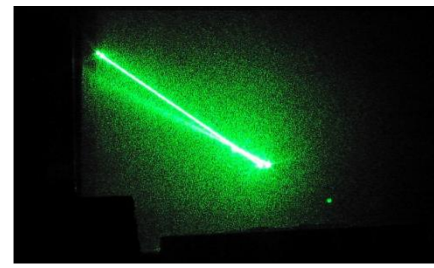
Measurement Techniques

Various optical techniques for visualization and velocity field measurements are commonly used at the Laboratory of Fluids Engineering. Those are advanced techniques which enable the detailed analysis of complex flows, whether they are turbulent, two-phase or through unusual test section geometries.

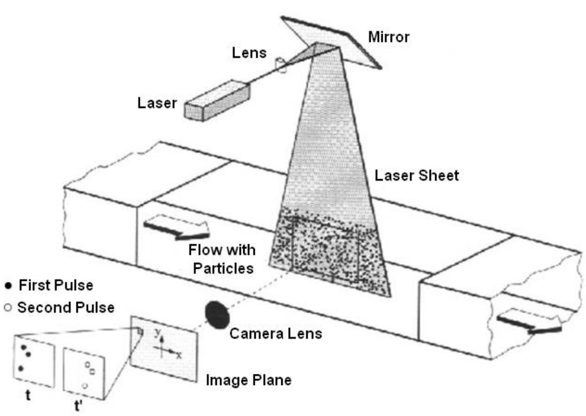
Each of the techniques offers particular implementation challenges, and all of them involve some degree of digital image processing and the development and application of algorithms (for example, 2D or 3D spatial correlation or particle tracking algorithms), which should be frequently optimized. Hence, the issues concerning those techniques are also an object of constant study and testing.



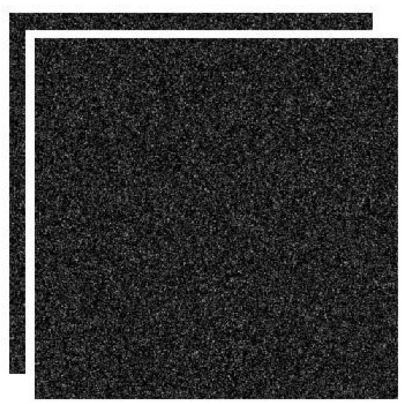
Laser beam in air flow with particles.

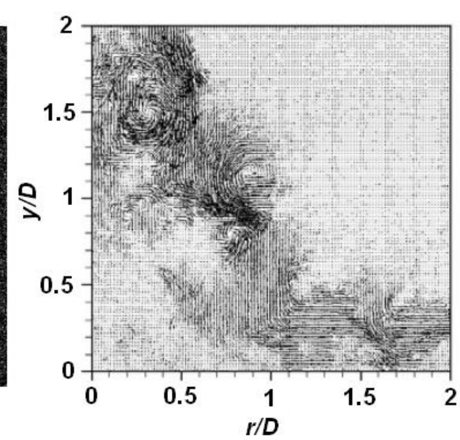
• Particle Image Velocimetry (*PIV*)

This velocity measurement technique, widely employed at LEF, is directly derived from flow visualization methods. Its standard two-dimensional form (2D PIV) consists of the evaluation of the displacement of tracer particles embedded in the flow and illuminated by a pulsed light sheet, usually produced by a laser source. A camera aligned orthogonally to the light sheet registers the positions of the particles in two or more consecutive instants in time, precisely known. Image processing and cross-correlation algorithms are used to determine the displacement field of particle groups in "interrogation windows", resulting in the vector field (two components) in that slice of the flow, thus characterizing a 2D-2C method. More sophisticated interrogation and post-processing algorithms are explored in Matlab and C++ programs developed at LEF.

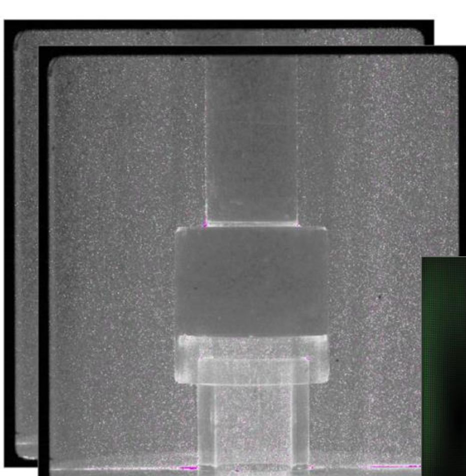


Basic configuration for 2D PIV measurements (Raffel et al, 2007).

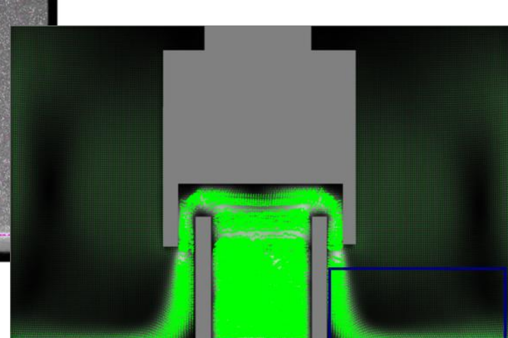


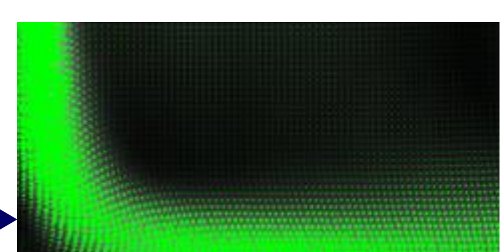


Swirling impinging jet (flat plate located at y = 0). Left: pair of particle images ; right: resulting instantaneous velocity field, in which one can observe vortices generated in the internal and external shear layers.



PIV 2D

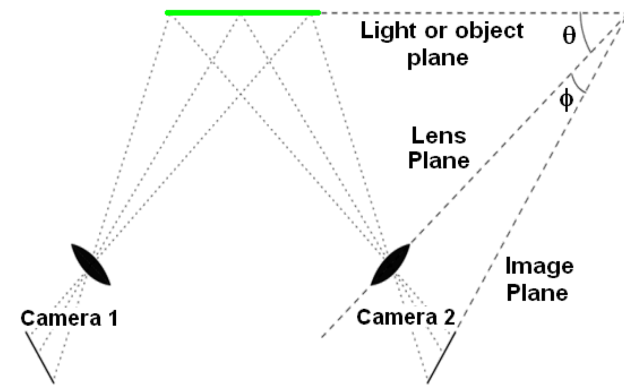




Small scale model of a pressure relief valve. Left: pair of images in the valve surroundings for a given open fraction during the transient lift; center: average velocity field for the given open fraction, obtained through phase averaging; right: magnified image of vectors in the indicated region.

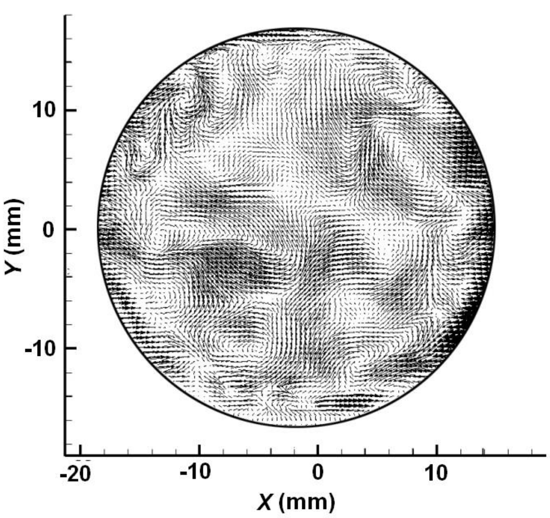
Measurement Techniques

Stereoscopic PIV

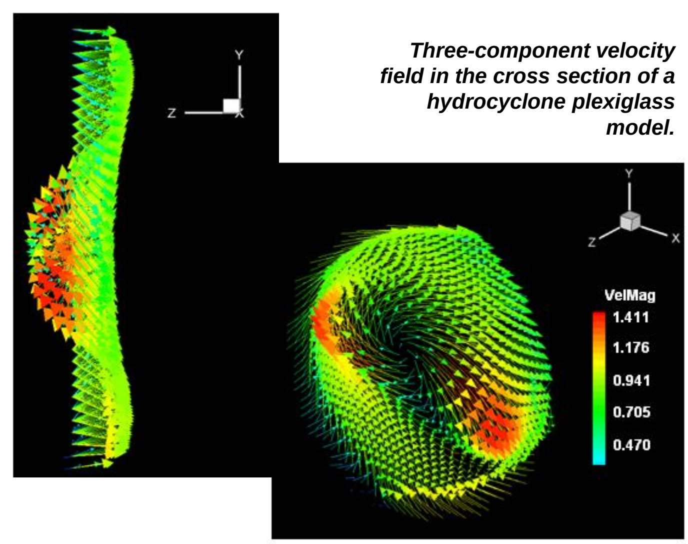


In this configuration, a laser sheet illuminates the region of interest in the flow, as in the case of 2D PIV, but with two cameras capturing images of the light scattered from the particles with different angles or perspectives.

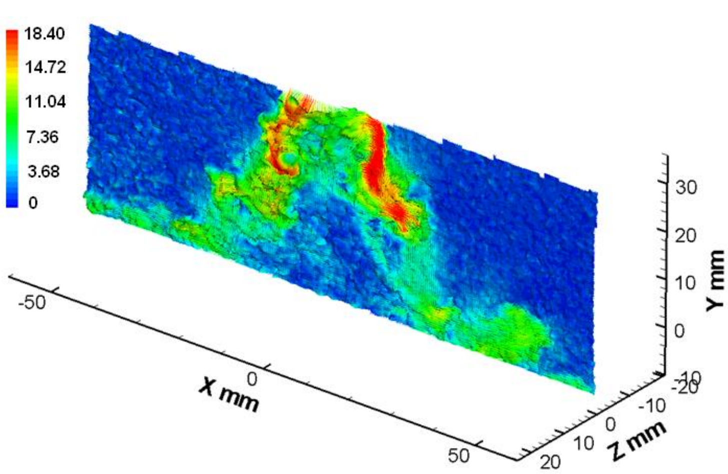
The combination of the projections from each camera and a correct calibration procedure allows for the reconstruction of particle displacements also in the direction perpendicular to the light sheet, resulting in the evaluation of all three velocity components in that plane, thus characterizing a 2D-3C technique.

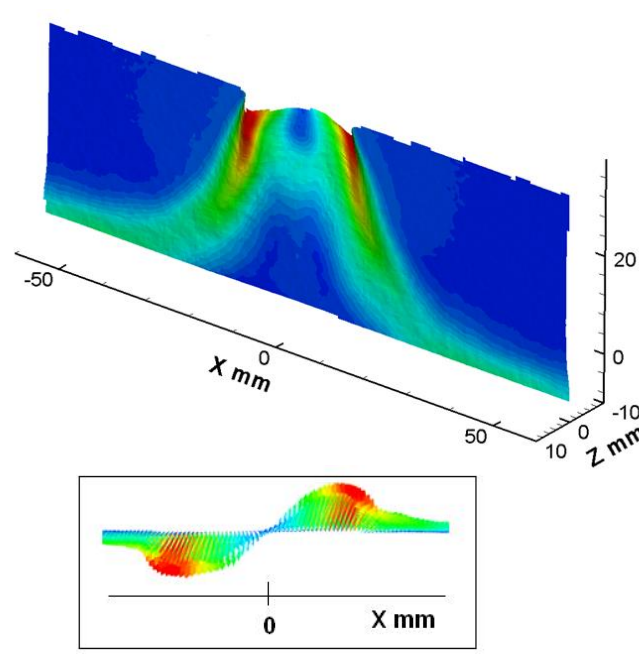


Above: Turbulent flow (Re=42000) through circular duct measured with stereoscopic PIV system, enabling calculation of velocity fields in the cross section. Around 5000 velocity vectors are represented in this image.



Three-component velocity field in the cross section of a hydrocyclone plexiglass model.





Swirling impinging jet. Above: instantaneous field. Right: average field obtained from 500 realizations (different instants in time). The strong tangential velocity component can be observed.

Measurement Techniques

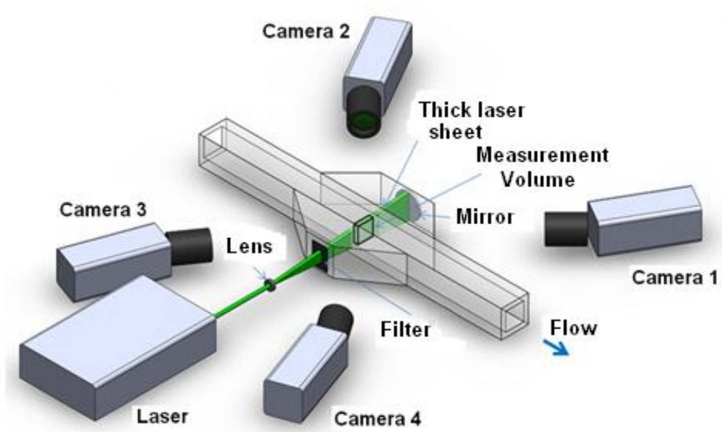
Tomographic PIV

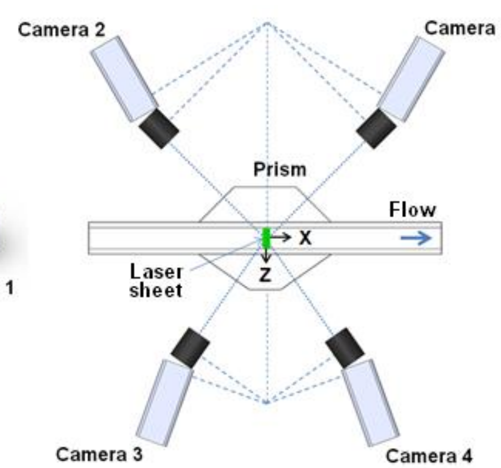
With the use of stereoscopic PIV being quite common for obtaining 2D fields with three velocity components, the next and ultimate step is to cover the three-dimensional space, in an attempt to better understand certain inherently 3D turbulent phenomena. Tomographic PIV is one of the techniques capable of measuring three-component instantaneous velocity fields within a volumetric region of the flow (3D-3C).

In such configuration, the tracer particles present in the flow are illuminated by a pulsed laser source in a three-dimensional region (usually a thicker plane). Multiple cameras are used to register focused images of the group of particles from different perspectives, allowing for the volumetric distribution of particles in the region of interest to be reconstructed a posteriori.

Once reconstructed, the volume is analyzed with 3D cross correlation algorithms, which estimate the displacement of a group of particles within "interrogation volumes" between two known instants of time. This analysis procedure then generates the three components of displacement for each interrogation volume. Different reconstruction algorithms and interrogation methods can be studied and employed.

The reconstruction of the volume from the images registered by the different cameras requires the knowledge of the mapping function between the various image planes and the physical space, which is done with a calibration procedure similar to the stereoscopic PIV one, but with the function being defined in a volumetric domain.

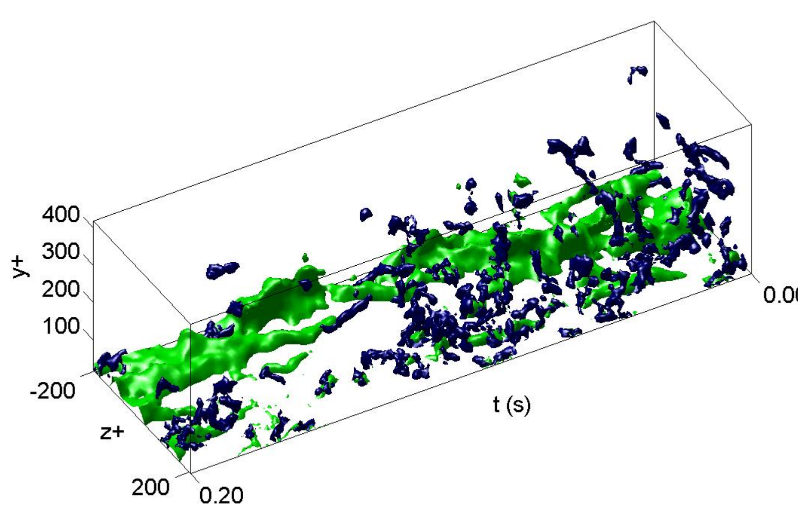




Above: experimental test section design for measurements with TomoPIV in square water channel.

Right: experiment performed at École Centrale de Lille, in a partnership with LEF (PUC-Rio). Application of the TomoPIV technique for measuring boundary layer flow in a wind tunnel.

Organization of turbulent structures: green iso-surfaces correspond to low speed streaks, while blue ones to vortices identified through the Q criterion.

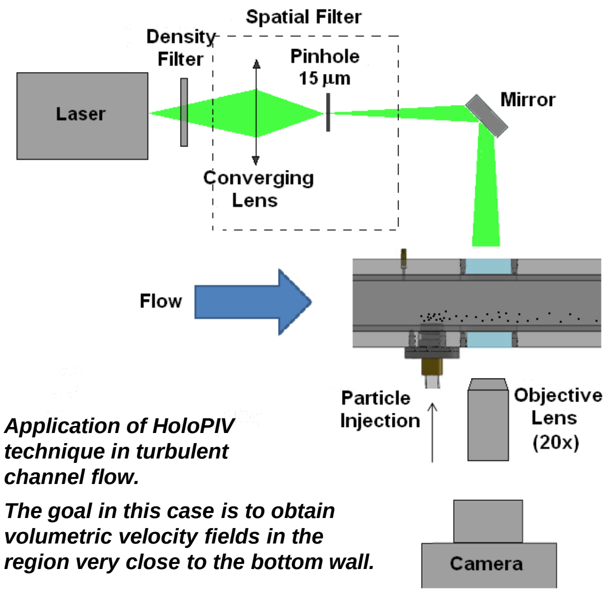


Fluids Engineering Laboratory

Measurement Techniques

PUC RIO

Holographic PIV



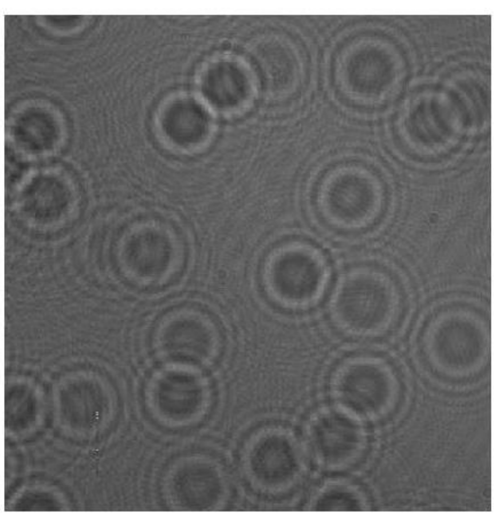
Application of HoloPIV technique in turbulent channel flow.

The goal in this case is to obtain volumetric velocity fields in the region very close to the bottom wall.

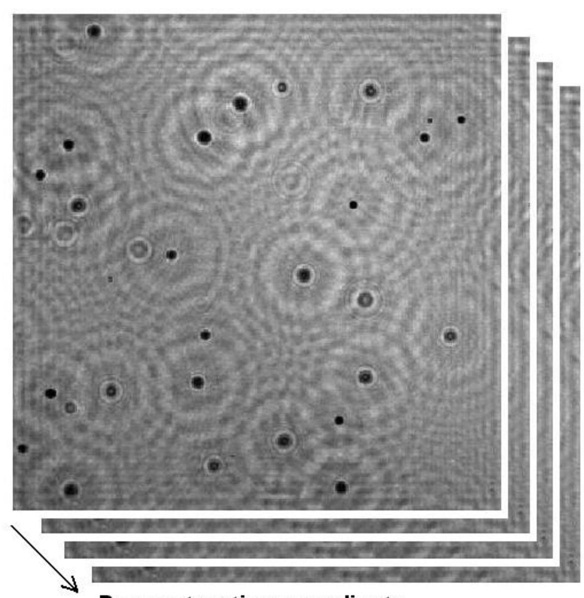
Making use of the optical phenomenon known as holography is another way of obtaining 3D-3C measurements. Advances in electronics have led to the availability of high spatial resolution digital cameras, which in turn made it possible to register digital holograms.

Particles are added to the flow in the proximity of the measurement volume, being illuminated by a laser beam. The interference pattern generated by diffraction of the coherent light and registered in the camera sensor is called a digital hologram, and can be numerically reconstructed a posteriori, retrieving the volumetric information of the group of particles and their 3D coordinates.

From pairs of reconstructed volumes, correlation or tracking algorithms can be used to evaluate 3D velocity fields, representative of the physical mechanisms and structures from that region of the flow.

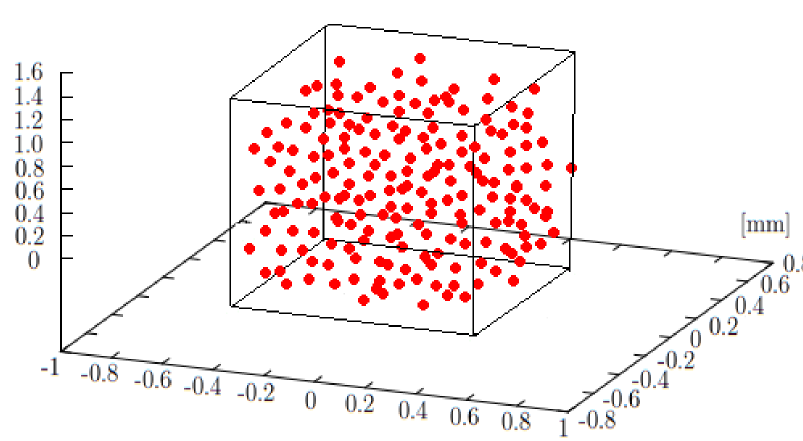


Hologram



Reconstruction coordinate (depth)

Left: example of a digital hologram taken from a spray of particles. Reconstruction is performed numerically, in different planes along the optical axis, retrieving, thus, the volumetric information.



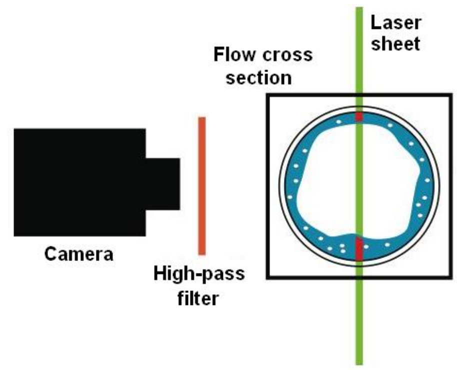
Right: typical instantaneous particle volume, reconstructed from a magnified digital hologram. With 3D particle coordinates in two very close instants in time, the 3D velocity field can be calculated.

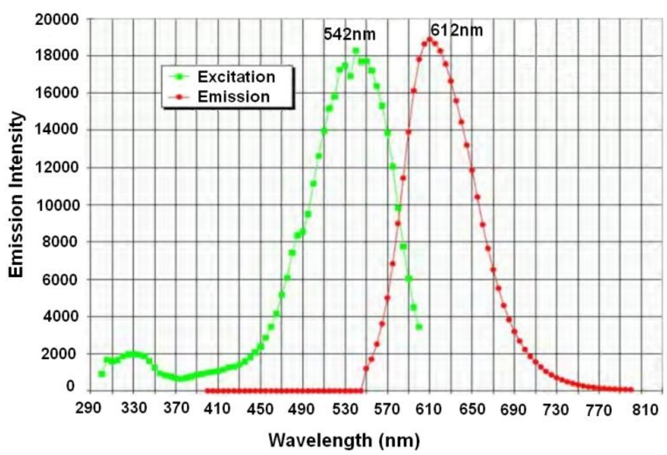
Measurement Techniques

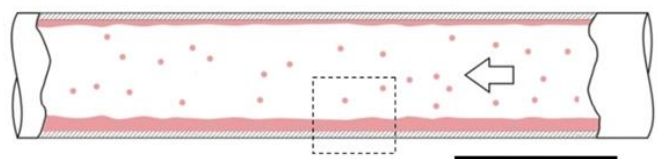
• Optical visualization techniques: laser induced Fluorescence (LIF) and refraction index matching

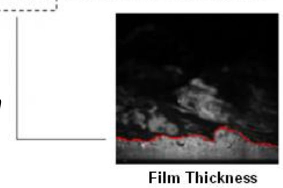
Right: LIF technique for annular flow studies. Rhodamine, a substance added to the liquid (water) phase, emits red light when exposed to green light, according to the graphic representation below. If an adequate filter is put in front of the camera, images solely of the liquid film are acquired, without undesired reflections, which would normally be exist due to the interface between phases and to the presence of a surface.

For this reason, and also for being non-intrusive, this technique has been extensively used at LEF for multiphase flow studies.

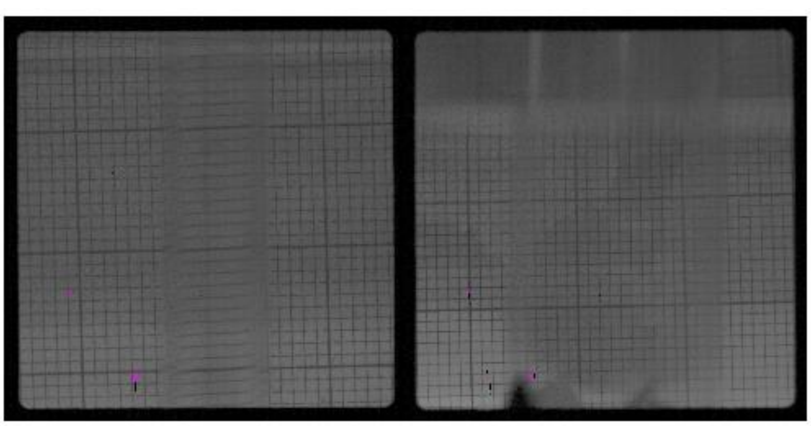






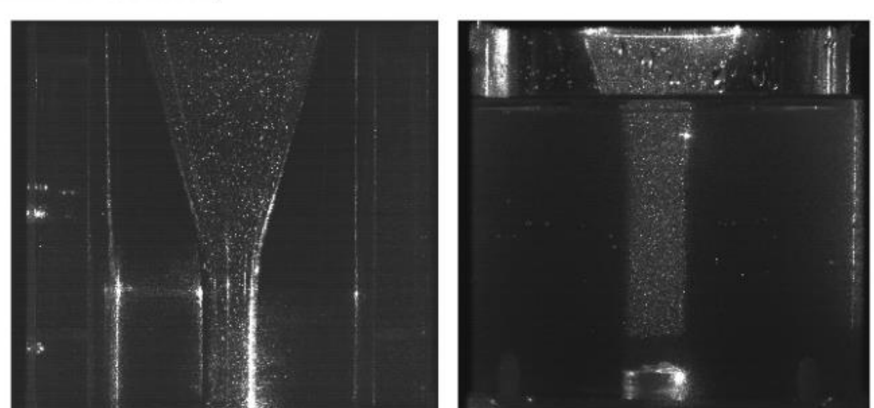


Thickness measurement and temporal evolution of liquid film from longitudinal image acquisition.



Examples of distortion correction. Above, water in glass and FEP tubes. FEP *(fluorinated ethylene propylene*) and water have approximately the same index of refraction.

Right: elimination of reflections by addition of a saline solution to the water.

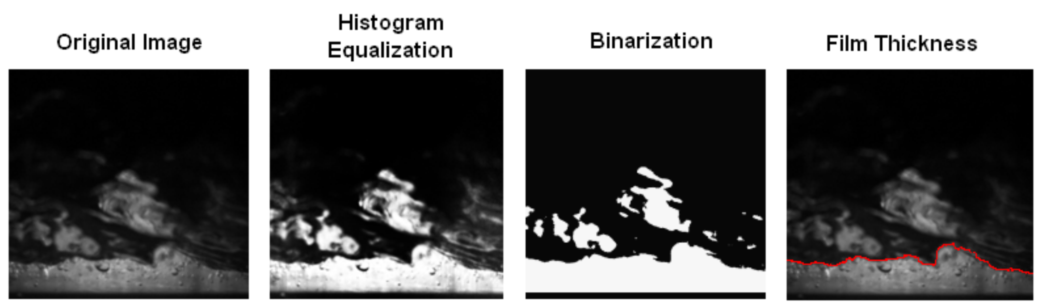


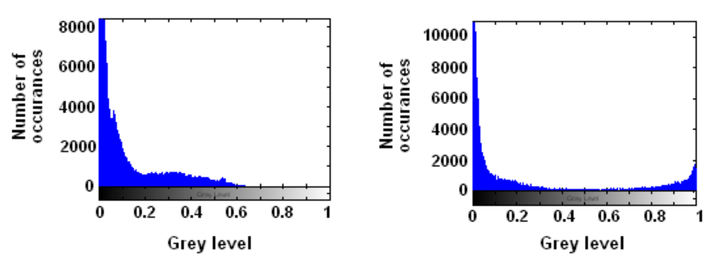
Measurement Techniques

• Development of digital image processing tools

In the different research lines at LEF, developing digital image processing algorithms is a necessary step in experimental data analysis. For example, to improve quality and contrast of particle images (pre-processing) in PIV applications, represent final data (post-processing), or to improve image quality in the wax deposition visualization process.

[Two-phase flow studies]() are another good example of the importance of developing good image processing tools. In these flows, detection of the interface between fluids is extremely relevant for understanding the physical phenomena. Because the interfaces evolve and have irregular and distinct shapes at every moment, a quantitative evaluation cannot be made manually in a fast and precise manner. Thus, procedures are developed at LEF with the goal of extracting both qualitative and quantitative information semi-automatically or automatically.

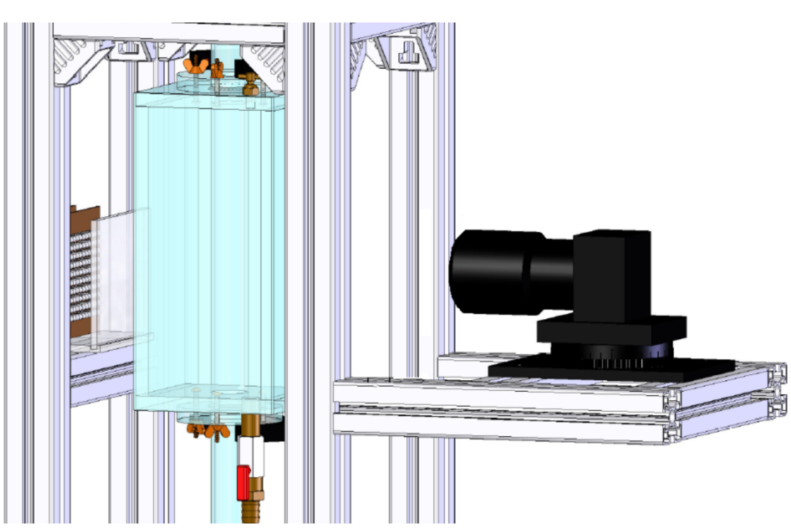




Application of digital image processing for characterization of the liquid film in annular flow.

• Pulsed Shadow Technique (PST)

The pulsed shadow technique is normally employed in the study of two-phase flows, allowing an improvement in the determination of the liquid-gas interface shape and contrast. It is an optical technique which does not interfere in the flow, and consists in illuminating it from the back with an uniform light source (commonly LED panels), in order to acquire shadow images with high-quality interface definition by positioning a camera on the opposite side.

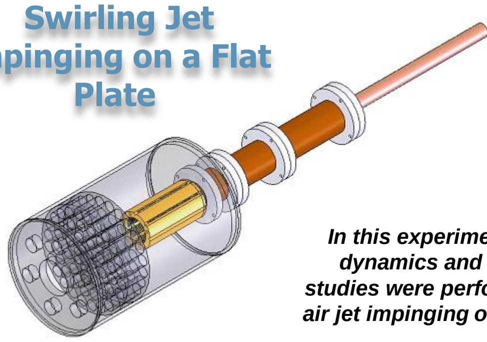


Visualization of a Taylor bubble with the pulsed shadow (PST) technique.

Measurement Techniques

• **Some examples of the application of laser techniques at the laboratory**

Swirling Jet Impinging on a Flat Plate

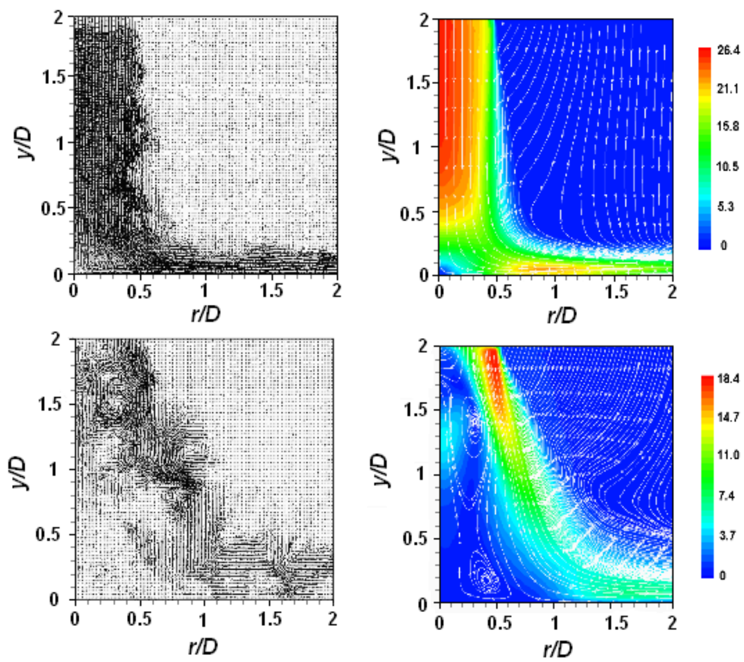


In this experiment, both flow dynamics and heat transfer studies were performed for an air jet impinging on a flat plate.

The experimental setup allows jets with different intensities of the circunferential velocity component – given by the swirl number S – to be generated. Intensities ranging from S=0 to S=0.5 were studied, the first case corresponding to a conventional jet and the last to a strong swirling flow.

For the characterization of velocity and turbulent intensity profiles at the nozzle exit, the Laser Doppler Velocimetry technique is employed. In order to obtain instantaneous velocity fields in the axisymmetric plane of the jet, 2D and stereoscopic PIV techniques are used. For the heat transfer studies, a plate instrumented for constant heat flux conditions and thermocouple array measurements is used to evaluate the radial distribution of the Nusselt number.

Above: schematic drawing of the swirl generator.

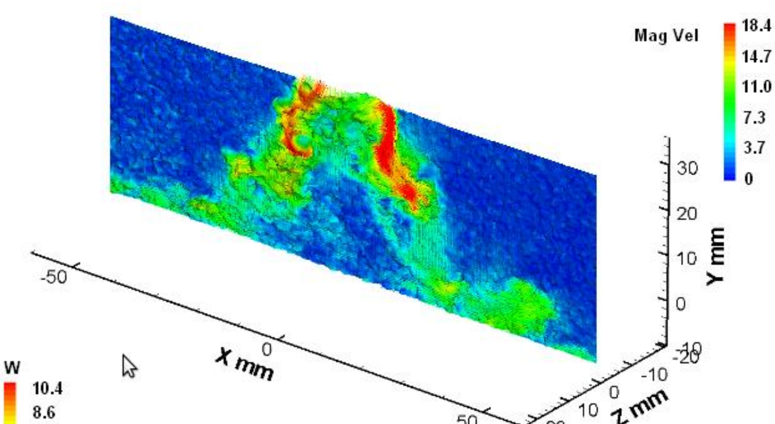


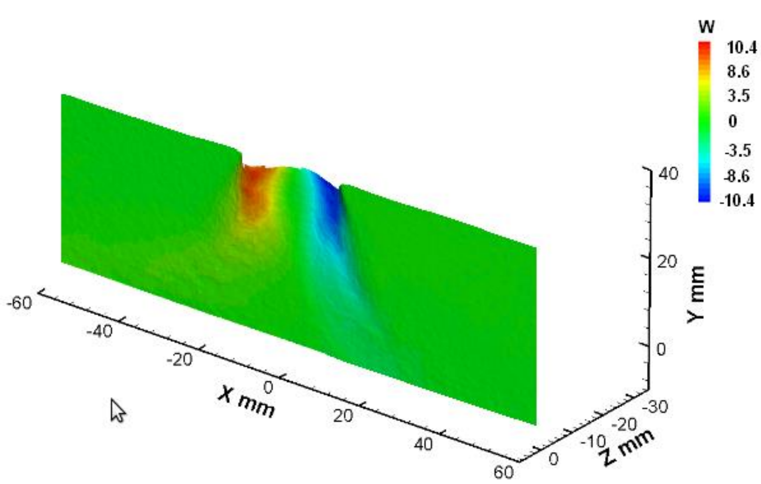
Above: velocity vector fields (instantaneous) and contours (average) with streamlines, in the axisymmetric plane of the jet, obtained with 2D PIV. Distance from nozzle exit to the wall is twice the nozzle internal diameter.

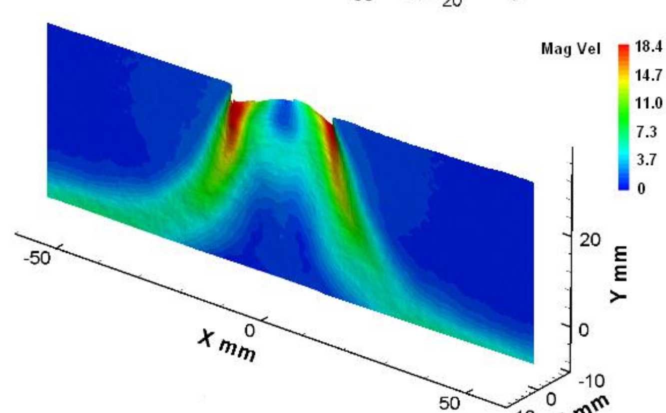
Results of stereoscopic PIV measurements.

Right: instantaneous (top) and average (bottom) velocity magnitude fields.

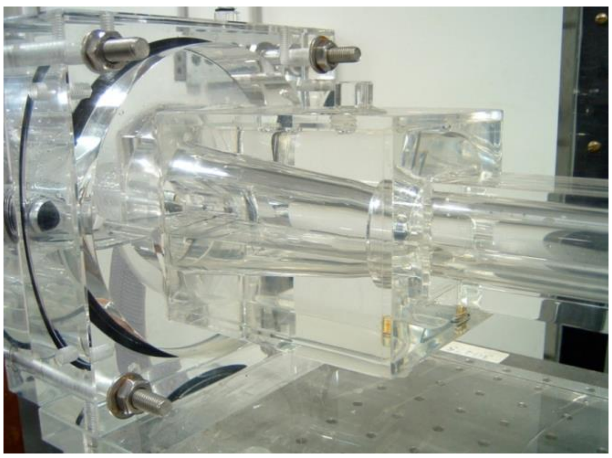
Below: Average field coloured by the magnitude of the circumferential velocity component.





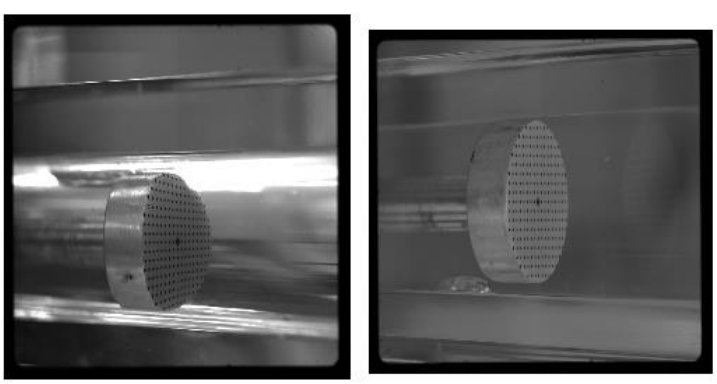


Measurement Techniques



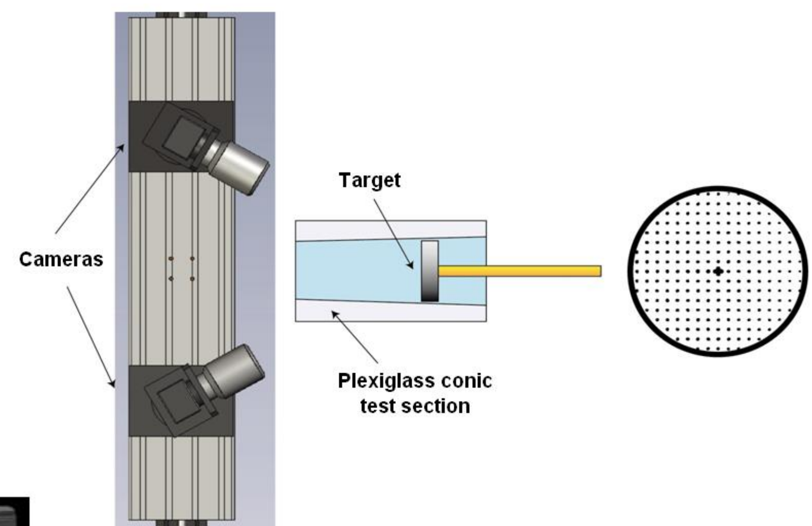
Above: detail of the plexiglass model of the hydrocyclone. The conical geometry may cause considerable and undesired optical distortions in the particle images.

Below: image of the calibration target used in the experiment. Addition of saline solution to the water removes most reflections and optical distortions.

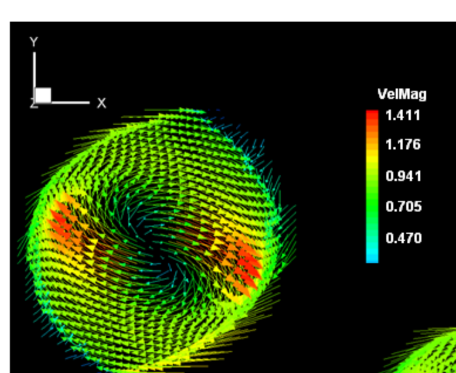


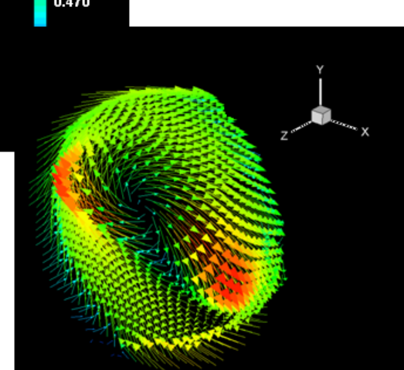
water | water + saline solution

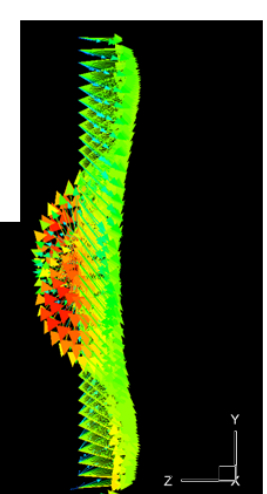
Flow inside a Hydrocyclone



Above: schematic drawing of experimental setup for image acquisition with stereoscopic PIV.



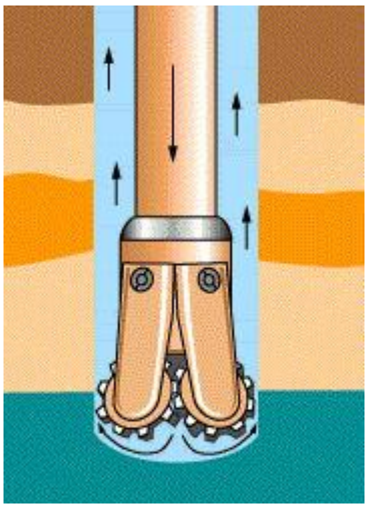




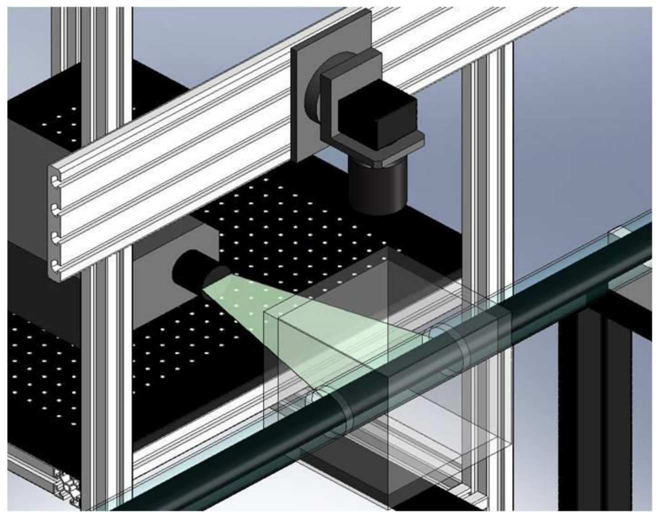
Vector fields coloured by velocity magnitude, obtained with stereoscopic PIV in a cross section of the hydrocyclone.

Measurement Techniques

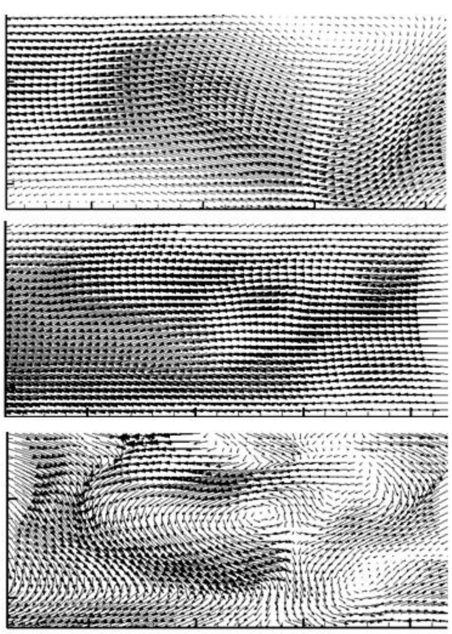
Annular Flow (Taylor-Couette)



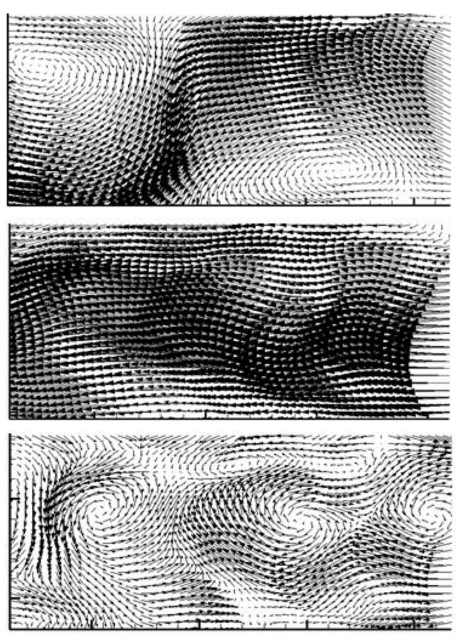
One of the practical motivations for studying this type of flow is the similarity to the flow generated in well-drilling processes.



Left: schematic drawing of test section for 2D PIV measurements. A controlled rotation is imposed to the external cylinder.

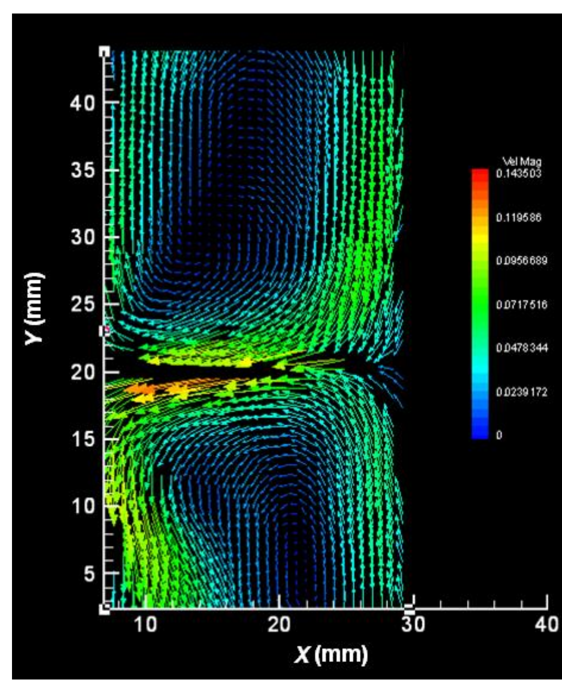


$Re_{ax} = 980$, $Re_{rot} = 700$



$Re_{ax} = 662$, $Re_{rot} = 900$

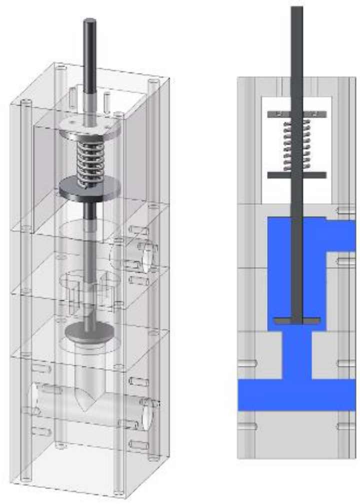
Temporal evolution of velocity fields for two cases of the experimental test matrix, characterized by axial and rotational Reynolds numbers.



Velocity field obtained by subtraction of the average flow: toroidal (Taylor) vortices can be distinguished and their behavior can be studied for the different test cases, with high temporal resolution (video).

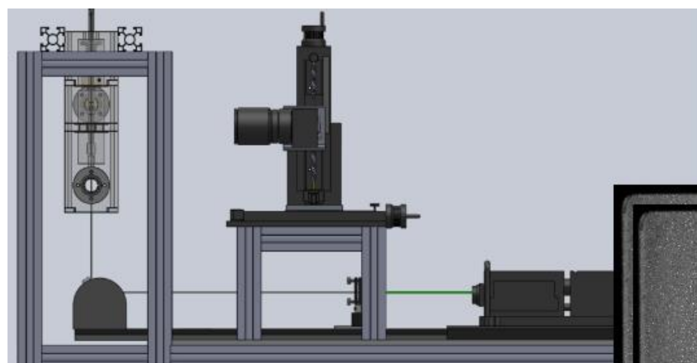
Measurement Techniques

Pressure Relief Valve (PRV) Model



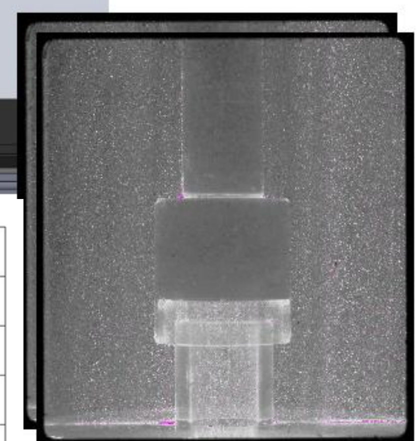
Study of the dynamics of the transient flow regime in a spring-loaded relief valve: a small-scale plexiglass model is used for pressure, lift, and phase-averaged PIV measurements.

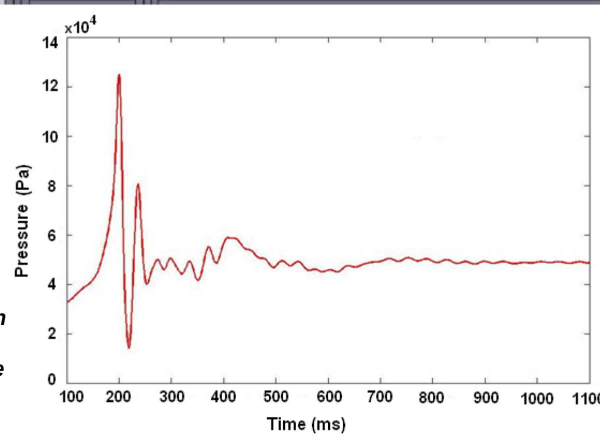
The phase-averaged PIV measurements of the velocity field in the central plane of the valve's chamber, obtained with a special synchronization scheme, allow for average flow fields to be observed at different lift positions, as if they were "frozen" during the valve sudden opening.



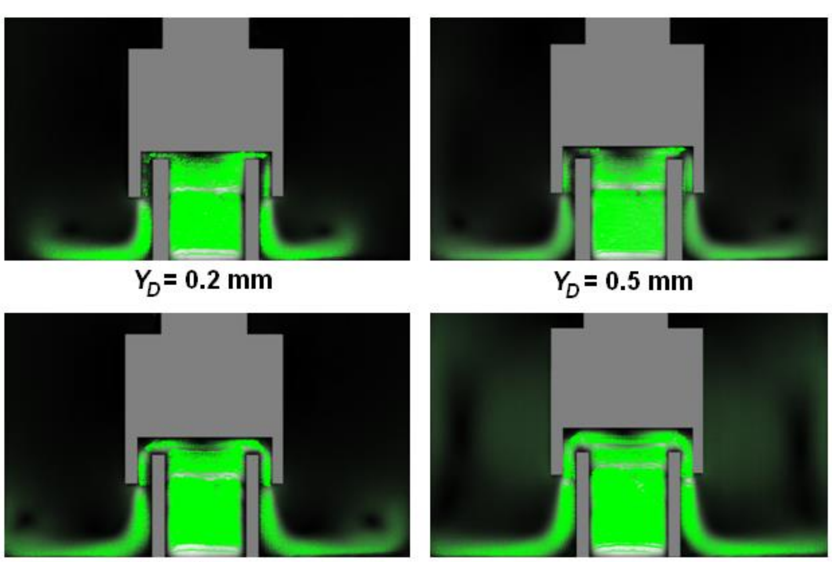
Left: experimental arrangement for PIV measurements.

Below: typical pair of particle images around the body of the valve within its enclosure for a given lift position (lift).

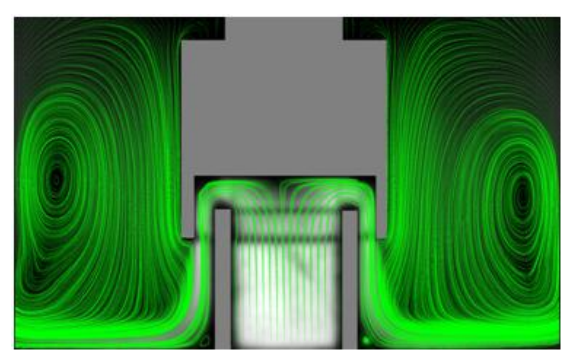




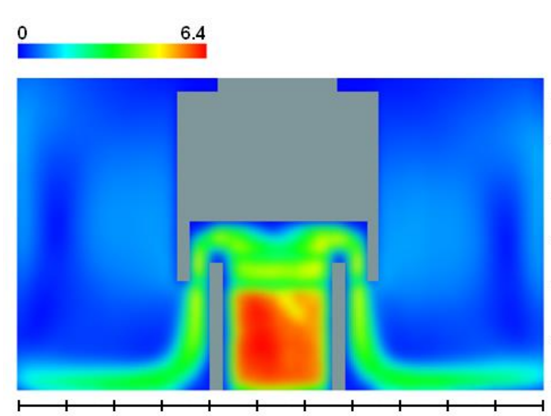
Left: differential (downstream/upstream) pressure versus time during lift. Average of 500 realizations.



Sequence of (average) flow velocity fields during lift, obtained by phase-averaging 500 realizations for each height.



Above, to the right: lines tangent to velocity vectors make flow visualization easier and emphasize the recirculations within the plexiglass chamber that encloses the PRV.



Right: contours of average velocity magnitude. Due to the superposition of plexiglass in the optical path crossing the border of the valve's "cup", there are localized distortions and, consequently, flaws in the velocity field. This can be improved with the addtion of a saline solution to the water.

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Measurement Techniques

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Besides the various PIV configurations and visualization methods, other velocity measurement techniques are used at LEF. Classical pointwise measurement techniquessuch as hot wire and laser Doppler anemometry, for example, are of extreme importance for the analysis of some flows of interest. Some of these methods are briefly described next.

• Thermal Anemometry

Hot wire anemometry is a tool for pointwise velocity measurements widely used in studies of turbulent gas flows. Compared to other techniques, it has the advantage of providing higher frequency and sensitivity responses, thus allowing the measurement of velocity fluctuations with up to 100kHz, and amplitudes of the order of 0.01% of the base flow velocity. The main disadvantage is due to the fact that it is an intrusive technique , that is, the introduction of a probe is necessary for the measurements.

The working principle is based on the forced convective heat transfer between a heated filament and the fluid flowing around it. The variation in electrical resistivity of the wire with temperature is recognized by a circuit that transforms this variation in electrical signal. If the temperature of the fluid that flows over the filament is constant, then the heat transfer is a function of the flow velocity only. In this way, it becomes possible to convert the electrical signal from the anemometry system to velocity, by means of a calibration correlation.

• Laser Doppler Anemometry

Laser Doppler Anemometry is another pointwise technique often used for flow velocity measurements. It has the advantage of being non-intrusive, which allows for measurements in locations where placing a probe is impracticable. Besides, it also resolves direction of the flow, which is not true for conventional thermal anemometry.

LDA systems use monochromatic laser beams intersecting at a small region in space. The light reflected by the passage of a particle in this measurement volume is detected by photodetectors. According to the Doppler effect, a change in the frequency of reflected light occurs when a particle with non-zero velocity crosses the beams intersection. From the frequency measurement it is then possible to evaluate the particle's velocity, which is in turn representative of the fluid velocity at that point.

• Some of the equipment available at the Fluids Engineering Laboratory for measuring velocity and other quantities are:

✓2 IDT X3 Motion Pro Plus high speed cameras with 1kHz @ 1megapixel;

✓4 Phantom Miro 320 high speed cameras with 1.4kHz @ 2megapixels;

✓4 megapixel TSI cameras with 15Hz sampling rate;

✓10-30 TSI camera;

✓Set of Nikkor lenses;

✓Pulse generators for event synchronization;

✓Several data acquisition systems;

✓Low-frequency Nd-YAG lasers with 120mJ/pulse (Big Sky, Evergreen);

✓High-frequency New Wave Pegasus laser, with 10mJ/pulse @ 1kHz;

✓High-frequency Litron LDY.300 laser, with 30mJ/pulse @ 1kHz;

✓Computers and softwares (in-house and comercials) for image acquisition and processing;

✓Computer server for processing and storage of large experimental databases;

✓Laser Doppler with 2 channels;

✓TSI hot wire anemometry;

✓Reference meters for gases and liquids, and various pressure, flow rate, and temperature measurement equipment;

✓Linear travel stages of multiple sizes, anti-vibration tables for optical mounting;

✓Optical components such as mirrors, optical windows, density filters, wavelength filters, beam splitters, sets of spherical and cylindrical lenses, polarizers, prisms, etc;

✓Precision mounting apparatus for optical components, such as rails, mirror and lens supports, posts and post holders, among others.

Partnerships

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