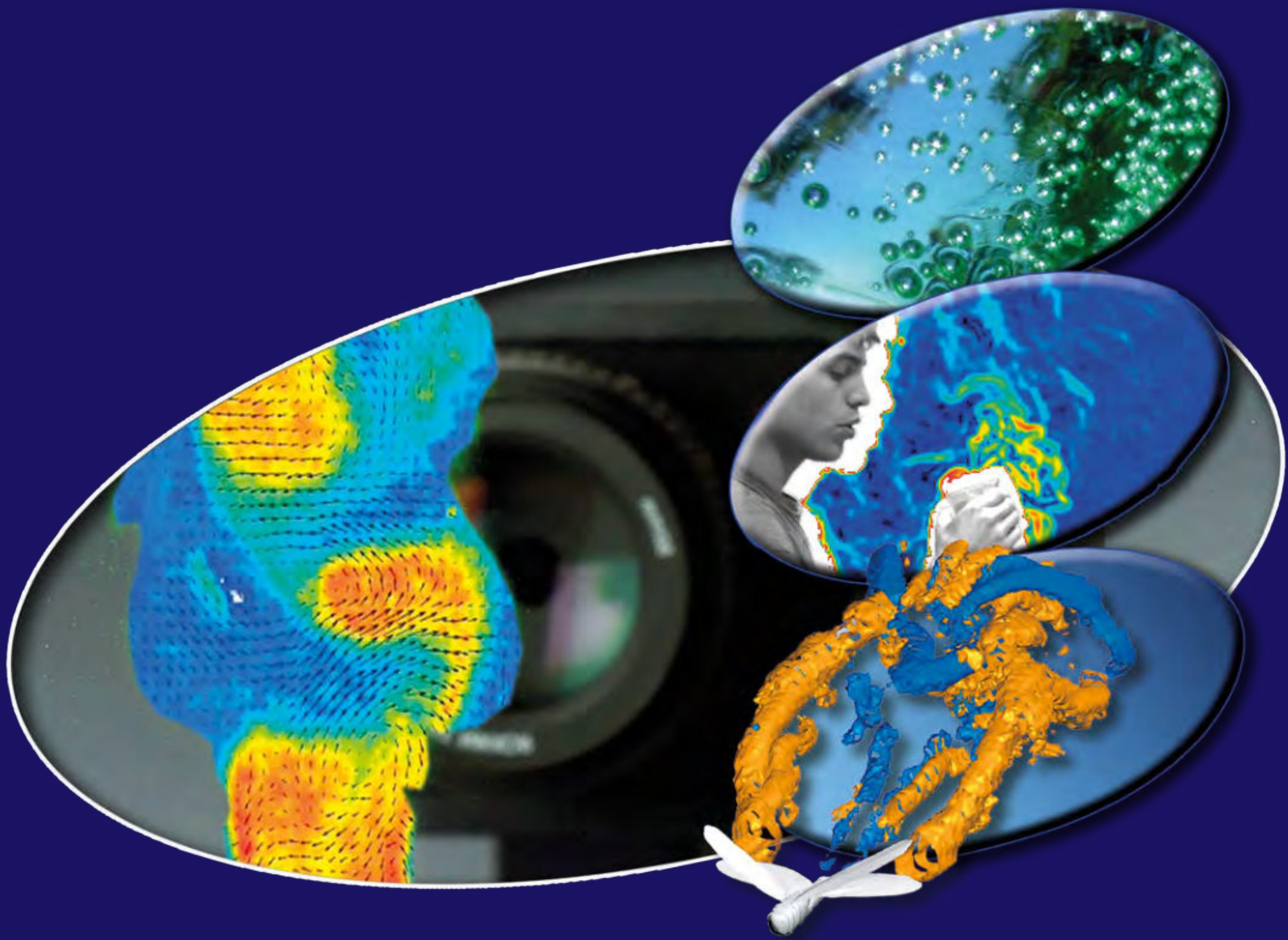


Focus on Fluid Dynamics

Advanced Laser Imaging Solutions

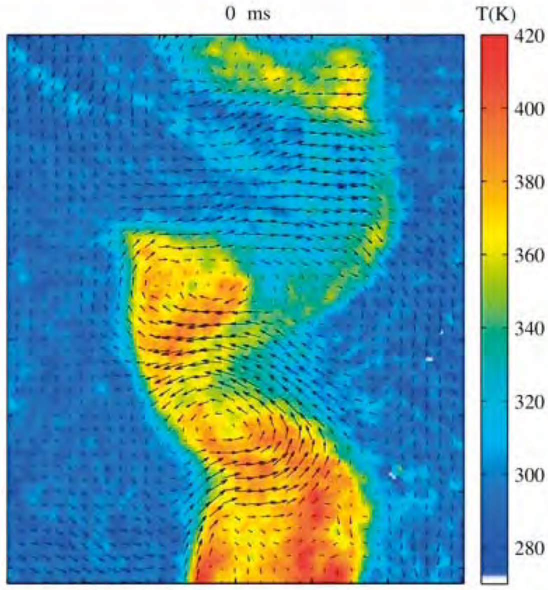
LAVISION
FOCUS ON IMAGING

Laser Imaging in Fluid Dynamics

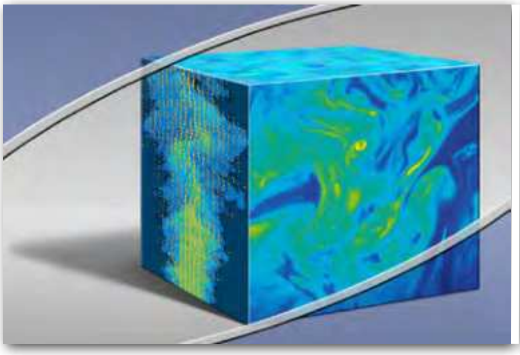
Laser imaging is recognized as the most valuable diagnostic tool in fluid dynamics applications. Instantaneous 2D and 3D flow images are measured with high spatial and temporal resolution. Even time-resolved 3D (= 4D) imaging is possible for a comprehensive characterization of e. g. turbulent flow structures.

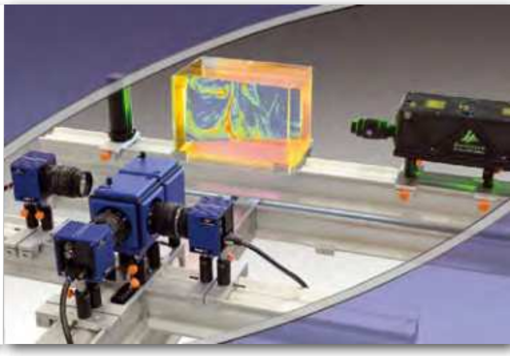
Laser Induced Fluorescence (**LIF**) is the most versatile and practical laser imaging technique for measuring scalar flow parameters such as concentration, mixture fraction, fluid composition and temperature. **Particle Image Velocimetry** (**PIV**) is the established and most powerful method for flow field imaging.

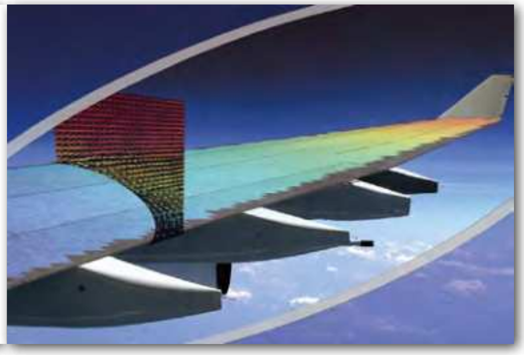
Laser imaging is applied in all kinds of fluid flows such as laminar, turbulent, reactive and multiphase flows and is used for the investigation of e. g. thermal flows, mixing processes and detailed flow field analysis.

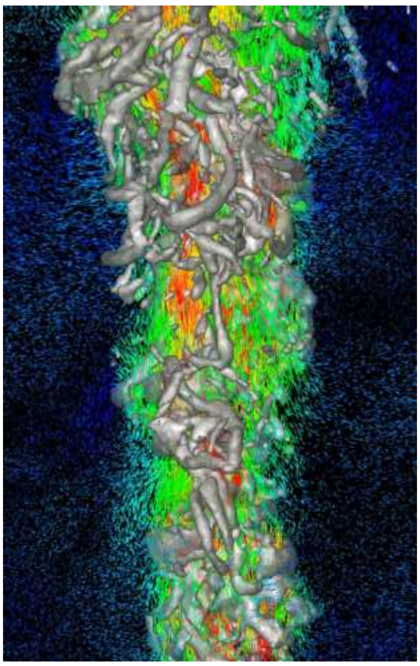


Thermal flow field imaging (see page 8)









3D flow field of a large scale convective air plume (see page 9)

For the investigation of non-repeatable transient flow phenomena 4D imaging is the only option to capture time-resolved 3D flow motion (example: time-resolved 3D flow fields in convective air flows).

Digital Image Correlation (**DIC**) for surface deformation imaging can be simultaneously applied with PIV measuring the interacting flow field for the investigation of **Fluid-Structure Interaction** (**FSI**) phenomena (see page 11).

Advantages of laser imaging

- **instantaneous, non-intrusive and quantitative flow imaging**
- **excellent spatial and temporal resolution**
- **2D, 3D and even 4D flow imaging**
- **versatile technology supporting multi-parameter flow measurements**

Laser Imaging Techniques
Flow Fields & Scalar Quantities

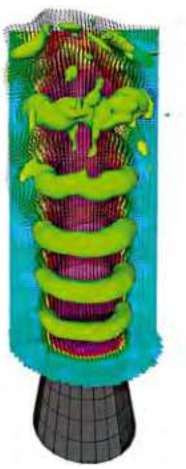
LaVision's laser imaging systems are called **FlowMaster** for flow field imaging (see also **FlowMaster** brochures) and **FluidMaster** for scalar imaging in fluids. Both systems are using nearly the same hardware components, and their software modules are working on the same **DaVis** platform. Both systems can be combined for multi-parameter measurements measuring e. g. flow fields together with fluid temperature or concentration maps.

Image scans in space as well as time (phase) scans are automatically performed complying with even the most challenging synchronization requirements of the experiment.

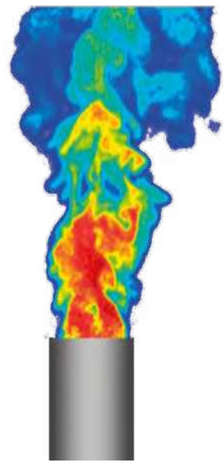
For laser imaging – in most cases – accurate flow seeding is required: particle seeding for PIV and LIF-active molecular flow tracing for LIF. The right way of flow seeding is critical for successful measurements. LaVision has a strong expertise in flow seeding including the appropriate use of each flow marker and in providing the necessary seeding generators.

Laser imaging in microfluidics

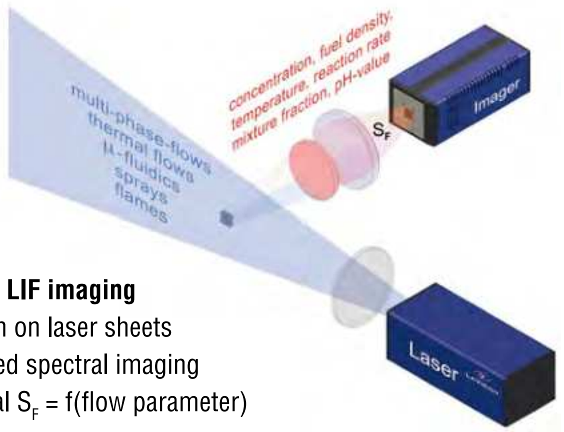
LaVision's laser imaging systems are designed for uncompromised performance in terms of measurement accuracy, hard- and software quality, system operation, data handling and service.



Flow Parameter	Laser Imaging Technique	Flow Marker	Laser Imaging System
Concentration Mixture Fraction **Flow Temperature**	Tracer LIF	LIF Tracers for Liquid and Gas Flows T-sensitive LIF Tracers	**FluidMaster** (**Scalar Imaging in Fluids**)
Flow Field	PIV	Particles	**FlowMaster** (**Flow Field Imaging**)
Temperature & Flow Field	Thermographic PIV	T-sensitive Phosphor Particles	**FlowMaster** (**Multi-Parameter Imaging**)



Laser imaging applications in fluid dynamics are numerous and cover high resolution imaging in microfluidics to large scale flow visualization in wind tunnels, fluid mixing and thermometry as well as the validation of CFD models.



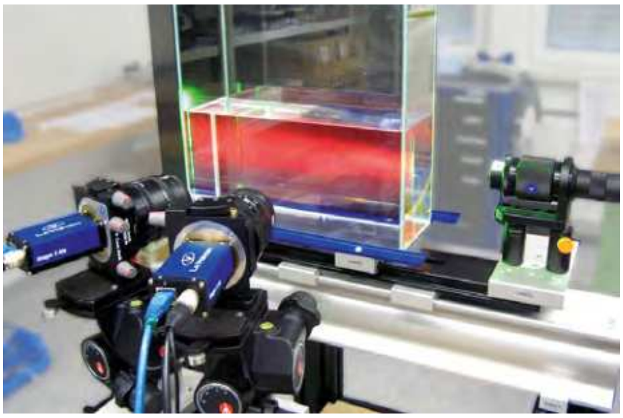
Principle of LIF imaging
- excitation on laser sheets
- time-gated spectral imaging
- LIF-signal S_F = f(flow parameter)

For combustion and spray imaging LaVision is offering its (laser) imaging systems FlameMaster and SprayMaster, respectively. Integrated turn-key imaging systems with unique capabilities for demanding R&D measurements as well as for quality control applications are our specialty.

Laser imaging system features
- **integrated and modular system designs**
- **state-of-the-art DaVis laser imaging software**
- **upgrades for multi-parameter and 3D imaging**
- **complete hardware control using DaVis software**
- **high quality and quantitative flow imaging**

Reactive mixing of liquid flows

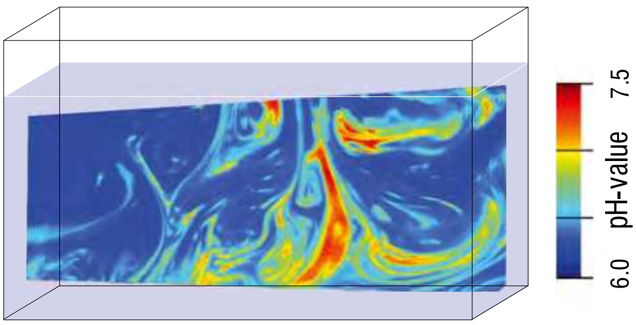
LIF imaging monitors in-situ the process of mixing on micro and macro scales with high spatio-temporal resolution. In the case of reactive mixing of two different pH-solutions a LIF tracer with a pH-sensitive spectral response is used allowing ratiometric 2-color LIF imaging for quantitative pH measurements.



Laser imaging setup for ratiometric 2-color LIF measurements

Flow parameter and laser imaging technique
Degree of mixing: **2-color Tracer LIF** ratiometric imaging

For scalar flow imaging the ratiometric 2-color LIF method is best practice, because its LIF signal ratio is independent of local laser energy and tracer concentration variations and laser beam absorption effects, thus leaving the LIF signal ratio only dependent of the measured flow parameter.



pH-mixing in a water tank

The usually high signal levels in liquid LIF experiments allow high quality (low error) measurements without the need of specialized equipment like image intensifiers or high power lasers usually necessary for laser imaging in gas flows. LIF signal calibration is carried out in calibration samples with known pH-solutions.

For time-resolved imaging the image frame rate has to exceed the time scales present in the flow and has to be increased accordingly for time-correlated measurements.

Time-resolved 3D flow field imaging of a liquid jet flow

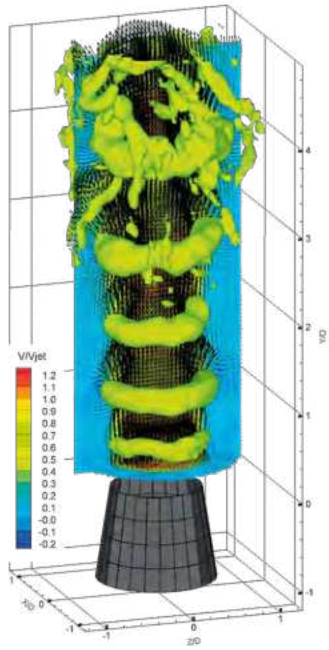
The turbulent flow field of a liquid jet is 3D in nature and requires for a complete understanding a 3D imaging approach, for time-resolved measurements a 4D imaging technique.

Tomographic (Tomo-) PIV using tomographic reconstruction for particle localization in 3D space is the most advanced and field-proven technique for 3D flow field imaging today as well as its high-speed imaging version for 4D flow motion analysis.

Flow parameter and laser imaging technique
4D flow field imaging: **Time-resolved Tomographic PIV**

2-camera Tomo-PIV setup

Tomo-PIV imaging starts with 2 cameras (views) and provides outstanding spatial resolution with its standard setup of 4 cameras. For high-speed Tomo-PIV using Motion Tracking Enhancement (MTE) for particle reconstruction a 2-camera setup is already able to resolve the complex vortex structure of the presented liquid jet flow, showing iso-surfaces of vorticity and one axial velocity plane within the reconstructed measurement volume (60 x 65 x 65 mm^3).



movie and more

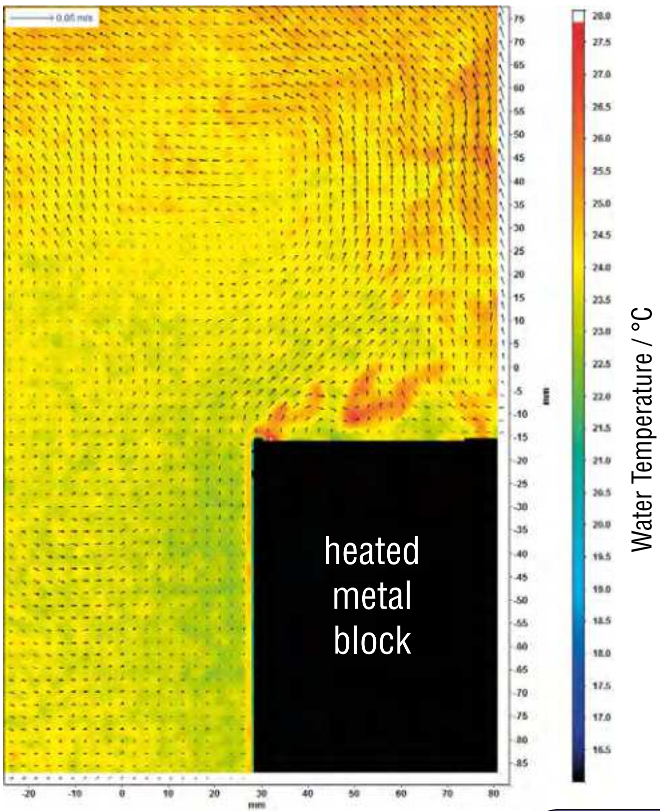
Time–resolved 3D flow field of a liquid jet flow recorded at 1kHz

Courtesy of F. Scarano et al., TU-Delft, 15th Int. Symp. on Applications of Laser Techniques to Fluid Mechanics, Lisbon, 2010

Simultaneous thermometry and flow field imaging in convective water flows

Natural convection in a water tank is created by a heated metal block located at the bottom of the tank. The water is seeded with particles for PIV and with a LIF-active dye solution consisting of two dyes one of which shows a temperature sensitive LIF emission. This tracer LIF strategy supports ratiometric 2-color LIF thermometry measurements which are independent of other experimental parameters such as laser energy or seeding concentration.

On the other hand, 1-color LIF thermometry is an alternative technique, but the temperature sensitive LIF tracer has to be uniformly seeded into the flow, and the locally applied laser energy has to be carefully monitored.



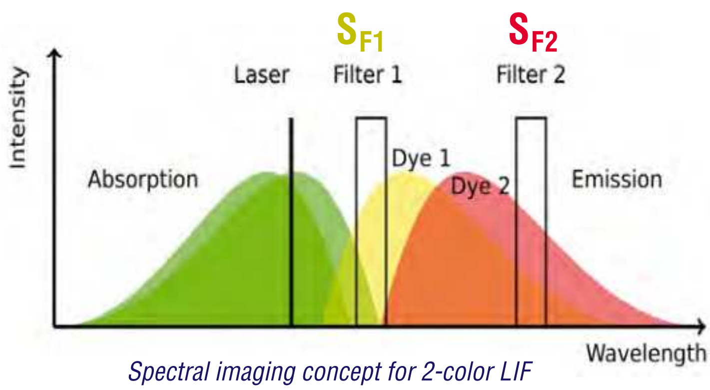
Time-resolved thermal flow field imaging

movie and more

In the presented experiment ratiometric 2-color LIF thermometry is recorded with an image doubler placed in front of the lens of the LIF camera. Two more cameras are used for Stereo (2D3C) PIV measurements. The same green laser pulses are used for the synchronized PIV and LIF recordings. This time-resolved multi-parameter flow imaging experiment is realized with a frame rate of 10 Hz. The minimum resolvable temperature difference is better than 1K at a spatial resolution in the order of 1mm.

Multi-parameter flow imaging and laser imaging techniques
Thermometry: **2-color LIF thermometry** ratiometric imaging
Flow field: **Stereo-PIV** (2D3C)

Laser imaging in water convection flows



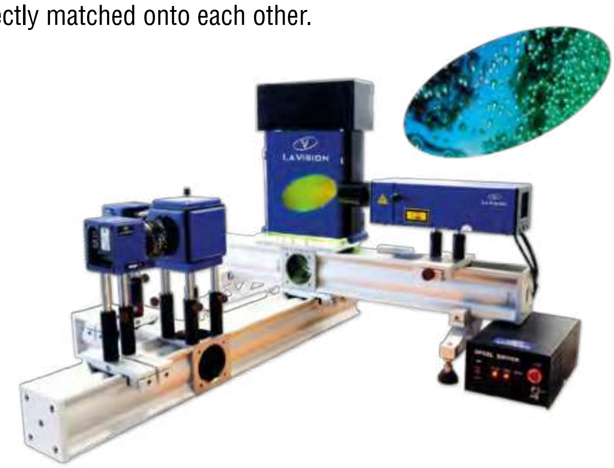
Spectral imaging concept for 2-color LIF

Laser imaging in liquid flows

- **laser imaging in the visible spectral range**
- **strong PIV and LIF signals at moderate laser energy levels**
- **distortion-free imaging applying refractive index matching**

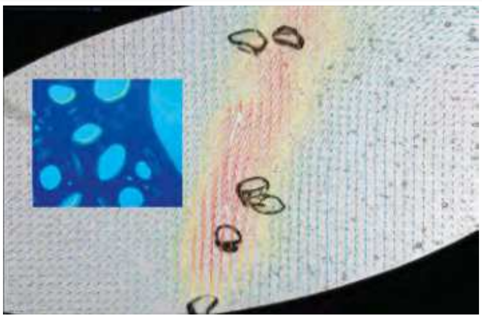
2-phase flow fields and bubble sizing

In a bubble-water flow the interaction of both phases is investigated applying a color-coded dual imaging approach: for flow field imaging in water a green light sheet is used to excite the red fluorescence of the PIV particle for 2D-PIV, and a blue backlight LED screen is used for shadowgraphy tracking bubble shape, size and velocity. A beam splitter in front of the cameras separates the color coded information from both phases before detection. The recordings of both channels are synchronized in time, and their fields of view are perfectly matched onto each other.



Dual channel imaging setup for combined PIV and shadow measurements in two phases

Multi-phase flow imaging and (laser) imaging techniques
Bubble sizing and velocimetry: time-resolved shadowgraphy
Continuous phase flow field: 2D-PIV w/ fluorescent particles



2-phase flow fields of a bubble-water flow

This dual color imaging setup shows excellent wavelength separation with no cross-talk between both channels. Higher spatial resolution is achieved replacing the camera lenses by a (long distance) microscope used for both channels.

(Laser) imaging in multiphase flows

- color-coded (spectral) imaging channels for different techniques and flow parameters
- light sheet imaging combined with backlight illumination

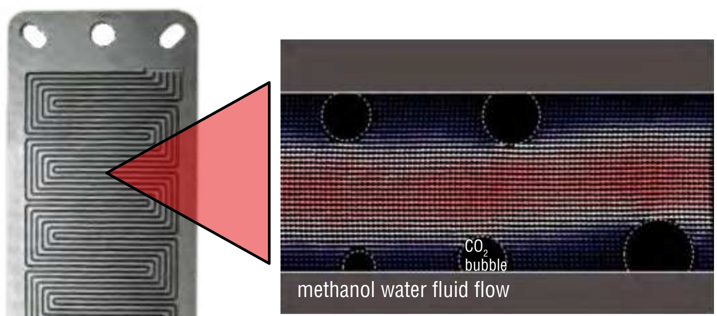
Microfluidic imaging in fuel cells

The detailed understanding of transport processes in fuel cells is crucial for the optimization of their performance. For flow field design optimization Micro (µ)PIV is applied in multiphase flows of a bipolar plate of such a fuel cell.

In µPIV the light sheet applied in standard PIV applications is replaced by a volume illumination of the flow, and the depth of field is determined by the numerical aperture of the objective lens of the microscope. In µPIV the flow is seeded with fluorescent particles to remove the strong background light scattered from the nearby channel surfaces. These particles have to be much smaller than the channel dimensions and also small enough to faithfully follow the flow. LaVision's µPIV **FlowMaster** systems support 2D, stereo as well as tomographic flow field measurements.

Stereoscopic µPIV setup

Multi-phase flow imaging and laser imaging technique
Continuous phase flow field: µPIV w/ fluorescent particles



Flow field in a micro channel of a fuel cell

Courtesy of Ralf Lindken, ZBT

Flow field imaging in microfluidics: µPIV

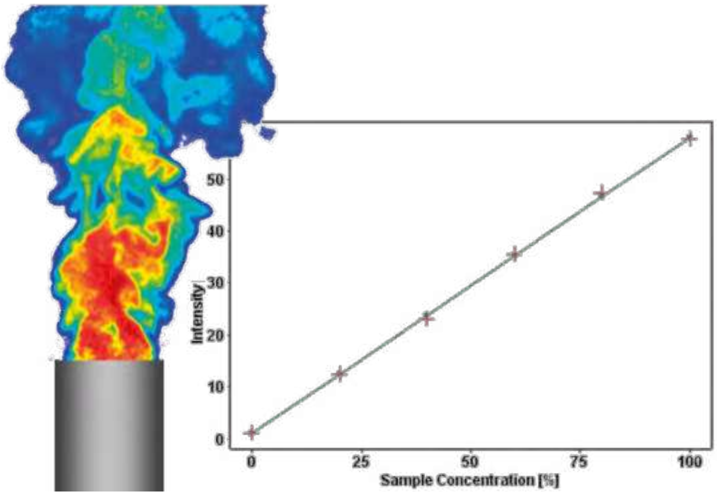
- volume illumination of fluorescent particles
- application specific selection of microscope, light source and camera(s)

Gas concentration and temperature imaging

LIF imaging in gas flows is using gaseous LIF tracers featuring high signal levels allowing even 3D imaging of concentration, mixture fraction and temperature fields with sufficient temporal resolution to freeze even the fastest flow motion. Time-resolved measurements applying high-speed LIF imaging is possible at tens of kHz framing rates.

Tracer LIF flow markers are numerous and the right choice is dependent on the target flow parameter. Among other gas phase tracers acetone is the most popular molecular LIF tracer up to 1000 K due to its high vapor pressure, fortunate LIF properties and nontoxic behavior. Nearly all gaseous LIF tracers need pulsed UV-lasers for LIF excitation and intensified UV-sensitive cameras for detection.

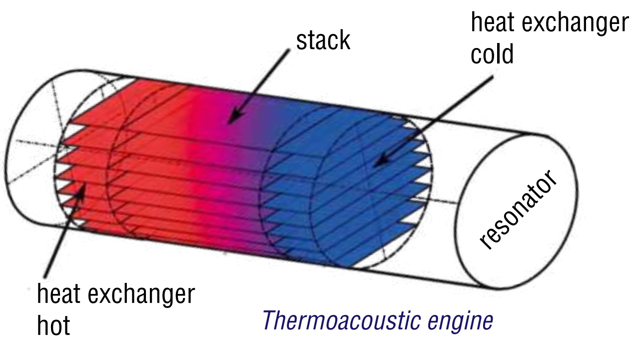
Quantitative concentration maps of the LIF marked gas flow component are obtained after correcting the LIF images for inhomogeneities and distortion effects introduced by the illumination and imaging system, as it is shown for the acetone seeded gas jet injected in air.



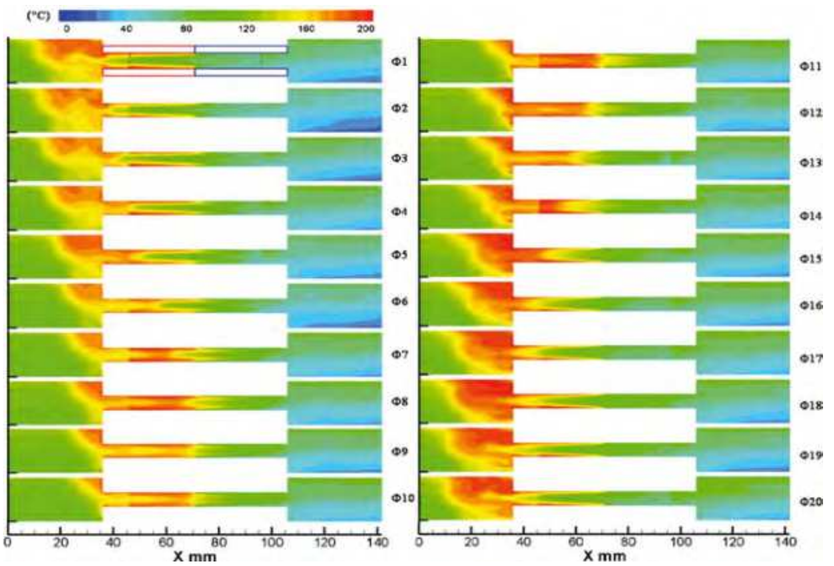
Concentration map of a LIF-active gas jet issued in ambient air

Flow parameter and laser imaging techniques
Gas mixing: Tracer LIF
Gas thermometry: 1-color LIF thermometry

Gas temperature imaging is performed using 1- or 2-color LIF thermometry, which works nicely also in small cavities, as it is shown for the planar temperature measurements carried out in a thermo-acoustic device. The periodically changing temperature field is sampled applying phase-locked LIF imaging and scanning successively the phase over the whole cycle.



Thermoacoustic engine



Temperature fields in a thermoacoustic device at 20 phases within an acoustic cycle

Courtesy of Jaworski et al.,
University of Manchester
Meas. Sci. Technol. 21 (2010)

LIF imaging in gas flows

- pulsed UV-lasers for gaseous LIF tracers
- intensified cameras for higher signal levels
- kHz LIF imaging for time-resolved measurements

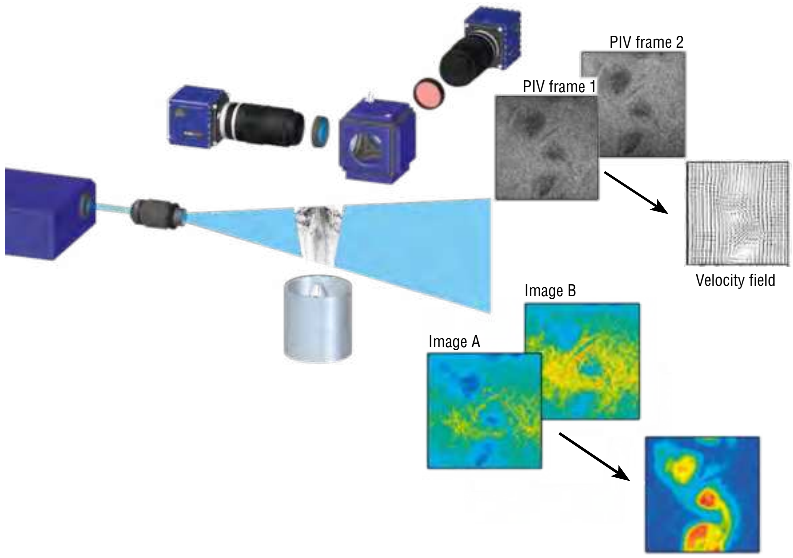
High-speed imaging of gas thermometry and velocimetry using thermographic phosphor particles

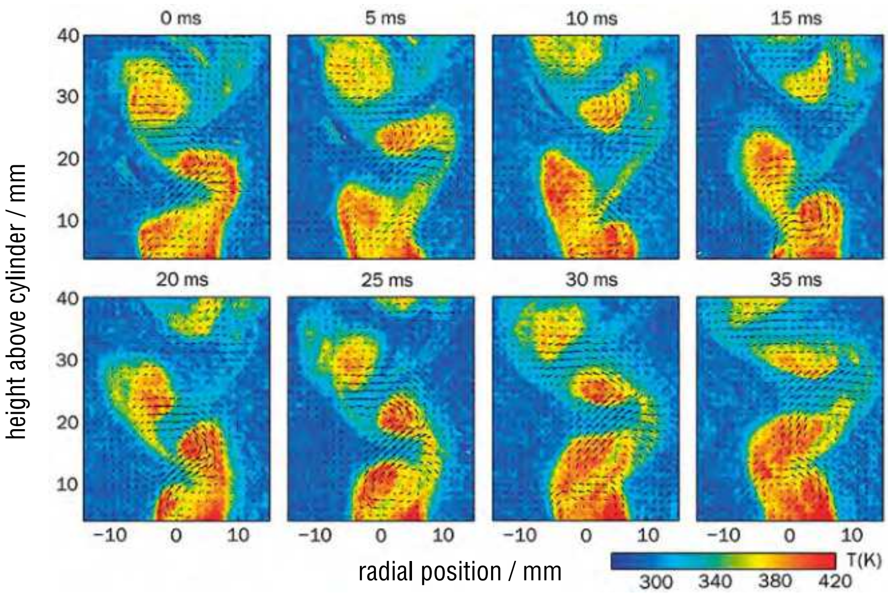
For simultaneous temperature and flow field imaging particle seeding is needed for PIV, and a separate temperature-sensitive tracer for LIF thermometry. This multi-parameter flow imaging approach often involves different light sources and cameras for both imaging techniques.

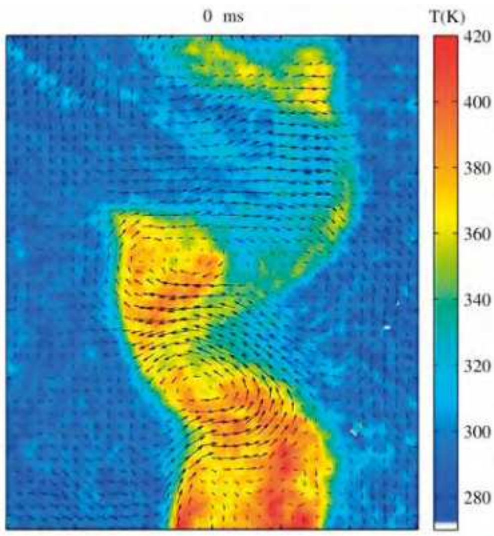
Thermographic PIV marks a real breakthrough for such simultaneous velocimetry and thermometry flow measurements, because it works with phosphorescent PIV particles, which are suitable for PIV and temperature measurements using the same laser pulse and the same cameras!

This phosphorescent PIV seeding material comes as a ceramic powder consisting of 2 µm particles. The Laser Induced Phosphorescence (LIP) signal of these particles is sensitive to the surrounding gas temperature up to 900 K with a sufficiently short response time to follow even fast changing thermal flow fields. After UV-light sheet illumination these particles emit phosphorescence with a temperature dependent emission spectrum, which allows for ratio-metric 2-color LIP thermometry, while each LIP image itself is used for PIV applying time-correlated recordings.

Multi-parameter flow imaging and laser imaging technique
Thermometry & flow field: Thermographic PIV







movie and more

Simultaneous high-speed (3 kHz) imaging of temperature and velocity fields of a particle seeded air flow in the wake of a heated cylinder (530 K)

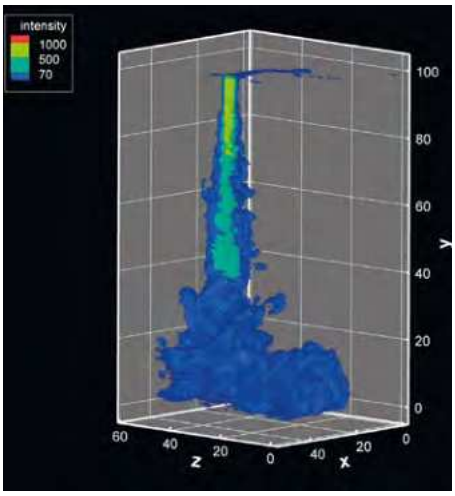
Courtesy of F. Beyrau et al.
University of Magdeburg & Imperial College London,
Appl. Phys. B. 111, 150 - 160 (2013)

Thermographic PIV for thermal flow field imaging

- simultaneous single-shot velocimetry and thermometry imaging using the same flow tracer and imaging setup
- 2-color LIP thermometry possible up to 900 K
- high-speed (kHz) imaging for time-resolved measurements

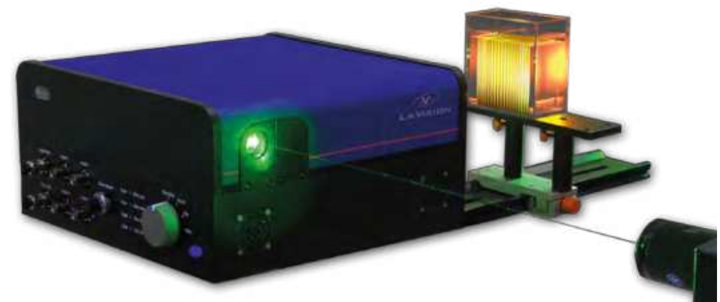
Time-resolved 3D liquid mixing

For the investigation of turbulent liquid mixing processes a high-speed light sheet scanner is used in combination with a high-speed camera. In this experiment the volume scan rate of 30 Hz enables resolving the 3D flow structure of the mixing process.



movie and more

Flow parameter and laser imaging technique
4D mixture fraction imaging: High-speed scanning planar LIF

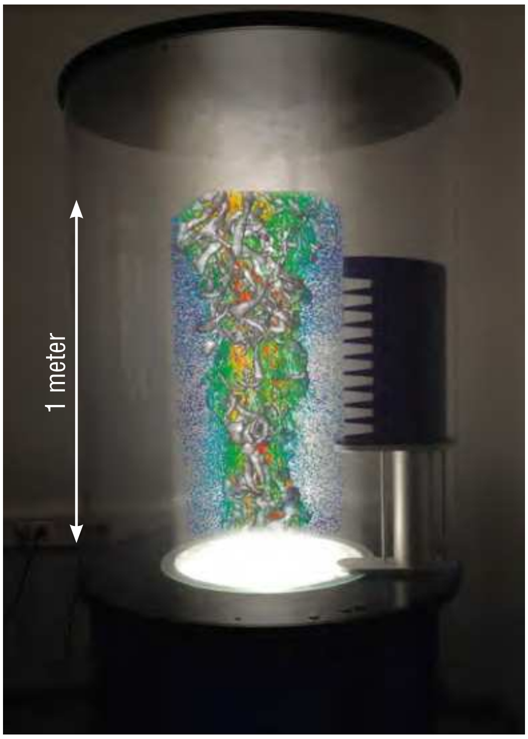


Laser sheet scanner

Shown to the left is the time-resolved injection of a LIF-active liquid jet into water. The dimensions of the scanned volume are 60 x 60 x 100 mm³.

Time-resolved 3D convective flow field in air

For flow field measurements in large volumes up to 1 m³ or more very bright, i.e. large scattering particles with sufficient flow tracking fidelity are necessary.



Courtesy of D. Schanz, A. Schröder
German Aerospace Center (DLR)

movie and more

Large scale 4D velocimetry in a convective air flow calculated with Shake-the-Box (STB) particle tracking algorithm.

Flow parameter and laser imaging technique
4D flow field imaging: Time-resolved particle tracking (STB)

Sub-millimeter diameter **H**elium-**F**illed **S**oap **B**ubbles (**HFSB**) are neutrally buoyant and more than 10000 times brighter compared to standard micron-sized particles enabling 3D flow field measurements in very large volumes. With a relaxation time of only 11 µs these flow tracers follow the flow perfectly, even at high velocities and flow gradients. Pulsed LED arrays are used to illuminate such large measurement volumes.

LaVision's **HFSB generato**r produces 40000 mono-sized helium bubbles per second and per nozzle and can operate up to 50 nozzles in parallel resulting in a max production rate of 2 million bubbles per second. With these high seeding rates and a bubble lifetime of several minutes the seeder can fill large measurement volumes with high seeding concentration levels necessary for PIV measurements with excellent spatial resolution. The flow motion of these millions of seeding bubbles is recorded and processed with LaVision's time-resolved **Tomographic-PIV** or **Shake-the-Box** (**STB**) particle tracking systems.

Large volume time-resolved velocimetry

- buoyant and extremely bright helium bubbles
- bubble generator with seeding rates up to 2 million bubbles/sec
- time-resolved Tomo-PIV and Shake-the-Box particle tracking systems

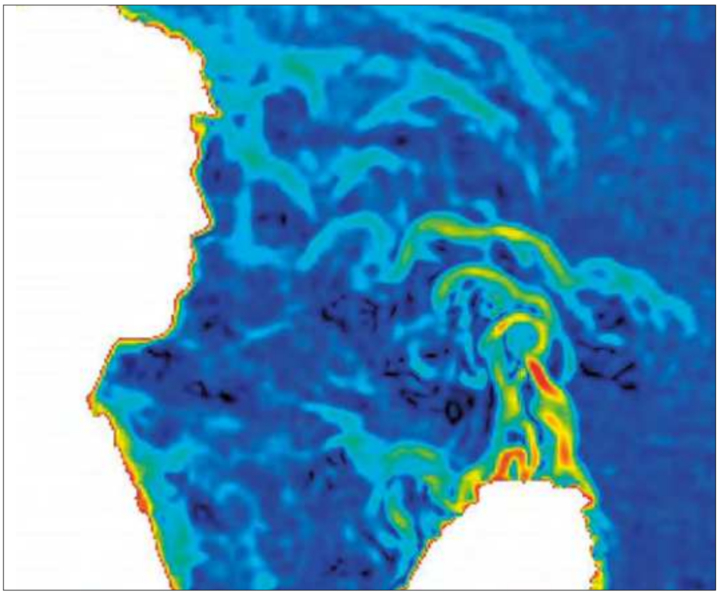
Large scale flow visualization

For the visualization of gas motion based on local refractive index variations **B**ackground **O**riented **S**chlieren (**BOS**, also known as Synthetic Schlieren) is a simple and cost-effective alternative to laser imaging methods, because it doesn't need any complex illumination device like a laser needed for laser imaging, and it works without seeding the flow.

BOS is a line-of-sight imaging technique and measures locally the density gradient as an integrated value over the line-of-sight. In practice, only a random dot pattern in the background of the flow is imaged with a high resolution camera before and during the test. By comparing the two pictures (or more precisely correlating the two patterns similar to the image correlation in PIV) the local displacement of the background pattern can be used to provide lateral information on path-integrated refractive index variations.

Although BOS is able to qualitatively visualize the smallest changes in gas density, its line-of-sight imaging technique can only measure absolute density (temperature) fields in 2D or in axisymmetric flows.

Beside conventional Schlieren systems LaVision offers BOS imaging systems for qualitative flow visualization as well as for quantitative gas density (temperature) measurements in 2D or in axisymmetric flows.

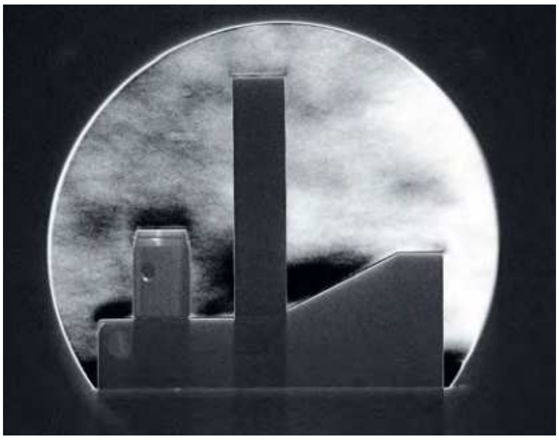


movie and more

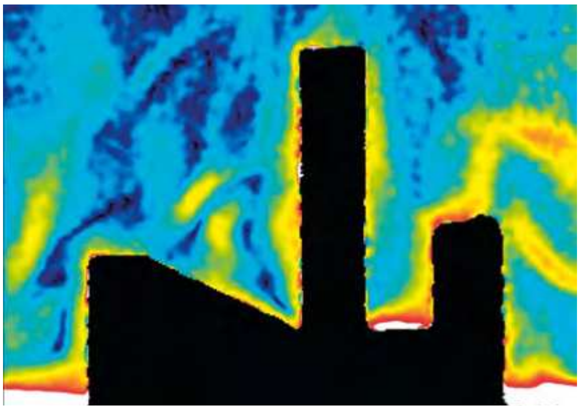
BOS imaging of a thermal flow

BOS imaging in transparent media

- **simple flow visualization approach without laser**
- **advanced image correlation applied on background target**
- **quantitative density (temperature) fields for 2D and axisymmetric flows**



Thermal flow visualization around a heated building model



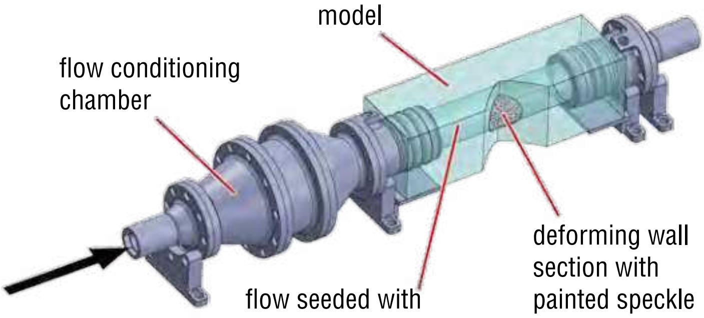
Comparision of a conventional Z-type Schlieren system (left) with an equivalent BOS setup imaging the same thermal flow

Fluid-Structure Interaction

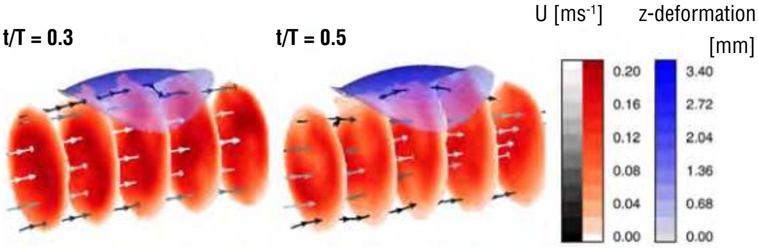
For the investigation of **Fluid-Structure Interaction** (**FSI**) processes both the measurement of the flow field around a flow model as well as the detection of the flow induced structural response of the model are of interest. While PIV quantifies the fluid dynamic features around the flow structure, **Digital Image Correlation** (**DIC**) measures the 3D surface deformation and strain of the structure. DIC - like BOS and PIV – is based on an advanced image correlation technique, that calculates the displacement of a random dot pattern attached to the model surface.

For full-field, non-intrusive FSI measurements LaVision is offering integrated imaging systems supporting in a unique way simultaneous PIV and DIC measurements based on our proven **FlowMaster** and **StrainMaster** systems. Both imaging techniques are using the same **DaVis** software platform for synchronized image recording and data processing. Our FSI imaging solutions allow a direct and intuitive analysis of complex FSI phenomena including high-speed systems for time-resolved measurements.

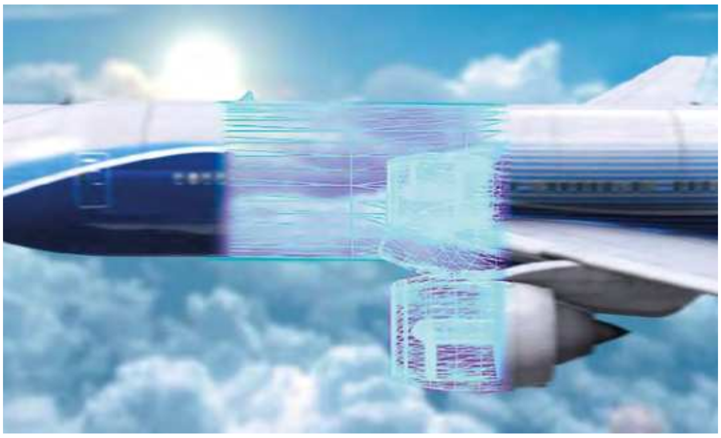
The power of LaVision's **FSI** imaging solutions is proven in many experiments. The Royal Veterinary College in the UK applied time-resolved **FSI** measurements for the investigation of a pulsating blood flow inside an abdominal aortic aneurysm and for wing profile studies of a flying locust together with the resulting wake flow behind the insect.

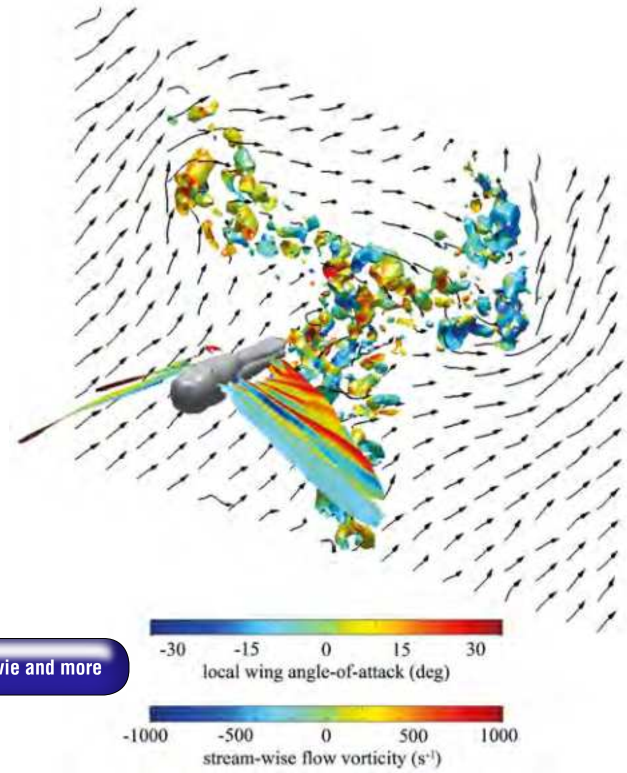


Experimental setup for FSI studies of an aortic aneurysm model



Deformation of an aortic wall shown in blue as a function of the pulsating blood flow field





movie and more

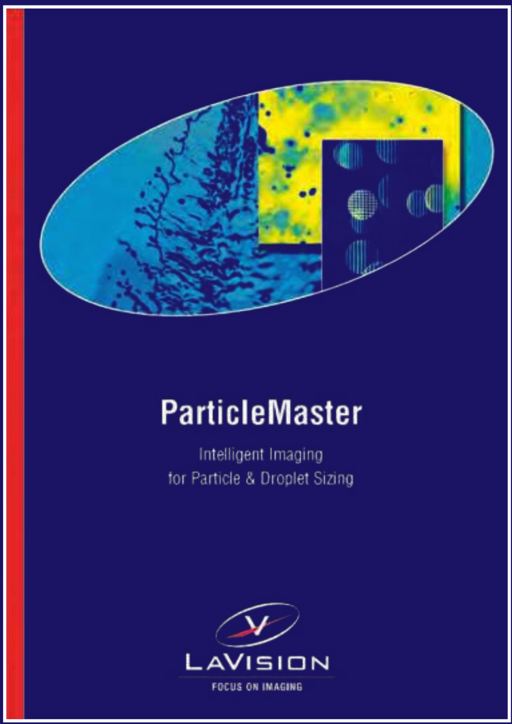
FSI measurements of locust flight dynamics

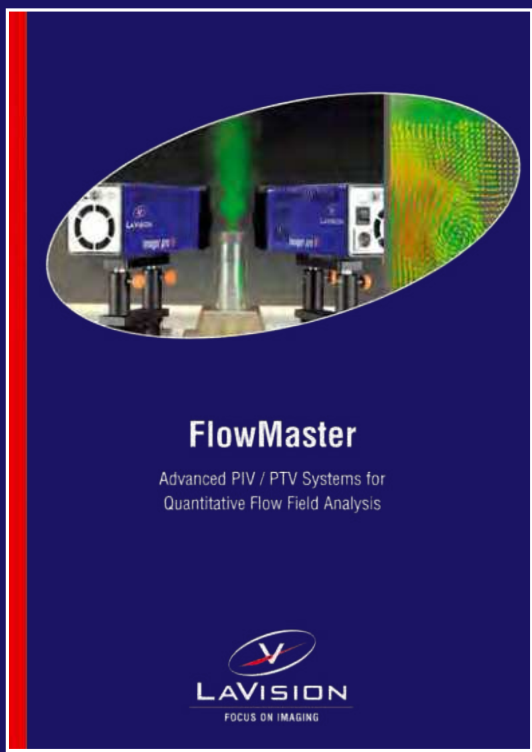
Courtesy of N. Phillips et al.
Royal Veterinary College University of London, UK

Fluid-Structure imaging solutions

- combined and fully integrated PIV-DIC systems
- same hardware and software platform
- advanced image correlation algorithms for both techniques including uncertainty quantification

Related Product Information





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