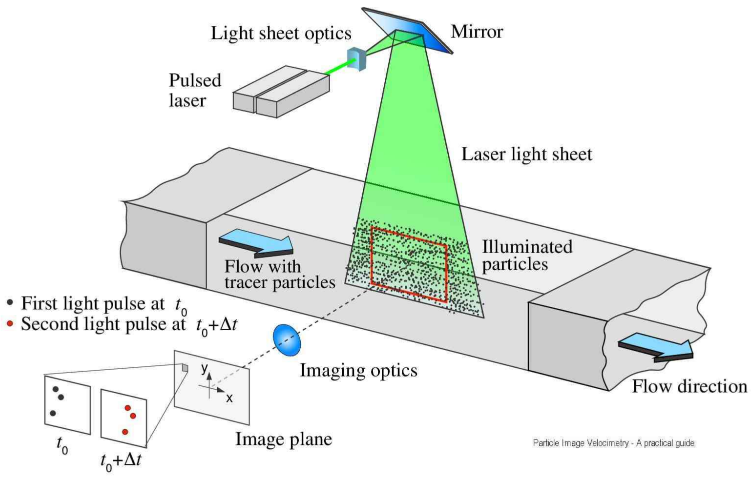
Guiding Principles for Use of PIV

Scientists investigating unsteady flow phenomena are primarily interested in detecting and understanding the structures present in unsteady, three dimensional flows, being wall-bounded or free shear flows, which requires temporally and spatially well resolved qualitative and quantitative information of the flow volume under consideration. In case of flow phenomena involving flexible or moving walls the knowledge of the shape and deformation of the walls is needed in addition. All data must be acquired non-intrusively so that no interference of the flow field by the measurement is to occur.

PIV having become a mature technique, scientists interested in unsteady flow phenomena are rather end users than developers of the PIV technique. As such, when designing an experiment and selecting a PIV system, very often they may not be aware of all implications provided by the selected equipment and experimental set-up on the data which can be measured. The considerations and competing design objectives discussed in Section 1.3 Principle of Particle Image Velocimetry (PIV) make clear that there does not exist a 'one-fits-all' PIV system. Based on the discussions of Section 1.3 a brief overview of the measurement of flow velocities employing different configurations of PIV systems will be given next.



Experimental arrangement for planar 2C-2D PIV in a wind tunnel.

Two component — two dimensional PIV system (2C-2D PIV). The development of PIV started in the 1980s with 2C-2D PIV systems, comprising one camera, one illumination source and planar illumination (light-sheet), see Figure. The focus of the scientific work concentrated on seeding problems, particle scattering, following behavior of tracer particles, development of evaluation algorithms, accuracy, etc. The PIV plane was typically aligned with the mean flow direction in order to keep the tracer particles from leaving the light-sheet in between the two illuminations. Also, it was quickly recognized that under certain imaging conditions so-called perspective errors affect the recovered measurement data. Later on, with the development of robust stereoscopic PIV systems, that is, using two cameras and a planar illumination, these problems could be avoided and stereoscopic PIV became the standard PIV configuration for the investigation of complex flow phenomena (see below).

The simplest variant of PIV, a 2C-2D configuration, see Figure, is the easiest to use and thus considered a recommended starting point for first time practitioners. In general, their use is recommended if:

- The flow field is nearly two-dimensional.
- The object to be investigated allows only one viewing direction (e.g. due to restrictions by walls).
- The PIV measurement shall serve to obtain an overview of an unknown flow field (location and size of structures, range of spatial and temporal scales etc.) before a more complex and costly investigation will start.

- The PIV measurement shall check the seeding quality, tracer behavior, functionality of PIV system, that is, with respect to triggering to an external event, functionality of external devices (structural performance of PIV set-up (due to vibration, noise), model vibrations, operated model movements, actuators etc.).

If due to lack of equipment a 2C-2D PIV system must be used for research, the previously mentioned problems involved in the use of such an arrangement should be minimized for the experiment and their remaining implications on the results need to be addressed in the publication. The required knowledge of optics, lasers, imaging technique, image processing, etc. as well as the complexity of the hard- and software of PIV systems increase from 2C-2D systems to stereo and volume-resolving systems, requiring advancing expertise and growing investment. Thus, for persons starting to use the PIV technique it is recommended to begin with a 2C-2D PIV system in order to familiarize themselves with the technique and to understand its fundamental principles, to characterize and optimize the flow facility and the seeding with tracer particles, the light-sheet optics and the imaging system, to avoid background light or light scattering from surfaces, to learn the laser safety procedures, to develop a reliable calibration procedure for the whole system, to check and optimize the internal triggering of the PIV system and its connection to external events, to get familiar with the evaluation software and the post processing of the data, and to check the accuracy of the obtained data and to validate them.

Three component - two dimensional (stereo) PIV system without (3C-2D PIV) and with temporal resolution (3C-2D-(t) PIV). To upgrade a PIV system from a 2C to a 3C system requires a second camera, two Scheimpflug mounts to keep the images of the tracer particles in focus for an oblique arrangement of the cameras and suitable 3C PIV evaluation software. If the 2C-2D PIV system has been optimized and can be operated routinely, then -– in particular -- the following topics need to be addressed for operation of a 3C-2D PIV system:

- Operation of Scheimpflug mounts (one or more axes)
- More complex calibration of the arrangement of measurement plane, light-sheet plane, Scheimpflug mounts, and cameras. As data obtained by two cameras need to be combined to calculate the third velocity component, misalignments will lead to artifacts (e.g. distortion of the shape of vortices). Thus, such calibration algorithms need to be well understood and calibration procedures need to be well trained as any mistake during calibration cannot be recovered later.
- Understanding of scattering behavior of the tracer particles. With two cameras the first one being located in forward and the second one in backward scattering direction, such an arrangement will lead to different levels of intensity of the scattered light.
- Robust construction of recording set-up, to minimize effects of vibrations such as defocusing or individual movement of each of the two cameras, which would deteriorate the 3C results. Today to some limit the re-arrangement of PIV recordings captured by vibrating cameras can be done by software after the measurement.
- Measurements in planes perpendicular to the main flow direction require the possibility to modify the light-sheet optics in order that the plane of the first and the second illumination can be displaced.

If these problems have been solved the 3C-2D PIV system can be routinely used for fundamental research and industrial development. The huge number of data that can be captured with such a system will require fast evaluation algorithms, fast computers and large capacity data storage. One possible upgrade of a single 3C-2D PIV system would be to operate two 3C-2D PIV systems simultaneously,

- to extend the observation areas (placing the systems side by side),
- to image with different magnification for each of the systems to be able to resolve large and small scale spatial structures simultaneously,
- to place the two systems in the same or in a slightly displaced plane to follow the spatial and temporal evolution of structures (for application in air, this usually requires to make use of differently polarized light for illumination to be able to separate the light scattered by the tracer particles for each illumination).

The upgrade for two 3C-2D PIV systems would require a doubling of the components (lasers, cameras, Scheimpflug mounts) and more or less a doubling of cost.

Standard 3C-2D PIV systems for air flows use Nd:YAG lasers for illumination (pulse energies of 200 mJ to 400 mJ at 10 ns pulse width and wavelength λ = 532 nm). These lasers allow illuminating quite a large area of the flow, but do not allow taking recordings with a frequency of more than 10 or 15 Hz. Velocity vector maps taken with such a temporal resolution can either be analyzed statistically or –- in case of repetitive or periodic events -- the method of conditional sampling can be applied.

However, for many fluid mechanical problems a higher temporal resolution is desired to be able to follow the temporal behavior of individual structures. This can be done with some limitations by upgrading to a 3C-2D-(t) PIV system. Such a system requires the purchase of a special laser and special cameras with higher repetition rate (up to a few kHz). The disadvantage of such a 3C-2D-(t) PIV system is, that the laser power per pulse is less and, thus, only a much smaller observation area can be covered than with a standard 3C-2D PIV system. This means, for general demands, both, a 3C-2D standard PIV system and a 3C-2D-(t) PIV system should be available for a research group investigating complex unsteady flow phenomena.

Three component - three dimensional PIV system with temporal resolution (3C-3D-(t) PIV), volume-resolving PIV systems. After two decades of development of planar PIV new ideas allowed to address the ultimate goal, that is, to be able to measure all three components of the flow velocity vector (3C) in a volume (3D) of the flow in a feasible manner, with high accuracy and even temporally resolved. In this case the volume illuminated flow is imaged with several cameras (> 3) under different observation angles. Using photogrammetric or tomographic approaches the acquired images are used to reconstruct volumes of particle distributions. Through 3D correlation it is then possible to determine the instantaneous flow velocity in the observation volume. Intense development work of quite a few research groups allowed to solve most of the challenges involved in the use of the new three-dimensional techniques (see Section 9 Techniques for 3D-PIV).

Today volumetric PIV has been developed far enough to be used in complex applications of fundamental research. Compared to a 3C-2D PIV system volume-resolving PIV requires at least two additional cameras and Scheimpflug mounts, for the 'snap-shot' PIV system as well as for the high-speed PIV system. Also, more complex evaluation software for 3D reconstruction of the grey level distribution in the flow volume and 3D cross correlation, or, alternatively, Lagrangian particle tracking software, and calibration of the multi-camera system is required. PC clusters are used to be able to evaluate the huge amount of data within a reasonable time. As the size of the observation volume for tomographic PIV is limited due to the limited laser power available, the spatial resolution of a 3C-3D PIV system will be less than that of a 3C-2D PIV system for the same observation volume/area.

In addition to the capabilities mentioned above, the user of a volume-resolving PIV system should have extensive knowledge and experience in setting up complex illumination and imaging arrangements. Calibration procedures are quite sophisticated. Generally, no immediate on-line evaluation as for 2C-2D or 3C-2D PIV is possible, such that all steps performed during the measurement (illumination, imaging, recording, calibration etc.) must be performed with great care in order to obtain high-quality results. Improvement of the quality of the data after the measurement is usually not possible. In many cases volume-resolving PIV measurements are carried out in cooperation between several research groups due to the costs (and availability) of the required equipment.