

# Investigation of small-scale wall near flow structures using NO-tagging

Johann von Saldern, Sören Doose, Claus Orlemann, Christof Schulz, Jürgen Wolfrum

Physikalisch-Chemisches Institut

Universität Heidelberg

Im Neuenheimer Feld 253, 69120 Heidelberg; Germany

## ABSTRACT

A detailed understanding of transport phenomena (species, heat) in turbulent flows and especially through near-wall laminar boundary layers is essential for a total description of reactive flows. Our research aims at a better understanding of such transport processes by providing experimental data with both, high spatial and temporal resolution to validate the results of mathematical simulations. The main interest of the experimental work focuses on the detection of wall/flow interaction (Doligalski et al., 1994) and the visualization of small-scale turbulent structures and their evolution.

The use of molecular tracers (Hiller and Hanson, 1988; Miles and Lempert, 1997; Grünefeld et al., 1998; Miles et al., 1987; Ribarov et al., 1998, and Krüger and Grünefeld, 1999) circumvents typical problems with particle seeding, where tracking of the gas motion is poor due to the momentum of the particles at high speeds and high turbulence. Furthermore, investigations close to walls become feasible, where particle methods tend to fail due to window fouling caused by electrostatic forces. Experiments monitoring the behavior of molecular tracers can also help to verify CFD-calculations which additionally consider molecular transport. This is essential for the description of reactive flows. Therefore, we developed and applied a flow tagging technique using photodissociation-generated nitric oxide as a molecular tracer (Orlemann et al., 1999, and Doose et al., 1999).

In the study presented here, air flows were homogeneously seeded with NO<sub>2</sub> at low concentrations. By photodissociation of NO<sub>2</sub> using an excimer laser (308 nm), NO was produced along the beam path, forming a spatial line of NO-molecules which was imaged by laser-induced fluorescence (LIF) at various delays after its generation (Orlemann et al., 1999). The detected NO-distribution shows the altered shape of the NO-line, caused by convective and diffusive effects during the time interval between the two lasers shots. Whereas several other tracers disappear rather quickly due to energy transfer processes (from vibrationally excited molecules (Miles et al., 1987)) or high reactivity (in the case of OH (Ribarov et al., 1998)), NO is stable on the time-scale of interest (some milliseconds) due to small reaction cross-sections. Therefore, using NO, the motion of volume elements can be imaged at longer times and larger distances compared to other techniques. Furthermore, with the molecular weight of NO in between those of N<sub>2</sub> and O<sub>2</sub> and diffusion coefficients close to nitrogen, NO turns out to be a good choice to characterize the small-scale behavior of turbulent air flows.

## 1. INTRODUCTION

In recent years different approaches to measure flow patterns using molecular tracers have been published (Boedeker, 1989; Exton and Hillard, 1986; Hiller and Hanson, 1988; Miles et al., 1987; Miles and Lempert, 1997; Ribarov et al., 1998; Paul et al., 1989; Miles et al., 1978; Lozano et al., 1993, and Grünefeld et al., 1998). In contrast to droplet or particle seeding, molecular tracers are able to follow flows with higher velocity gradients. This circumvents typical problems, e.g. tracking of the gas flow by particles may be poor at high speeds and high turbulence. Homogeneously seeded flows enable experiments that investigate the center of turbulence elements, where due to centrifugal forces the injection of particles is difficult, and areas close to walls where electrostatic forces may cause problems with window fouling. Furthermore, even in large-scale facilities, uniform seeding with molecular tracers becomes possible.

On the one hand the contribution of the molecular tracer to the total mass flow is negligible, avoiding any significant alteration of the flow. On the other hand effects of diffusion play an important role. This indicates a suitability of molecular tracers at high flow velocities or small scales, therefore molecular tracers are dedicated to applications on interactions between molecular and turbulent mixing.

Three different applications of molecular tracers are common: First, the Doppler shifts of LIF- or Raman-signals can be used to evaluate velocities. Different experiments using this method have been carried out in seeded flows (e.g. by LIF of an NO seeded supersonic flow (Paul et al., 1989), LIF of iodine (Hiller and Hanson, 1988), LIF of sodium vapor (Miles et al., 1978)) and by Rayleigh (Miles and Lempert, 1997) or Raman (Exton and Hillard, 1986) scattering in unseeded flows.

In inhomogeneously seeded flows, velocities or mixing are visualized by the detection of concentration gradients which are induced by partial or pulsed seeding of the gas flow, e.g. using acetone (Lozano et al., 1993) or NO (Grünefeld et al., 1998).

Flow tagging techniques in contrast are based on the displacement of structures which are generated within the flow by photo-induced processes. For unseeded flows, Miles et al. proposed RELIEF (Raman-excitation and laser-induced electronic fluorescence) of O<sub>2</sub> (Miles et al., 1987). Boedeker et al. measured velocities by H<sub>2</sub>O photolysis and LIF detection of OH (Boedeker, 1989), and Ribarov et al. (Ribarov et al., 1998) showed the abilities of OTV (Ozone Tagging Velocimetry) by imaging an ArF-Laser written line of O<sub>3</sub>.

In the study presented here, air flows have been homogeneously seeded with NO<sub>2</sub> at low concentrations. By photodissociation of NO<sub>2</sub> using an excimer laser (308 nm), NO has been produced along the beam path, forming a spatial line of NO-molecules which has been imaged by laser-induced fluorescence (LIF) at various delays after its generation (Orlemann et al., 1999). The detected NO-distribution shows the altered shape of the NO-line, caused by convective and diffusive effects during the time interval between the two laser shots. Whereas several other tracers disappear rather quickly due to energy transfer processes (from vibrationally excited molecules (Miles et al., 1987)) or high reactivity (in the case of OH (Ribarov et al., 1998)), NO is stable on the time-scale of interest (some milliseconds) due to small reaction cross-sections. Therefore, using NO, the motion of volume elements can be imaged at longer times and larger distances compared to other techniques. Furthermore, with the molecular weight of NO lying in between that of N<sub>2</sub> and that of O<sub>2</sub> and diffusion coefficients being close to nitrogen, NO turns out to be a good choice to characterize the small-scale behavior of turbulent air flows.

## 2. EXPERIMENTAL

Experiments have been carried out in air flows passing through an optically accessible channel with a cross section of 50 x 20 mm<sup>2</sup>, seeded with 600 ppm NO<sub>2</sub>. To control the flow, mass flow controllers (*Tylan* FC 262) at a maximum flow rate of 600 slm have been used. In this channel, homogeneous turbulence has been generated by the use of various turbulence grids with different hole sizes and solidities.

To photodissociate NO<sub>2</sub> along a spatial line, the beam of a XeCl excimer laser (308nm) was focused to a diameter of approx. 0.8 mm (pulse energies at approx. 200 MW/cm<sup>2</sup>). The generated NO-line was imaged with excitation of the P<sub>1</sub>(1) line in the A-X(0,0) transition at 226 nm at various delays after its formation. The beam (1.3 mJ/pulse) of a XeF excimer-pumped frequency-doubled dye-laser has been formed to a light sheet of 0.1 x 2.7 mm<sup>2</sup>. LIF-signals of the NO A-X(0,1), (0,2) and (0,3) transitions (at 235–258 nm) have been bandpass-filtered and detected with a gated (100 ns) image-intensified slow scan CCD-camera (*LaVision*, Flame Star III), equipped with an achromatic  $f = 100$  mm UV lens, giving a resolution of about 60 microns per pixel.

Due to the effective suppression of wall-induced stray light, the NO-line was detectable close to the wall. With 600 ppm NO<sub>2</sub> seeding concentration, an optimal signal-to-background ratio was obtained. Since the generated

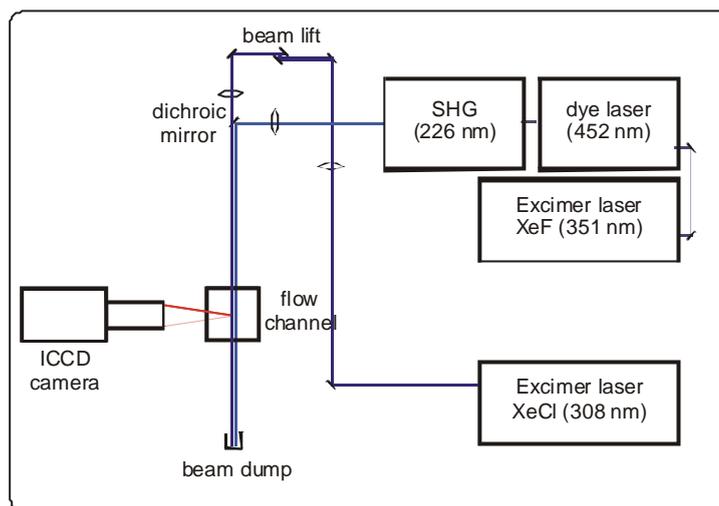


Fig. 1. Schematic drawing of the experimental setup.

NO-line is broadened by diffusion downstreams, the maximum delay where the tagged volume was detectable is up to 30 ms. Here the line broadens to approx. 3 mm but still can be discriminated against the background.

Handling and controlling constant flows of NO<sub>2</sub> under atmospheric or higher pressure conditions is difficult due to condensation of NO<sub>2</sub> and formation of N<sub>2</sub>O<sub>5</sub>. Therefore, to provide constant and reproducible seeding, NO<sub>2</sub> has been produced from the reaction of NO + O<sub>2</sub> by mixing NO with air in a 5 l reaction vessel just before entering the flow channel. The individual flows have been controlled by mass flow controllers (Tylan FC 262) with a maximum flow of 100slm for air and 66scm for NO resp. At standard conditions, the ratio of equilibrium concentrations of NO<sub>2</sub> and NO lies far on the side of NO<sub>2</sub>. To reach this equilibrium, a steel chamber of 50l has been used to increase residence times.

### 3. RESULTS AND DISCUSSION

At various flow conditions, the generated NO-line has been imaged downstreams at different delays after its formation. For further processing of the NO-line shifts, an unambiguous detection of the center of the shifted line

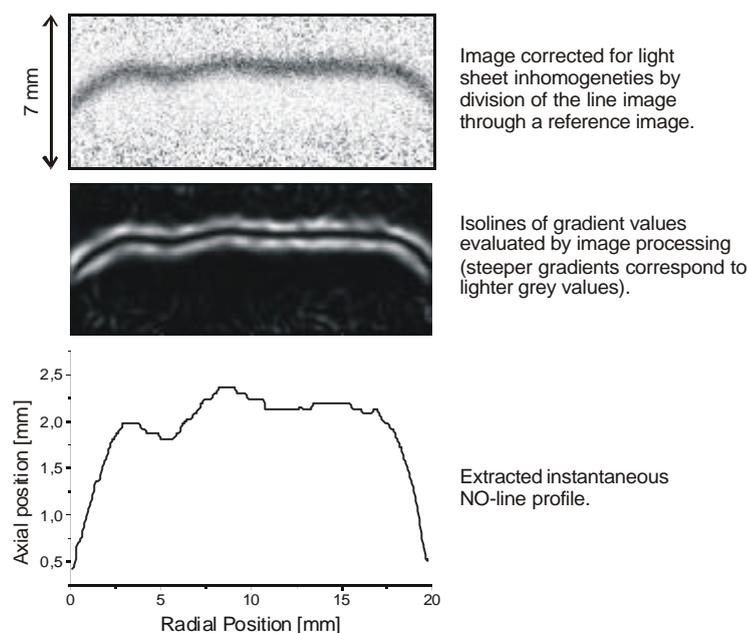


Fig. 2. Image processing scheme (1.5 ms between line formation and detection) (Doose et al., 1999).

is crucial. To minimize the influence of shot noise even at long delays between generation and detection a contour averaging and gradient evaluation technique (Doose et al., 1999) has been applied to process the detected LIF images. Figure 2 shows the image processing procedure (Geißler and Scholz, 1999) to extract the line from a single shot image of the shifted NO-line obtained 150  $\mu\text{s}$  after its generation by photo dissociation.

In this way, highly resolved flow structures in the sub-millimeter-range have become visible. Figure 3 shows typical instantaneous NO-line profiles for three different delays between formation and detection at a flow of 150 slm. Implicitly the effect of higher delays could be observed in the obtained structure of the NO-line. Furthermore the lower flow velocities close to the wall are visible in the smaller line shift in the boundary layer.

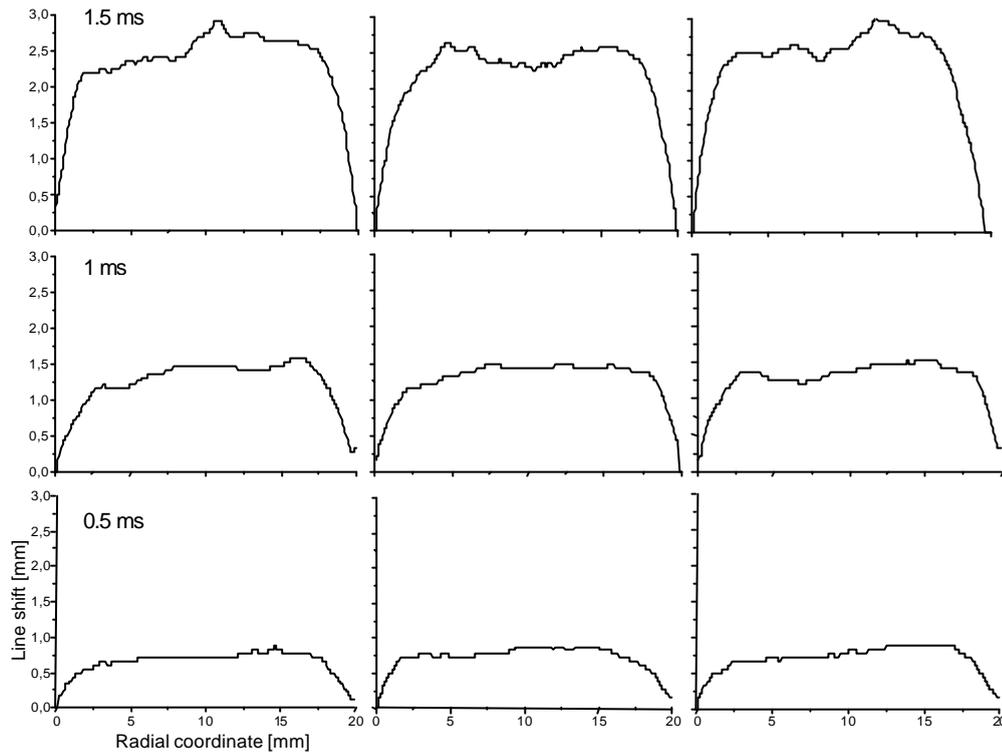


Fig. 3. Comparison of three instantaneous NO-lines at different delays between formation and detection (0.5 ms; 1 ms; 2ms delay). Center-flow velocity 1.4 m/s.

Subsequent generation of NO-lines with short temporal delay gives further insight in the dynamics of the turbulent flow. This has been realized using the third harmonic of a diode-pumped Nd-YAG-laser (*Lambda - Physik*, Starline) for the photodissociation of  $\text{NO}_2$ . The detection of the multiple NO-lines took place instantaneously using the experimental setup described above. Two of the pictures obtained are shown in figure 4.

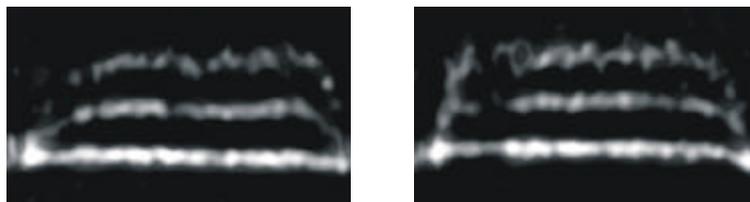


Fig. 4. Instantaneous measurement of subsequently generated NO-lines. Picture dimensions are about 10.5 x 20 mm; center-flow velocity 2.2 m/s. Time delay between generation of adjacent lines: 1 ms. Time delay between generation and detection of the line at the bottom of the picture: 0.5 ms.

Three different NO-lines can be identified easily within the area illuminated with the detection light sheet, the upper line being the one that has been generated first. The pictures have been processed with multi resolution based filtering using the  $\hat{A}$ trous algorithm. With the present setup only a limited laser power density was available per single shot. Therefore resulting NO-concentration and signal- to background ratios were limited. For this reason in further experiments another laser system providing higher pulse energies will be used.

A statistical treatment of the measured instantaneous NO-line profiles is shown in figure 5. It visualizes the standard deviation of the shifted NO-line position in main flow direction at different flow velocities and at delays of 1 ms between NO-formation and detection. Maximum standard deviations are found within the wall boundary layers where the highest shear stress is present, corresponding to earlier publications (Laufer, 1951). For longer delays the turbulent transport of NO-molecules perpendicular to the main flow direction gains more and more influence. This causes a broadening of the peaks of the standard deviation with increasing delays, and a corresponding decrease in peak values. A comparison of the peak position at the same delays between formation and detection of the NO-line shows that the peaks are moving towards the wall with increasing flow velocities. This can be attributed to the decrease of the boundary layer thickness with increasing Reynolds numbers (Laufer, 1951, and Schlichting and Gersten, 1997).

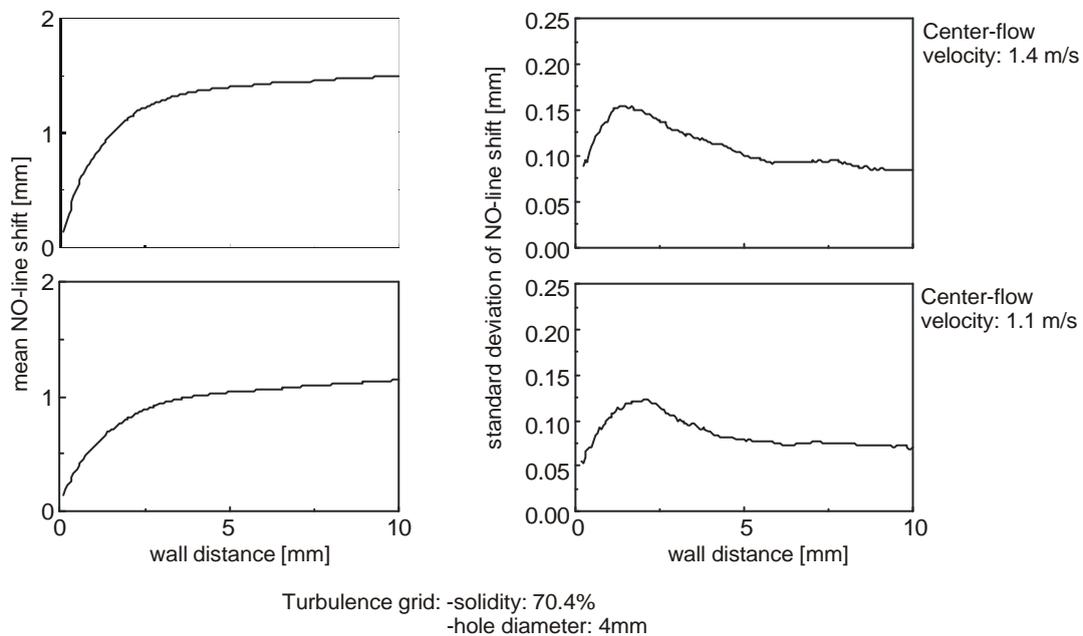


Fig. 5. Standard deviation of NO-line shift at different flow velocities. Delay between NO-line generation and detection: 1 ms.

Results are now available which allow a detailed comparison with the results of DNS- and PDF-simulations of near-wall behavior in turbulent flows. Experimental data like species concentration, volume flow, the standard deviation of the NO-line shift and the geometry of the experimental setup are used as input for the simulation. A comparison of the experimental data with a direct numerical simulation of the turbulent flow at a mean velocity in the center of the flow of  $u_0 = 2.2$  m/s, a standard deviation of the NO-line shift of  $u_{RMS} / u_0 = 0.3$  at an initial time  $t = t_0$  and a time delay corresponding to the experimental values is shown in figure 6. The time delays upwards are 0 ms, 0.5 ms, 1 ms and 1.5 ms. At the initial time a Gaussian profile of the NO-concentration has been used, equal to the profile of the photodissociation laser used in the experiment. More information about the simulation are available in Lange, 1998.

At first glance the line structure of the simulated flow shows a higher influence of turbulence elements. In general the development of the line is well described by the results of the simulation. The simulation has been carried out by Marc Lange, IWR, University of Heidelberg.

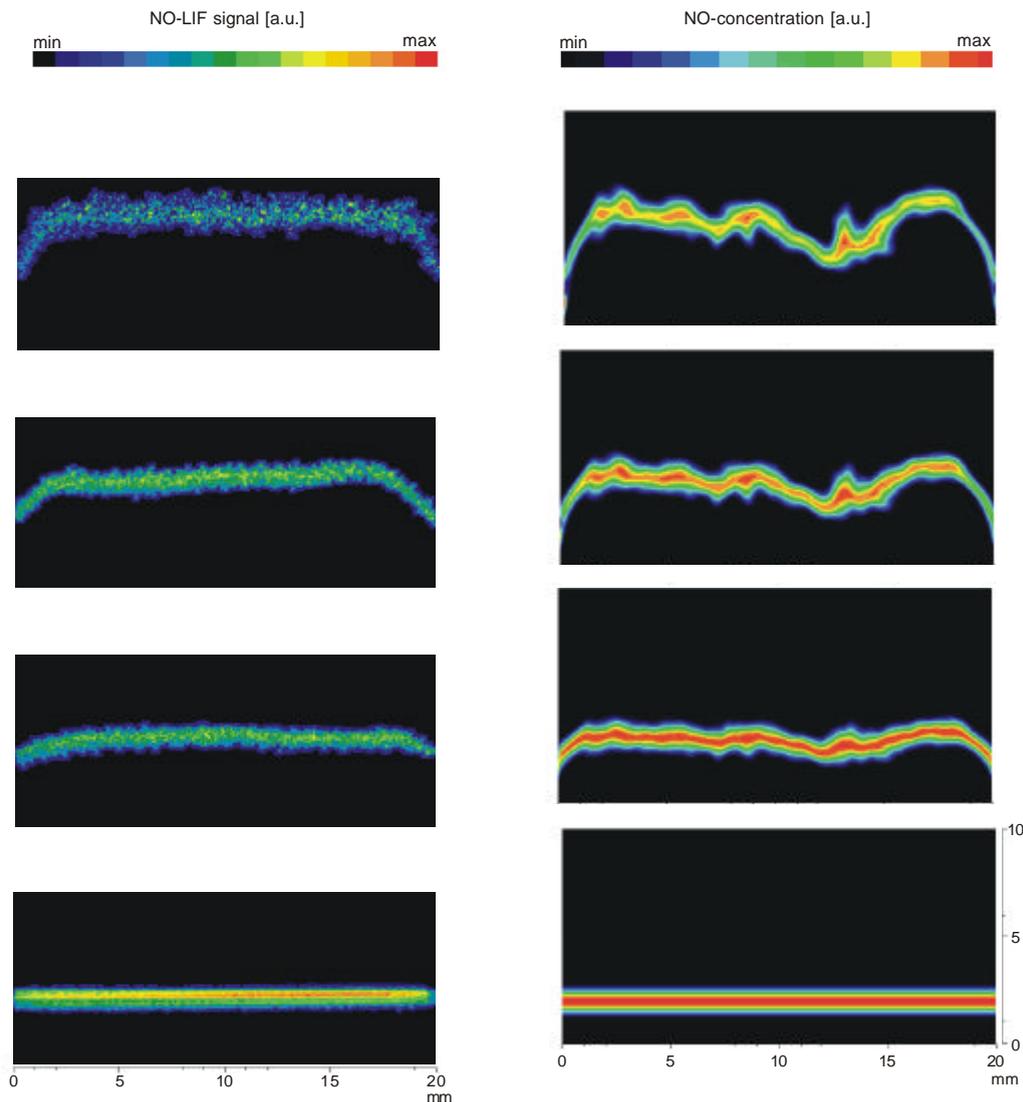


Fig. 6. Comparison of experimental results with results of DNS-simulation of the turbulent flow at  $u_0 = 2.2$  m/s and  $u_{RMS} / u_0 = 0.3$ . The left column shows the experimental results, the right column the results of a DNS-simulation initialized at  $t=t_0$  and corresponding delays. The time delays upwards are 0 ms, 0.5 ms, 1 ms and 1.5 ms (Simulation provided by of Marc Lange, IWR, Universität Heidelberg).

#### 4. CONCLUSIONS

The NO/NO<sub>2</sub> flow tagging technique has proved to be a promising tool to measure small-scale flow patterns. It offers a non-intrusive view into the characteristics of turbulent flows, allowing the extraction of flow parameters. Different flow rates and turbulence intensities give the possibility to measure instantaneous and average velocity distributions with high spatial resolution and circumvent the restrictions of particle scattering techniques. With this technique small-scale turbulent structures near a solid wall within turbulent channel flow have been monitored. Subsequent generation of multiple NO-lines offers the possibility to assess temporal and spatial development of turbulence elements yielding a more complete picture of the turbulent flow. Single-shot and statistical data are available for detailed comparison with results of Computational Fluid Dynamics (CFD) calculations.

## 5. ACKNOWLEDGEMENTS

This work has been funded by the Deutsche Forschungsgemeinschaft within the Sonderforschungsbereich 359 “Reaktive Strömungen, Diffusion und Transport“.

Direct numeric simulation were provided by Marc Lange, Interdisciplinary Center of Scientific Computing (IWR). Peter Geißler (IWR) provided imaging analyzing routines for structure analysis. Their contribution is gratefully acknowledged by the authors.

## REFERENCES

Boedeker, L.R. (1989). “Velocity measurement by H<sub>2</sub>O photolysis and laser-induced fluorescence of OH”, *Opt. Lett.* 14, pp. 473-475.

Doligalski, T.L., Smith, C.R. and Walker, J.D.A. (1994). “Vortex interactions with walls”, *Ann. Rev. Fluid Mech.*, pp. 573-616.

Doose, S., Orlemann, C., Schulz, C., Wolfrum, J., Geißler, P. and Jähne, B. (1999). “NO-flow tagging by photodissociation of NO<sub>2</sub>: applications of a new technique to visualize turbulent flow structures”, *Proceedings of the meeting of the British, French and German section of the combustion institute, Nancy*, pp. 427-429.

Exton, R.J. and Hillard, M.E. (1986). “Raman Doppler velocimetry: a unified approach for measuring molecular flow velocity, temperature and pressure”, *Appl. Opt.* 25, pp. 14-21.

Geißler, P. and Scholz, T. (1999). In “Handbook of computer vision and applications”, Eds. B. Jähne, H. Haußecker, P. Geißler, Academic Press, vol. 3.

Grünefeld, G., Gräber, A., Diekmann, A., Krüger, S. and Andresen, P. (1998). “Measurement system for simultaneous species densities, temperature and velocity double-pulse measurements in turbulent hydrogen flames”, *Comb. Sci. and Tech.*, vol. 135, pp. 135-152.

Hiller, B. and Hanson, R.K. (1988). “Simultaneous planar measurements of velocity and pressure fields in gas flows using laser-induced fluorescence”, *Appl. Opt.*, vol. 27, no 1, pp. 33-47.

Krüger, S. and Grünefeld, G. (1999). “Stereoscopic flow-tagging velocimetry”, *Appl. Phys. B* 69, pp. 509-512.

Lange, M., Thevenin, D., Riedel, U. and Warnatz, J. (1998). “Direct numerical simulation of turbulent reactive flows using massively parallel computers”, in “Parallel computing: Fundamentals, applications and new directions”, D'Hollander, E.H., Joubert, G.R., Peters, F.J. and Trottenberg, U., Elsevier Science, Amsterdam, pp. 287-295.

Laufer, J. (1951). “Investigation of turbulent flow in a two-dimensional channel”, *NACA annual report* 1053, 37-vol. 2.

Lozano, A., Smith, S.H., Mungal, M.G. and Hanson, R.K. (1993). “Concentration measurements in a traverse jet by planar laser-induced fluorescence of acetone”, *AIAA journal*, vol. 32, no. 1, technical notes, pp. 218-221.

Miles, R. Cohen, C., Connors, J. Howard, P. Huang, S. Markovitz, E. and Russell, G. (1987). “Velocity measurements by vibrational tagging and fluorescent probing of oxygen”, *Opt. Lett.* 12, pp. 861-863.

Miles, R.B., Udd, E. and Zimmermann, M. (1978). "Quantitative flow visualisation of sodium vapor seeded hypersonic helium", *Appl. Phys. Lett.* 32, pp. 317-319.

Miles, R.B. and Lempert, W.R. (1997). "Quantitative flow visualization in unseeded flows", *Ann. Rev. Fluid Mech.* 29, pp. 285-326.

Orlemann, C., Schulz, C. and Wolfrum, J. (1999). "NO-flow tagging by photodissociation of NO<sub>2</sub>. A new approach for measuring small-scale flow structures", *Chem. Phys. Lett.* 307, pp. 15-20.

Paul, P.H., Lee, M.P. and Hanson, R.K. (1989). "Molecular velocity imaging of supersonic flows using pulsed laser-induced fluorescence of NO", *Opt. Lett.* 14, pp. 417-419.

Ribarov, L.A., Wehrmeyer, J.A., Batliwala, F., Pitz, R.W. and DeBarber, P.A. (1998). "Ozone tagging velocimetry (OTV) measurements using narrowband excimer lasers", *AIAA-paper*, 98-0513.

Schlichting, H. and Gersten, K. (1997). "Grenzschicht-Theorie", Springer Verlag Berlin, Heidelberg, New York.