

# FLOW VISUALIZATION SYSTEMS FOR FLUID FLOW RESEARCH

APPLICATION NOTE PIV-019 (US)

Flow Visualization is an important part of fluid mechanics research. Often time, performing flow visualization can serve the first step toward more detailed flow analysis. The attractive feature of flow visualization is that it can start with simple system arrangement, using a camera and an illumination system, to obtain the general understanding of the flow structure and behavior. Once the information of the flow is captured, more sophisticated system can be employed to provide analytical study of the flow field. For example, a PIV, LDV or HWA system can be employed to study the quantitative velocity profile at some strategic areas identified by the flow visualization results. Benefits of flow visualization are:

- Obtain good understanding of the flow structure
- Help to solve some practical problems
- Simple to use and cost effective
- No calibration and synchronization required
- Upgradeable to more sophisticated quantitative systems, to Planar PIV, Stereo PIV and volumetric PIV (V3V)

There are different arrangements for flow visualization, dependent upon the hardware selected for the procedure. Planar or volumetric illumination determines the visualization region, while the camera sets up the image capture speed. As a result, the evolution of a flow pattern in a plane or the flow movement in a volume can be explored, as shown below.



Flow visualization for a planar region



Flow visualization of a volumetric region

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## System Components for Flow Visualization

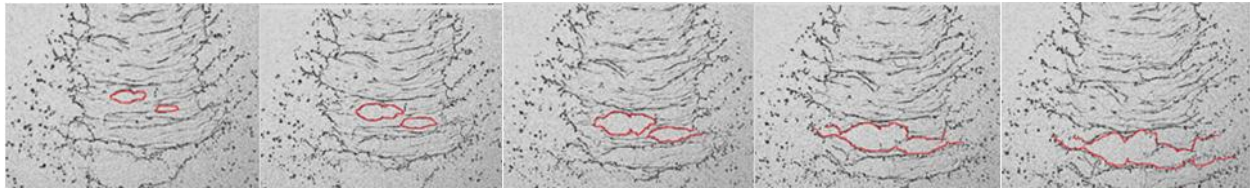
The table below shows some of the major system components for flow visualization. Detailed description and functions of the components are given in the following sections.

Camera	<b>PowerView™ System series of high resolution cameras; or high speed CMOS cameras</b>
Illumination system	Pulsed or continuous LED illumination; CW solid state laser; pulsed Nd:YAG laser with low energy
Software	Insight 4G™ software for image capture and image presentation

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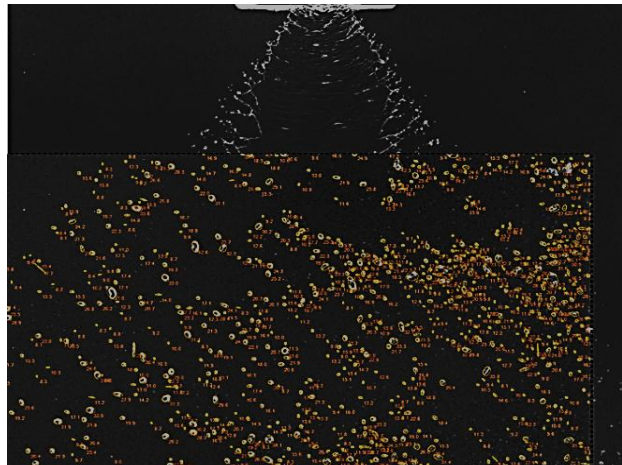
## Camera Hardware

Simple video cameras are commonly used for general flow visualization. When scientific grade CCD/CMOS cameras are employed, quantitative information from the image can be extracted. It also becomes easier to be upgraded to PIV for quantitative flow field measurements. High speed CMOS cameras are popular for flow visualization, particularly for flows with speed higher than 5 m/s. Due to its high capture rate, the high speed camera is able to capture at rate in the range of 1000 Hz to 50,000 Hz such that the evolution of the flow structure can be captured. Subsequently the flow speed can also be obtained. The picture below shows a sequence of spray images captured by a high speed camera running at 12,500 Hz. The result is that the formation of the ligaments in the spray (the Red region) can be tracked with high temporal resolution.



Identification of the ligament formation wrt Time using high speed camera

When a high pixel resolution camera, like 16 or 29 million pixels, is used for the image capture, analysis may yield quantitative results for flow field. For instance, the picture below shows the droplet structure in a spray captured by a 29 million pixel CCD camera. Due to the high pixel resolution of the camera, the size for the droplets was analyzed as shown in the picture.



Quantitative measurement of droplet sizes in a spray

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## **Illumination Hardware**

Some of the common illumination devices used for flow visualization are LED (Light Emitting Diode) illuminators and lasers (pulsed or CW). Regular continuous LED array can also be used; the tracer particles need to be large enough to scattering sufficient amount of light to allow the camera to capture the image. With the advance of Diode Pumped Solid State (DPSS) lasers, it becomes very feasible for the DPSS laser to provide high amount of laser energy to illuminate the measurement region. The advantage of LED illuminator and laser is that they can be triggered and synchronized with the camera such that precise timing of image capture can be achieved. As a result quantitative analysis of the images may produce the velocity information of the flow.

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## **Tracer Particles**

Tracer particles or dyes are needed for flow visualization. Typically bubbles or oil droplets are used as tracer particles for air or gaseous flows. Glass hollow spheres or polymer based particles are commonly used as tracer particles for liquid flows. Color dye is also frequently employed in liquid flow for flow visualization.

Flow Visualization is a powerful technique for fluid flow research. It provides good insight to the flow analysis and is often used as the pre-cursor for more sophisticated quantitative measurements.

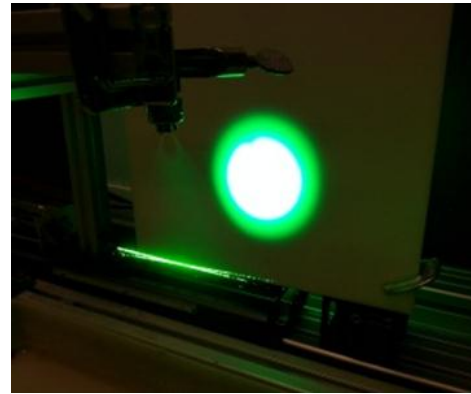
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## **Shadowgraph Imaging as Flow Visualization System**

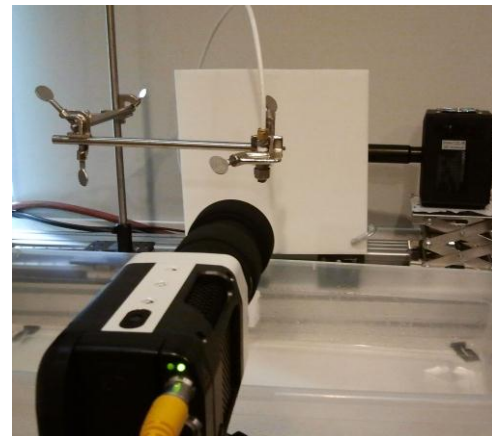
The shadowgraph imaging technique is often considered to be one of the most approachable spray analysis methods as it requires few resources to implement. Typically, backlit shadowgraphy involves an illumination source placed behind a light diffuser, and a camera positioned opposite of the diffuser plane. Generally, the spray experiment is situated between the diffuser and camera. The fundamentally, shadowgraph imaging relies on the re-direction of light due to refraction. The light traveling toward the direction of the camera, away from the diffuser, will be perturbed (refracted/reflected) due to the change in refractive index of the sprayed liquid relative to the spray environment. As such, un-reflected/refracted light rays will fill the image sensor. Light rays diverted by the spray will travel elsewhere causing a lack of photonic energy on the image sensor translating to a dark portion of the image, illustrating a 'shadow'. Thus the lack of light typically indicates the presence of the spray medium.

With the evolution in image-based diagnostics, there exist various approaches to obtaining and analyzing shadowgraph results. Primarily, implementation of back-lit shadowgraphy separates into two distinct families; that of 1) low-resolution but fast image capture and 2) high-fidelity non-consecutive still images. Both approaches apply the same fundamental principles for shadowgraph imaging, although nuances existing in the hardware. Distinctly, the former technique lends well to transient analysis such as understanding the evolution of wave instability leading to sheet breakup at the start of the spray. The latter, however, illustrates in great detail features like primary and secondary sheet breakup, formation and collapse of ligaments, and droplet formation and coalescence. In both cases, advancements in software analysis offer quantifiable information about the spray characteristics. Both approaches, however, offer unique and necessary insight towards full characterization of a spray.

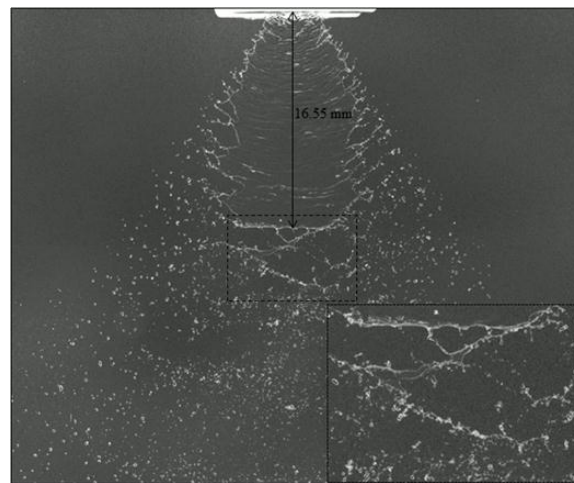
When a high speed camera is used, typically qualitative understanding of the time resolution of the flow structure can be obtained. If quantitative measurement is of interest, then camera with high pixel resolution in the order of 16 or 29 Mpixels will be more desirable. The illumination using LED illumination or CW DPSS laser is common for shadowgraph. The spray was arranged from the back of to allow the shadow of the spray structure to be captured. Such arrangement was beneficial because the distribution of the illumination could be very uniform with the arrangement of a “diffuser” plate in the path of the illumination. Uniform illumination was important such that the light scattering from the different structures (wave fronts, ligament, large and small droplets) in the spray could be captured. In addition, the forward scattering arrangement by the camera provided the highest sensitivity of the capture. The figure below shows the uniform illumination pattern for the flow visualization arrangement. Another picture shows the system arrangement using a high speed camera to capture the flow evolution of the spray. A result of the spray performed by the shadowgraph system is given. The image was captured by a 29 Mpixel camera; hence, the very fine structure of the flow can be visualized.



**Uniform back illumination of shadowgraph configuration**



**Shadowgraph arrangement using high speed camera**



**Result of a shadowgraph taken by a 29 Mpixel camera**



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