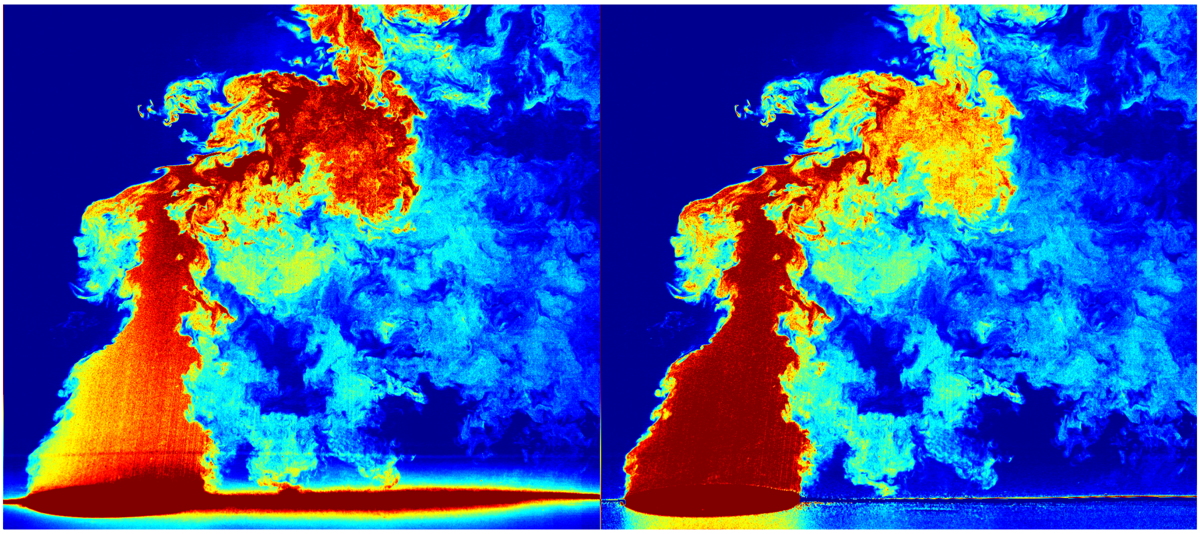

Figure 4: Example of light intensities of a raw (on the left) and processed picture. Background subtraction, laser sheet correction and normalization with the reference point were applied.

Where x and z describe the spatial coordinates and t the temporal resolution. In addition f is the mixture fraction, I the light intensity of the raw picture, I_{ref} the light intensity at the reference point, BG the background image, LS the light sheet correction, ρ the fluid density and ρ_{ref} the fluid density at the reference point.

A scheme of the algorithm is shown in figure 3.

The image of a flow without seeding is taken as the background image BS and subtracted from the raw intensity of all pictures of a time series. Furthermore a reference point in the jet core is defined, where the mixture fraction is always $f = 1$. At this point the reference intensity I_{ref} is measured for every frame to adjust fluctuations of the laser power and the seeding density. The result is a data set with normalized intensities which can be directly correlated to the mixture fraction, if there are no density gradients in the flow field. The result of the corrections can be seen in figure 4 which shows the differences between a raw and a processed picture.

Because of different temperatures of jet and cross flow in the cold case, the algorithm has to take different densities into account by calculating the mixture density as function of the mixture fraction f. The density ρ at any point can be expressed as a function of I and the initial densities of the two mixing flows as proposed by Sautet und Stepowski 1994.

The reacting case needs additional processing due to the density drop along the flame front. The density drop causes a drop of the scattered light intensity I but the mixture fraction f does not change over the reacting. To avoid this influence on the mixture fraction, the flame front is detected through the density drop and the unburnt as well as burnt regions are treated separately. The unburnt region is scaled with the reference intensity I_{ref} while the burnt region is scaled with the reference intensity reduced by the ratio of the density across the flame front $\rho_{burnt}/\rho_{unburnt}$.

In a last step, the time series of images can be used to calculate the PDF of the mixture fraction at different locations.

Validation for the cold case

To validate the updated MixPIV method the experiment is operated without reaction (cold case). The mixture fraction is measured both using the MixPIV method and by point wise temperature measurements. The quantitative comparison is made along the z-axis at y=0 and different x coordinates in figure 5. The results show that the agreement between the two measurement techniques is very good. The differences are in every point below 5%.

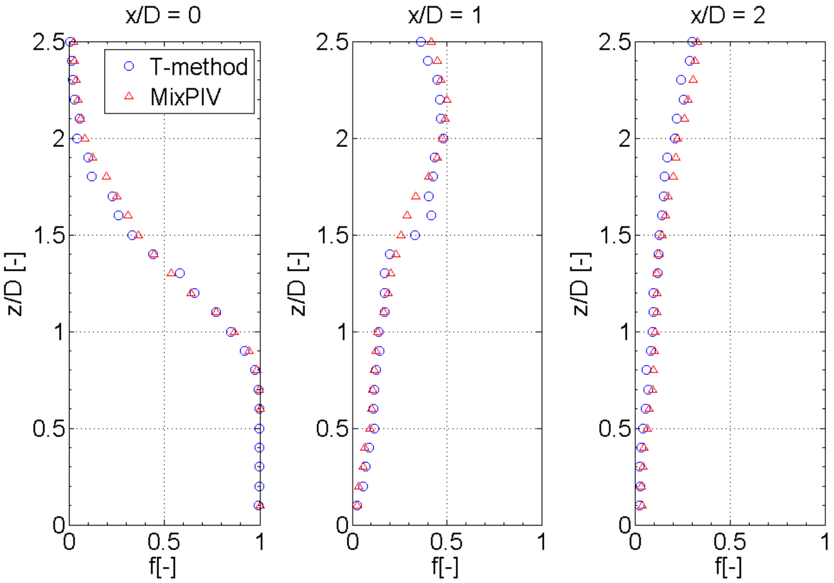

Figure 5: Quantitative comparison of the temperature and MixPIV method.

Results of the cold case

The cold case data of a plain jet is presented in figure 6. From the center plane of the mean mixture data it can be seen, that there is a stationary core region of the jet. Furthermore, the penetration depth of the jet is visible as well as the wake region with very small portions of jet material. To make statements about the instantaneous mixture fraction, the PDFs are necessary. The PDFs of the four characteristic regions labeled in figure 6 are shown in figure 7.

The homogeneous mixture between jet and cross flow depends on the mass flow ratio and is f = 0.0791 in this case. The previously mentioned figure 4 shows an instantaneous image of the flow field. This can further be used to get a better understanding of the transient turbulent structures of the jet in cross flow phenomenon which is reflected in the PDFs.

Region 1 is in the core of the jet and shows a spike at 1. That means that the mixture in every instantaneous frame is 1 and corresponds to the mean mixture. This also means that fluctuations in the seeding density are very low and negligible.

Region 2 is in the highly turbulent shear layer of the jet and cross flow. A maximum of the distribution is around 0.1. The fluctuations cause the fast transient mixing which results in the wide PDF distribution.

Region 3 is characteristic for the wake region of the jet. The PDF of the plain jet has its peak at 0 and thus contains many values between 0 and 0.1. Nevertheless, the mean value of 0.2 is not very frequent but values between 0.2 and 0.6 are. This PDF shows that the wake region is often passed by coherent structures of jet material which are not completely mixed, yet.

Region 4 is the tip of the jet core and has an average mixing fraction of 0.3. The PDF shows a wide distribution and a spike at 1. The distribution shows that the average value rarely appears. Also there is still a not negligible amount of jet material detectable which is not mixed at all at this point.

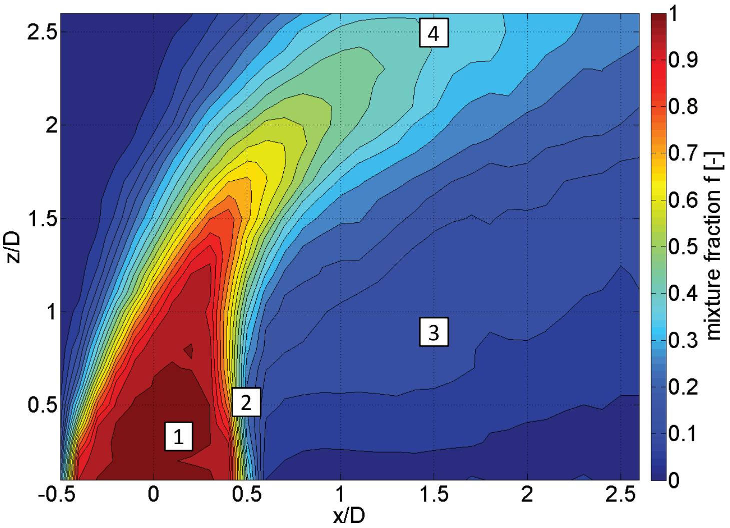

Figure 6: Mixture Fraction of the plain jet in the centerplain. The numbers mark the positons of the PDF evaluation.

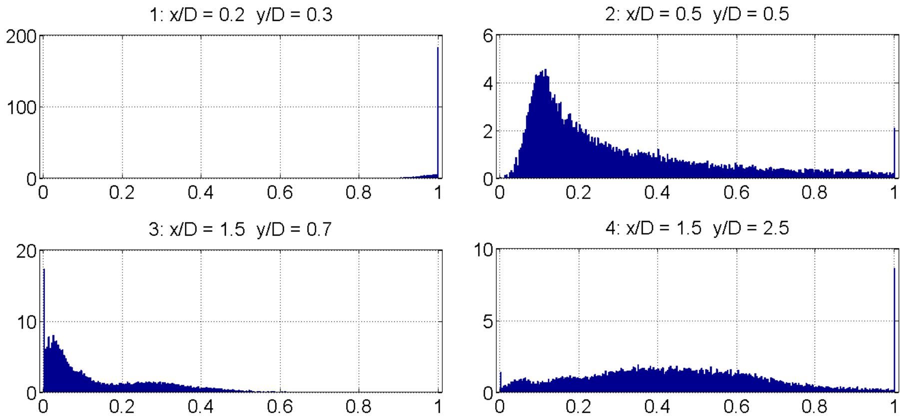

Figure 7: The PDFs of four different regions of the plain.

Results of the reacting jet in cross flow

In comparison to the cold measurements the mixture analysis of a reacting flow with temperatures of over 1700K and a heat source is much more challenging.

Nevertheless, the updated MixPIV algorithm can also be used for the reacting data. One processed instantaneous image of the reacting jet at a momentum ratio $J = 4$ and an equivalence ratio of the jet of $\phi = 0.77$ can be seen in figure 8. The flame front is detected by the algorithm using the density drop and is marked with a white line. The mixture fraction does not change over the flame front, which proves the density compensation to work. Furthermore, the turbulent mixing structures are clearly traceable. This data helps to identify the combustion regime and the length scales. As for the cold data PDFs can be generated.

A problem is the steep mixture gradient after the flame front. There is no physical reason why the burnt material should mix so fast with the cross flow. Diffusion is too slow and turbulent mixing would show turbulent structures. The explanation for this problem is probably the multiple scattering. This phenomenon describes the light exchange of adjacent particles. Reactive flows are seeded denser than cold flows to get high laser scattering after the density drop. Less seeding would decrease the influence of the multiple scattering substantially, but also increase the noise in the captured signal. Alternatively a filter could be applied to remove the multiple scattering (Voigt 1999).

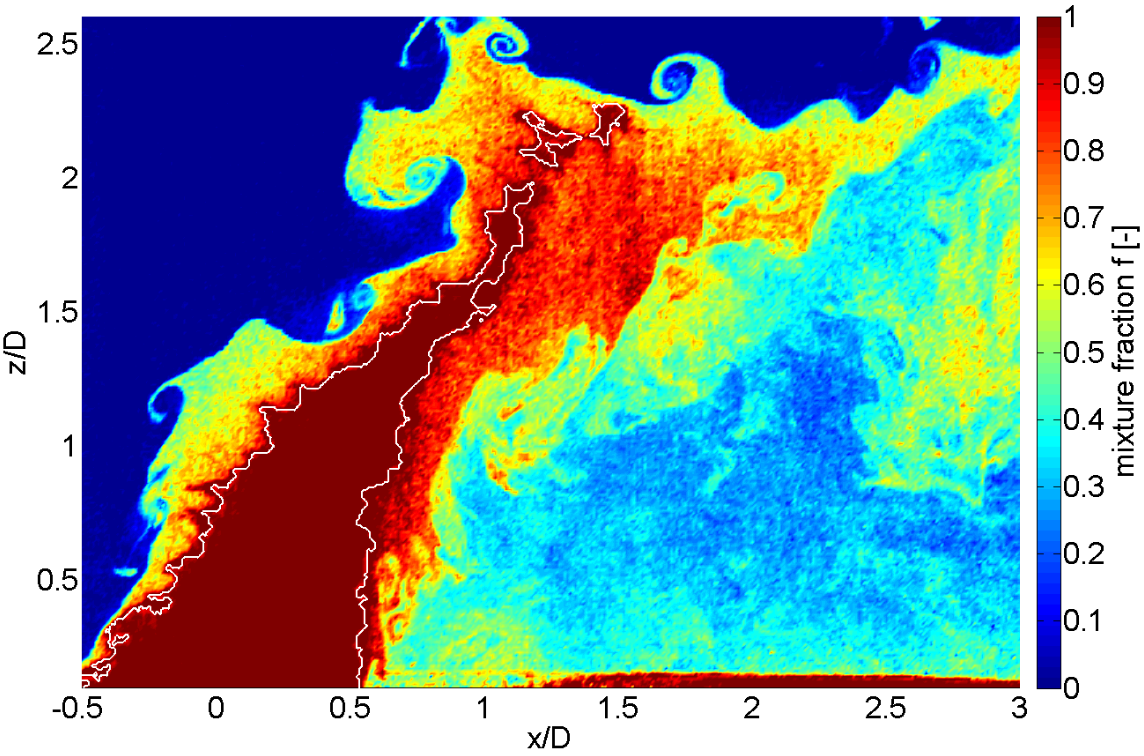

Figure 8: MixPIV data in the center plane for the reacting jet. The flame front is marked by the white line.

Conclusions

The previous presented MixPIV method was updated and improved. It could be validated that the new algorithm is able to resolve the mixing fraction of two mixing flows with different densities with a high temporal and spatial resolution. Additionally, the code is also able to calculate mixture fields for a reacting flow, which is a new application of Mie scattering. Furthermore, the time resolved visualization of the flame front is also possible.
The last problem to solve is the error created by multiple scattering. This problem can probably be solved in the future using an optimized seeding density or by quantifing and subtracting the multiple scattering, depending on the seeding density.

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