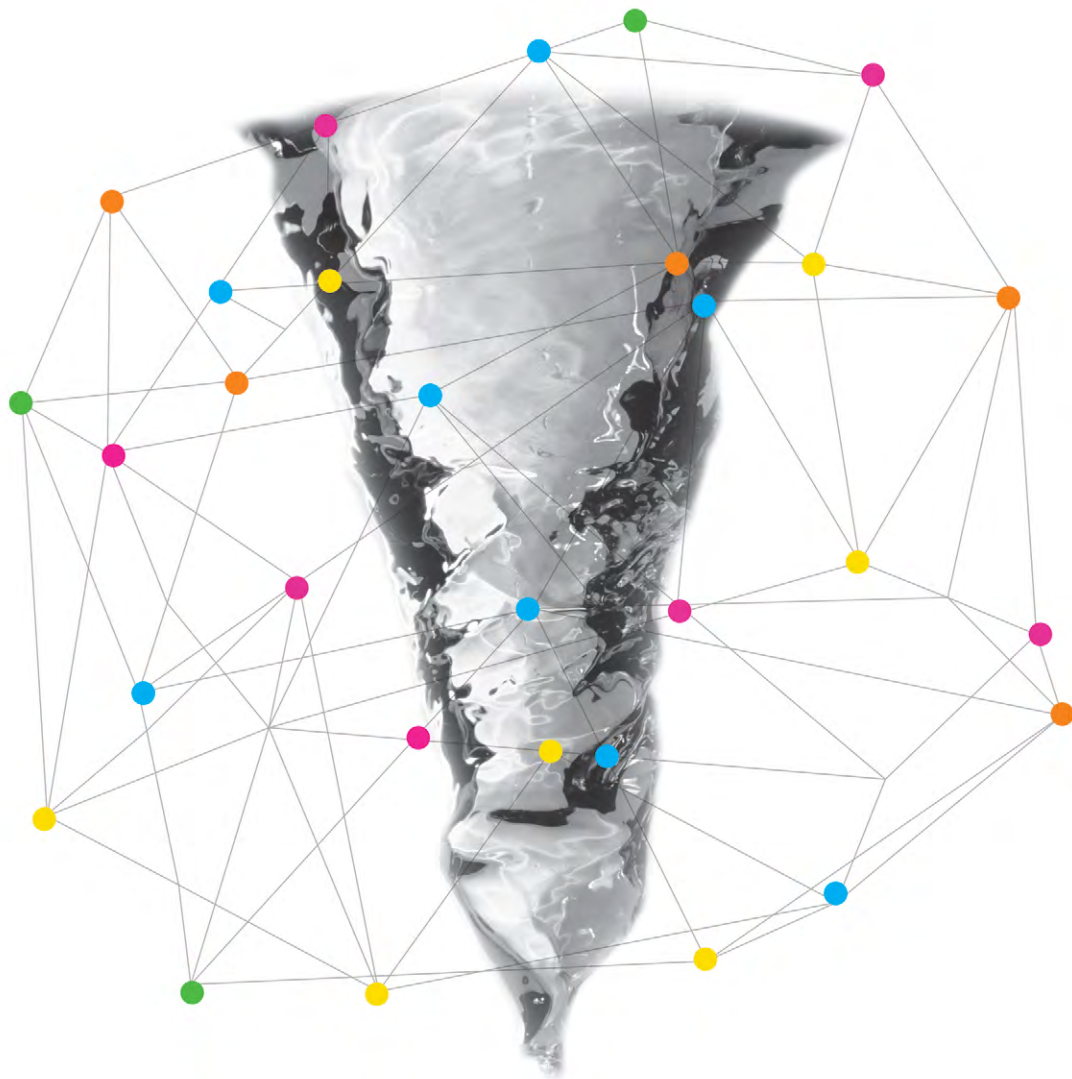


# FLUID MECHANICS SYSTEMS FROM TSI

A COMPLETE PORTFOLIO OF SOLUTIONS FOR  
CHALLENGES POSTED BY FLUID MECHANICS RESEARCH



UNDERSTANDING, ACCELERATED

# OVER 50 YEARS OF CONTRIBUTION TO THE FLUID MECHANICS RESEARCH COMMUNITY

## Complete Portfolio

TSI's fluid mechanics measurement systems, based on many years of research and development, have been trusted by researchers to make accurate measurements of flow velocity, turbulence, and all the associated properties at a point or over a planar region in a wide range of environments, varying from simple, to complex, to hostile. They also reliably measure particle size, velocity, number density and volume flux of spherical particles, droplets, or bubbles in similar environments and make noninvasive measurements of temperature, concentration and other scalar properties.

For example, our Laser Doppler Velocimetry and Particle Image Velocimetry Systems helped researchers understand how new aircraft might better handle sudden downdrafts. The volumetric 3D3C flow product, V3V, was used in breakthrough research aimed at building better heart valves.

Our innovative system-based solutions include:

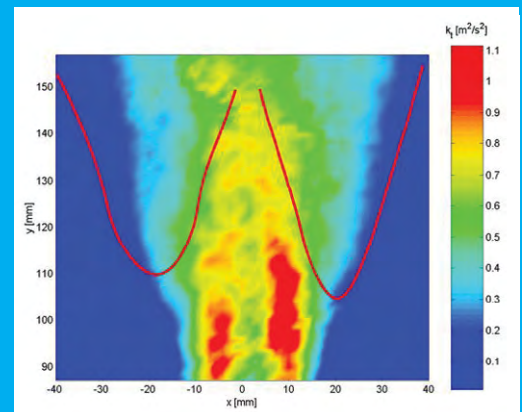
- + Volumetric 3-Component Velocimetry (V3V™ System)
- + Particle Image Velocimetry (PIV)
- + Planar Laser Induced Fluorescent System (PLIF)
- + Laser Doppler Velocimetry (LDV)
- + Phase Doppler Particle Analyzer (PDPA)
- + Thermal or Hot Wire Anemometry (HWA)

With a worldwide reputation for providing innovative and high quality measurement solutions, TSI is adept at applying emerging technologies to meet unique measurement requirements in fluid mechanics research for a wide range of applications.

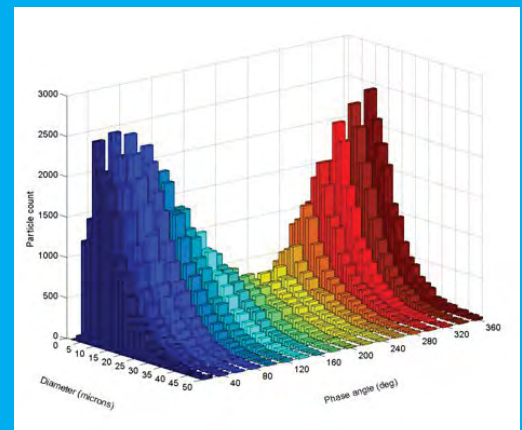
### Cutting Edge Research

The Fluid Mechanics division of TSI has worked to develop superior fluid flow and particle measurement instrumentation for the global research community for over 50 years. During this time TSI has been at the forefront of developing state-of-the-art systems to meet researcher's advanced measurement requirements in the following areas:

- + Hydrodynamics
- + Aerodynamics
- + Fundamental Flow and Particle Research
- + Turbulence
- + Spray Diagnostics
- + Bio-locomotion studies
- + Biomedical studies
- + Combustion studies
- + Multi-phase Flow



PIV measurement of Lifted flame from Stanford University, USA



Spray droplet diameter distribution in an acoustic driven flow

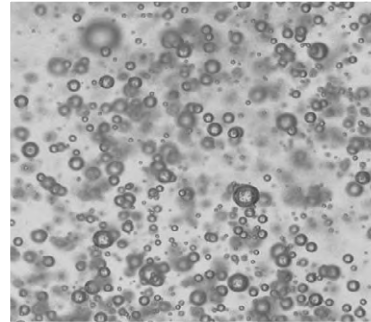
# SOLUTIONS FOR UNIQUE FLUID FLOW MEASUREMENT APPLICATIONS

## Hydrodynamics

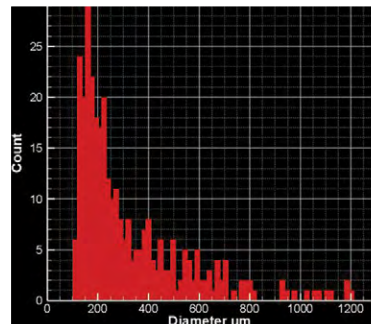
Marine hydrodynamics researchers, as well as investigators in other areas of study within this broad field, benefit from TSI's trusted solutions and knowledgeable team of experts that have helped enable them to break into 3-dimensional velocity measurements throughout a volumetric domain using TSI's award-winning V3V™ system. Hydrodynamics researchers can also investigate flow point-wise through the use of TSI's Laser Doppler Velocimetry (LDV) system, in addition to our other instrument offerings for further analysis.

## Multi-phase Flows

TSI's Global Imaging Systems, driven by the INSIGHT 4G™ Software Platform, feature the most advanced tools and widest range of measurement techniques for detailed analysis of multiphase fluid flow properties. Measured parameters include droplet size and velocity in sprays, object size-shape-velocity analysis (including diameter, Feret diameter, ellipticity, and area) in bubbly, particle laden, or liquid-liquid multiphase flows, and void fraction.



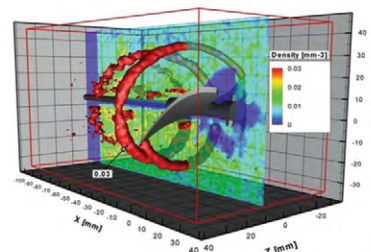
Size distribution  
of the bubbles



Measurement  
of Bubble size  
and velocity



3D LDV  
System for the  
measurement  
of flow behind  
propeller,  
INSEAN, Italy



3D3C measurement  
for the exploration  
of the tip vortex  
generated from  
propeller,  
INSEAN, Italy



## Spray Diagnostics

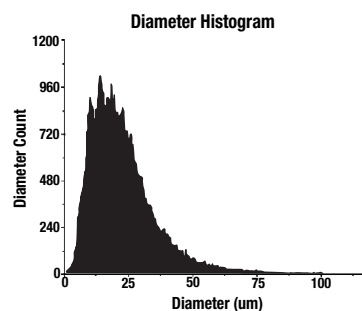
Researchers in fuel spray diagnostics and zero-gravity spray measurements alike have relied TSI's patented Phase Doppler Particle Analyzers (PDPA) for their ease-of-use, accuracy, and flexibility, permitting measurements in a wide variety of configurations to provide even the most unique of spray diagnostics measurements. In particular, TSI's PDPA systems allow spray analysts to: measure droplet size and velocity, obtain detailed statistics, including volume and flux data, with high spatial resolution, and determine size and velocity field of the spray by traversing TSI's standard PDPA system.

## Aerodynamics

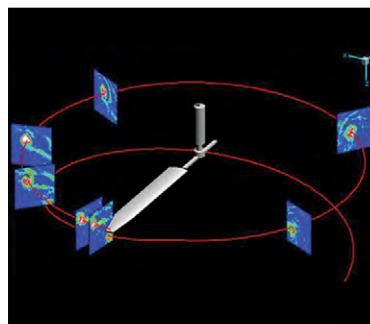
In fluid mechanics research, specifically related to aerodynamics measurements, obtaining detailed velocity measurements and associated flow properties is critical. Such information enables industrial designers to enhance the aerodynamics of bodies and vehicles -- from airplanes, ships, and automobiles to micro-size devices. Advanced research like this can be carried out using Particle Image Velocimetry (PIV) systems or thermal anemometers from TSI.



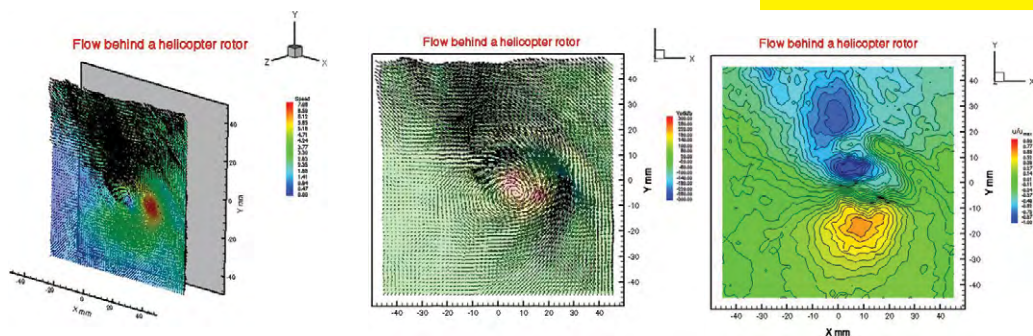
Measurement of high speed large scale dense foam spray



Droplet Diameter distribution of the dense foam spray with  $D_{10}=23 \text{ um}$ ,  $D_{32}=46.4 \text{ um}$  and  $D_{50}=54.4 \text{ um}$



Tip vortex generation at different phases of the rotor motion, University of Maryland, USA



Tip vortex field and velocity field from the helicopter rotor

# NEXT DIMENSION FLOW MEASUREMENTS WITH TRULY VOLUMETRIC VELOCIMETRY

## V3V™ System: Volumetric 3-Component Velocimetry

TSI's patented, award winning V3V™ Volumetric 3-Component Velocimetry System\* has been used extensively in many fluid flow (liquid and gaseous) research studies. Its unique ability to instantaneously capture the fluid velocity field in a volume up to 200 mm x 180 mm x 100 mm offers the most detailed flow structure imaging available, allowing researchers to uncover new insights into the field of fluid mechanics.

### Unique V3V™ System Features

- + Continuous data capture at full frame rate for up to thousands of captures and allows flow statistics and higher order quantities to be measured, even for transient flow situations
- + Patented Triplet Search Technique\*\* identifies seed particles in locations in 3D volumetric space accurately
- + Highest resolution of 3D tracking techniques
- + Accurate plug and play system sets up and gets results in minutes



## V3V-9000 Series: TSI's Flexible 3D3C Measurement System

TSI's V3V is the most flexible and powerful 3D3C flow measurement system available.

- + Selectable frame for volume size and spatial resolution
  - + V3V-PCM-CS probe for coherent flow with volume size up to 200 x 180 x 100 mm<sup>3</sup> and spatial resolution of 3 mm<sup>3</sup>
  - + V3V-PCM-TS probe for turbulent flow with high spatial resolution of less than 1 mm<sup>3</sup> and volume size of 70 x 60 x 20 mm<sup>3</sup>
- + Selectable camera sets with removable camera configuration
  - + 4MP-HS camera for frame rate of 32 fps
  - + 4MP-180 camera for frame rate of 180 fps
  - + 8MP camera for frame rate of 8.5 fps

Different frame configurations and camera systems can be used to customize your experiment. The cameras can be removed from the frame to be used separately. 3-Dimensional flow in a volume (3D3C), 3-Dimensional Flow in a Plane (StereoPIV), 2-Dimensional Flow in a Plane (2D PIV), and Stereo PIV + PLIF are the possible system configurations using the three cameras.

\* US Patent # 6278847

\*\* US Patent # 7006132

## The Technology Behind the V3V™ System Imaging System

- + Illumination created with a standard Nd: YAG laser and two cylindrical lenses. The size of the volumetric illumination is based on the orientation of the two lenses which can be optimized for the desired measurement size.

### Imaging Capture

- + Six images (three images corresponding to both Frame A, and Frame B) are captured in one shot utilizing the laser pulse separation to determine the velocity range for either high speed flow (up to 2,000 m/s) or low speed flow (mm/s).
- + The time between the two laser pulses can be adjusted from 100 ns to a few seconds to accommodate for the velocity ranges of interest.

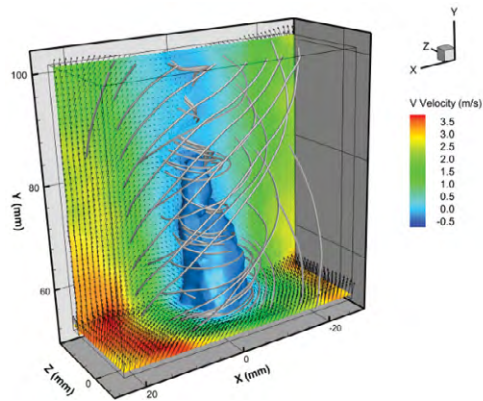
### 3D Particle Identification and Tracking

- + All six particle images from both Frame A (Time = t) and Frame B (Time = t +  $\Delta t$ ) combine to locate the particle in the volumetric 3D space using the patented Triplet Searching technique resulting in two 3D volumetric particle maps for Frame A and Frame B.
- + Using robust 3D particle tracking technique, a single velocity vector corresponds to the motion of a single tracer particle to measure from Frame A to Frame B. By definition, this is the highest possible spatial resolution of any particle velocimetry technique.

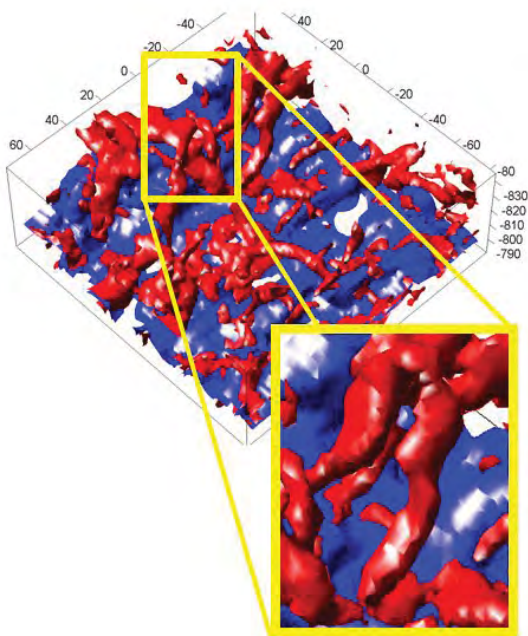
### Vector Field

- + Randomly spaced particle vectors are interpolated to provide vectors on a uniform grid (voxel)
- + Insight V3V 4G software displays volumetric 3D plots, slice plots, and even movies!

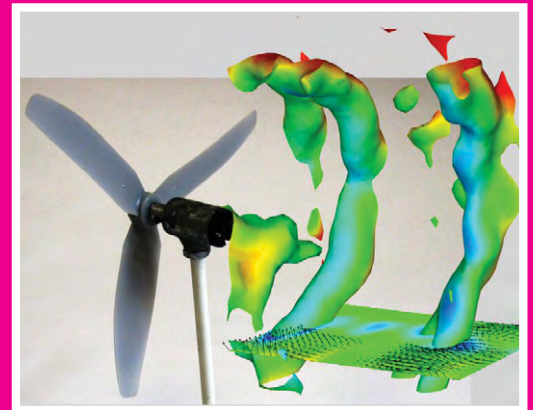
# V3V™ SYSTEM: INCREDIBLE 3-DIMENSIONAL MEASUREMENT RESULTS



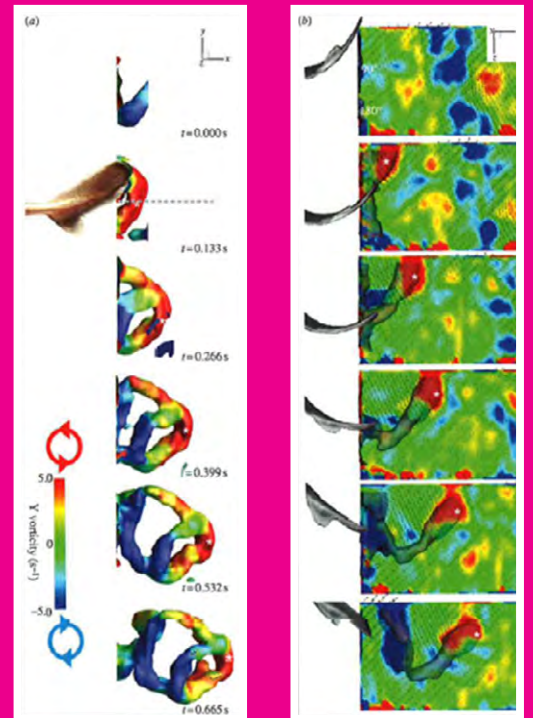
Combustion flow (non-reacting), ICARE CNRS, France



Hairpin structure in a turbulent boundary layer flow, University of Minnesota, USA



Wake downstream of a water turbine with flow from left to right. Slices represent streamwise velocity, with Red indicating high speed and Blue representing low speed fluid, University of Minnesota, USA



3D flow structure from a shark fin, Harvard University, USA

# GLOBAL VELOCITY MEASUREMENTS FROM LARGE TUNNELS TO MICRO CHANNELS

## Particle Image Velocimetry

Particle Image Velocimetry (PIV) is an optical imaging technique used to measure velocity at thousands of points in a flow field simultaneously. The measurements are made in "Planar slices" of the flow field to give two components or three components of velocity. This technique provides accurate results with very high spatial resolution, while TSI's Time-resolved PIV system allows for high temporal resolution of the velocity field.

## Unique PIV Systems

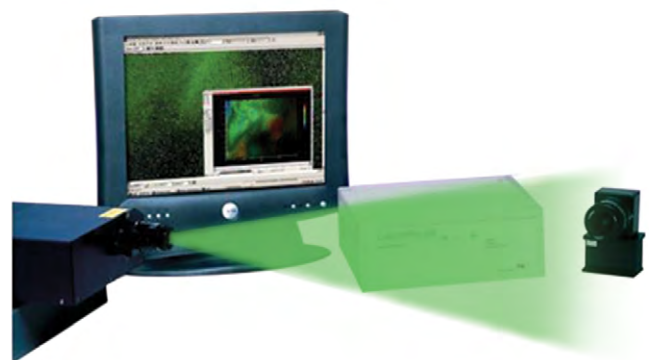
The PIV technique can be applied to measure flow fields in many environments, from microchannels to large scale wind tunnels, and for 2D to 3D with high spatial and temporal resolution. Example systems include:

- + 2D PIV
- + Stereo PIV
- + Time Resolved-PIV (TR-PIV)
- + Micro PIV\*
- + Tow Tank PIV (Underwater 2D or Stereo)

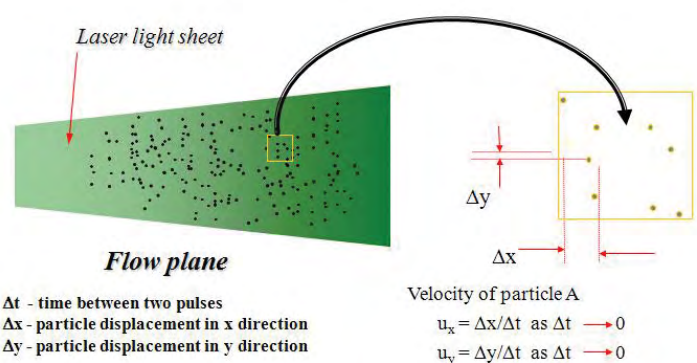
## How it Works: PIV

- + Use of small tracer particles to follow fluid flow
- + Images of particle positions, illuminated by a pulsed laser, are captured at separate times
- + Particle displacements are calculated across  $\Delta t$ , the time between laser pulses, to determine velocity
- + Measurement at many points at one instant of time
- + Instantaneous vector fields are produced while time averaged statistics are obtained by averaging many image fields

\*US Patent #6653651

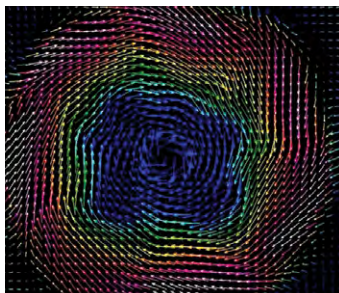


2D PIV system with a single camera and laser for planar 2D velocity field measurements.

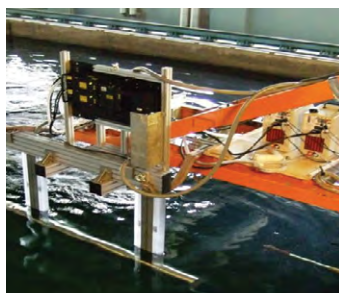




# PIV SYSTEM: DIVERSE APPLICATIONS AND MEASUREMENT RESULTS



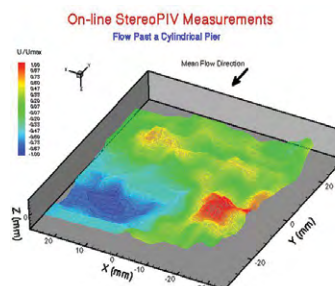
3-D planar velocity field of flow behind a propeller captured by tow tank PIV system, INSEAN, Italy



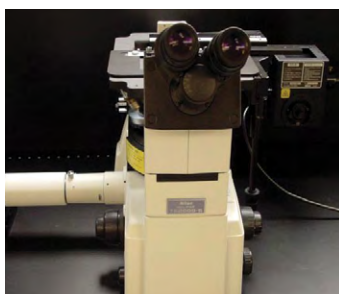
Underwater Towing Tank PIV system, Potsdam, Germany



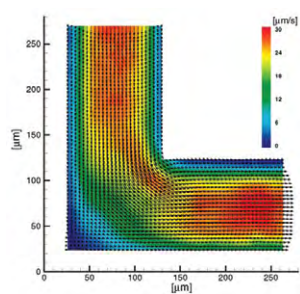
Stereo PIV system



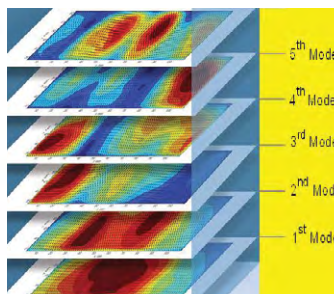
Stereo PIV measurement of flow past a cylindrical pier, South Dakota State University, USA



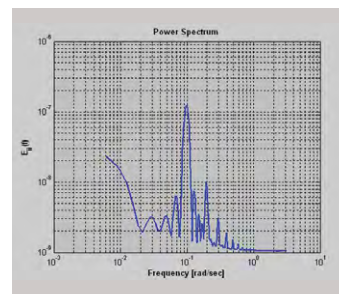
Micro PIV system using an inverted microscope



Velocity field in a 200 micron 90-deg channel, University of Tokyo, Japan



Proper Orthogonal Decomposition Analysis for Non-steady flow field captured by TR-PIV



Power spectrum and Autocorrelation function of non-steady flow field captured by TR-PIV

# GLOBAL IMAGING SYSTEMS FOR MEASUREMENT DIAGNOSTICS

## Planar Laser Induced Fluorescence (PLIF for Simultaneous Velocity and Scalar Measurements)

PLIF systems from TSI provide measurements of scalar quantities: concentration, temperature and combustion, in addition to fluid velocity in a flow which is needed to understand flows and their transport behavior. Similar to the measurement technique behind TSI's Particle Image Velocimetry (PIV), extending a PIV system to allow for measurement of some scalar quantities is easy!

### How it Works: PLIF

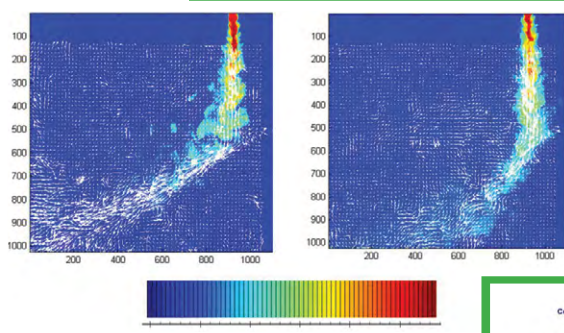
- + A flow is seeded with miscible species, which mix with any species naturally present, and absorb laser light in a plane.
- + The absorbed light, relative to the wavelength of the laser, excites the species to a higher energy state until it decays, causing the species to fluoresce.
- + The fluorescent light is then collected by a camera and analyzed to relate the light intensity to temperature or concentration, depending on the properties of the fluorescing species and other species present in the flow.
- + Finally, in-situ calibration using multipoint ratio metric and linear curve fit methods, interpret the intensity scales captured by the camera to the scalar quantity.

### PLIF and Combustion Species

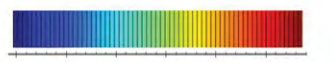
PLIF measurements of combustion species (i.e. NO, CH, OH and CO) require a Tunable Dye laser as the light source. The tunable dye laser allows the proper excitation wavelength of a particular species to be selected and ultimately measured. Often, the fluorescence emitted by this type of species is faint so an intensified camera is also required to detect the weaker signal.



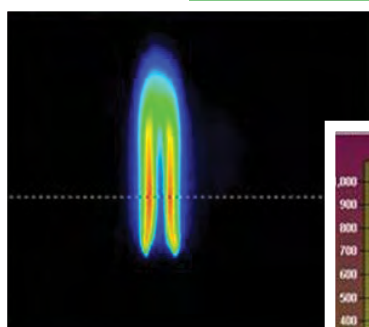
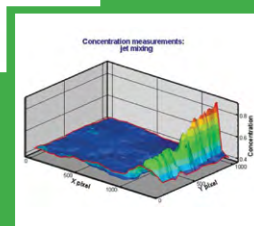
PLIF System using dichroic color separation arrangement for measuring velocity and scalar quantity



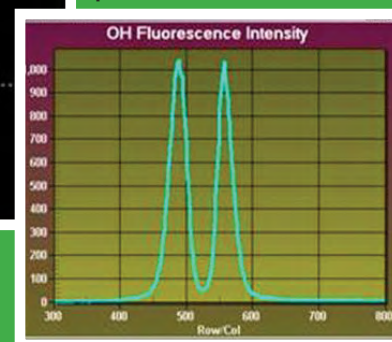
Plot of velocity and concentration of an impinging jet



3D representation of the concentration of the jet



Distribution of the CH species in a flame;  
Distribution of OH species in a flame



### Global Sizing Velocimetry (GSV) system

Global Measurement of droplet size and velocity of a spray is best performed using the Global Sizing Velocimetry (GSV) system\* from TSI. GSV is based on the interferometric scillation of light scattering from a droplet to provide the accurate measurement of the droplet size. Using the particle tracking technique, which requires two image captures of the droplet field, the velocity of the droplet can also be measured. TSI's GSV system is also very similar to the PIV setup – only a few additional accessories are needed to expand the PIV system hardware to be GSV compatible.

### Size Shape Analysis (SSA) Package

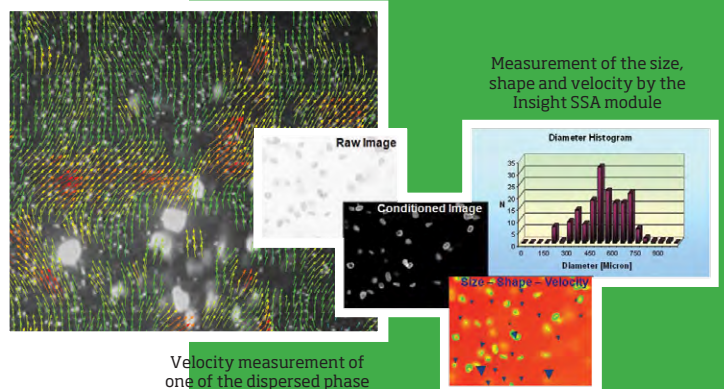
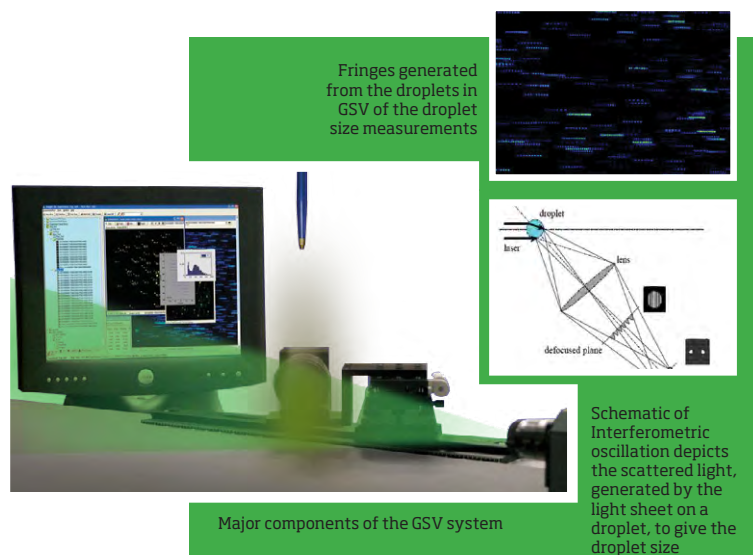
The Size/Shape Analysis package included in TSI's Insight 4G software is ideal for measuring the size and shape of a dispersed phase in multi-phase flow environment. Like TSI's PLIF and GSV Systems, SSA measurements require a set up very close to that of TSI's PIV package. In fact, only the illumination of the dispersed phase changes from a sheet (PIV system) to a volumetric illumination (SSA system) in order to measure properties of irregularly shaped droplets / particles / bubbles, including:

- + Displacement and Velocity
- + Mean Diameter
- + Major and Minor Ellipse axes
- + Ellipse Angle (Orientation)

### Global Spray Diagnostic of dense spray based on PIV's Optical Patternation Technique

This measurement technique utilizes a laser light sheet to illuminate a spray section while a camera captures the intensity of illumination in order to obtain the distribution of the droplet concentration. The concentration is representative of the size or mass distribution. Typically measurements in the vertical and horizontal sections of the spray are of interest, given the pattern of the spray (spray angle and patternation) in both orientations.

\*US Patent #7362421





# LASER DIAGNOSTICS OF VELOCITY AND PARTICLE SIZING

## Phase Doppler Particle Analyzer (PDPA) Systems

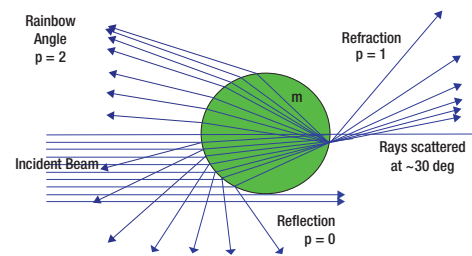
TSI's patented\* Phase Doppler Particle Analyzer (PDPA) system is a non-invasive laser based technique for the simultaneous measurement of velocity and particle size of a spray. The principle of size measurement is based on the detection of the phase difference using three detectors to determine when the particle goes through the measurement volume and subsequently passes through the intersection of two laser beams.

### How it Works: PDPA

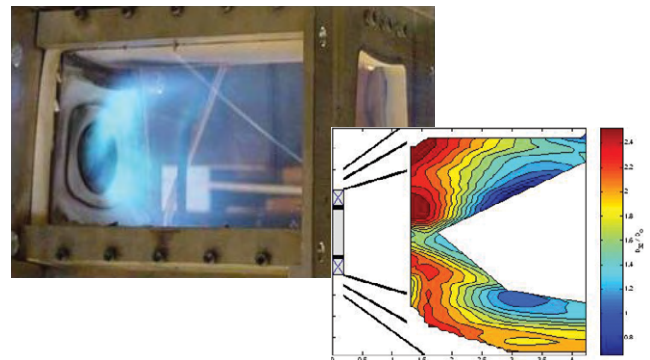
- + Laser beams are delivered from the Powersight Module and cross to form the measurement volume where the velocity and size analysis take place.
- + Phase analysis is then made with the Optical Receiver, which provides size information.
- + Velocity measurements using TSI's PDPA system range from mm/s to thousands of m/s dependent upon the optical arrangement; particle size measurements span 0.5 micron to a few mini-meters.



System layout of a 2-D Powersight PDPA system with Photo-multiplier module and Signal Processor



Light scattering from a spherical droplet. Collection of scattered light at 30 deg is typically used for Phase detection.



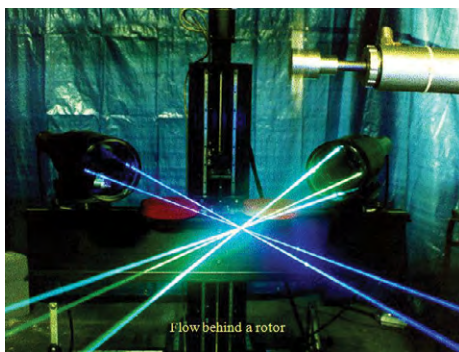
PDPA measurement of a Lean Low NO<sub>x</sub> Aircraft Combustible spray with SMD result, Georgia Institute of Technology, USA

\*US Patent #4986659

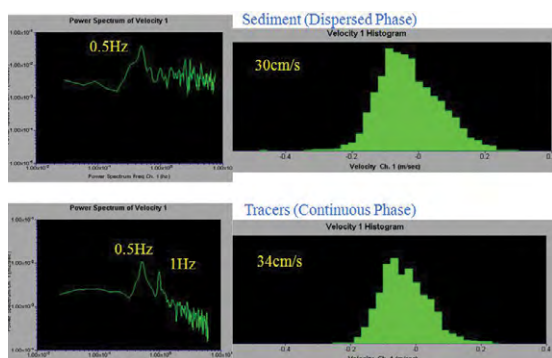




A 2-D Powersight with LDV System, photo-multiplier module and signal processor



LDV with two optical probes for 3-component of velocities for flow behind a rotor, University of Maryland, USA



Two velocity histograms from the Sediment and the Tracers (water) in a sedimentation flow model. Uses intensity separation to identify the two phases

## Laser Doppler Velocimeter (LDV) Component Systems

Laser Doppler Velocimetry (LDV) is an optical, laser based technique used to measure velocity at a single point with very high spatial resolution. LDV is a non-invasive method that provides accurate measurement with high frequency response. This measurement technique can be employed for flows in wind tunnels, water tunnels, open channels, hostile environments, and other areas where all three components of velocity data are required.

### How it Works: LDV

- + Seed particles - suspended in the flow field - pass through the measurement volume where fringes are formed based on the intersection of the two laser beams, and generate a Doppler signal detected by an optical probe.
- + The Doppler signal is then analyzed to measure the frequency of the signal.
- + Once the frequency is known, the velocity is simply the product of the fringe spacing and the frequency of the Doppler signal.
- + The system can be configured to measure 1 to 3 components of velocity and with range from mm/s to thousand of m/s dependent upon the optical configuration.

# THERMAL ANEMOMETRY FOR TURBULENT FLOW DIAGNOSTICS

## Thermal Anemometers

Thermal anemometry is a technique requiring a sensor to measure velocity at a single point with high accuracy and high frequency response. A typical thermal anemometry system has two major components, the Control circuit and the sensor. There are also two types of Control circuits, one is the Constant Temperature Anemometer (for velocity measurements), and the other is the Constant Current Anemometer (for temperature measurements).

There are many different types of sensors, wire or film, for 1D, 2D, and 3D velocity components, and for gaseous and liquid flows.

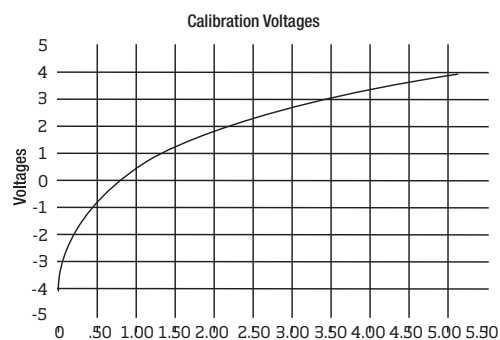
The thermal anemometry system is an excellent tool for turbulent flow because of its high frequency response to measure the fluctuation of the flow and there are many versions of sensors used in different flow environments. 1D, 2D and 3D sensors for gaseous and liquid flows are offered. There are also the sensor type, wire or film sensor, to match the required frequency response of the flow. Proper selection of the sensor is critical to the success of the measurement. Typical velocity range for a thermal anemometry system is from a few cm/s to hundreds of m/s.

## Features and Benefits

- + Single Point measurement with sensor for velocity range from cm/s to hundreds of m/s
- + Sensor calibration for velocity output
- + Good spatial resolution and high frequency response
- + 1, 2 and 3 components of velocity with proper sensor type
- + Even time sampling with high sampling rate
- + Power spectrum and statistics of flows are measured m/s



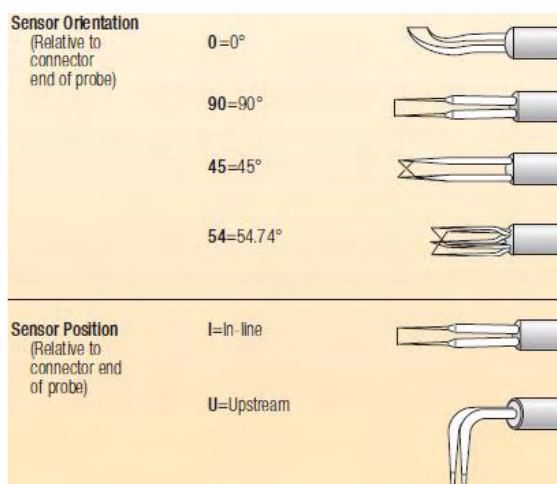
System layout with the control circuit of anemometer, sensor and software



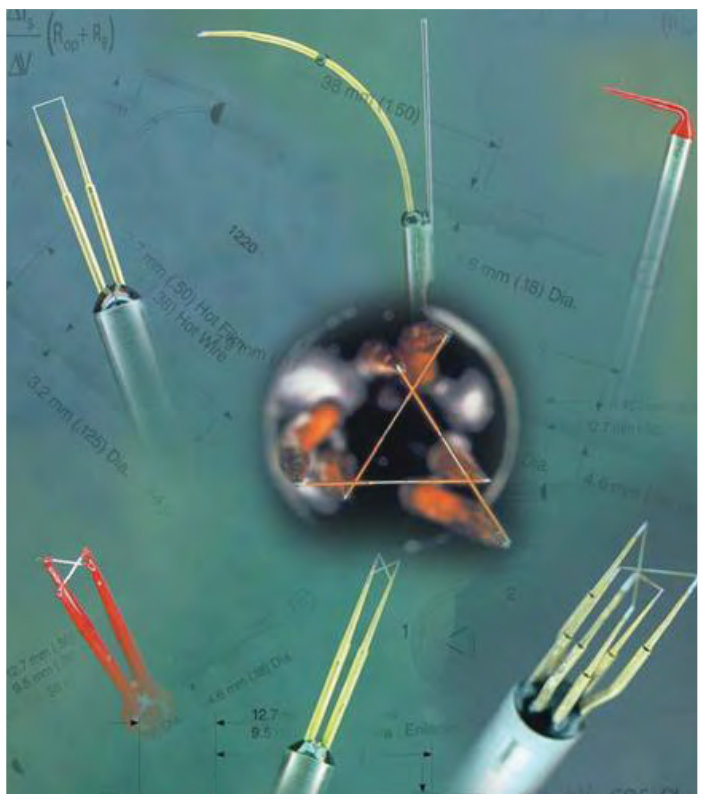
Typical calibration curve to relate the voltage output from the anemometer and the velocity

## How it Works: Thermal Anemometry

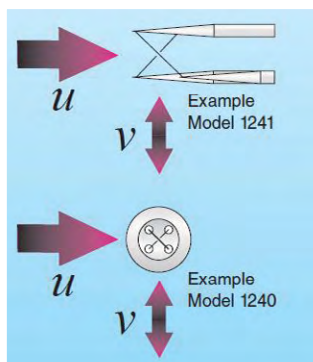
- + Thermal Anemometry requires that a sensor be heated to a specific high temperature
- + When the sensor is exposed to a flow, it is cooled and the amount of current needed to maintain its original temperature is an indication of the velocity around the sensor
- + A calibration is performed to relate voltage to velocity



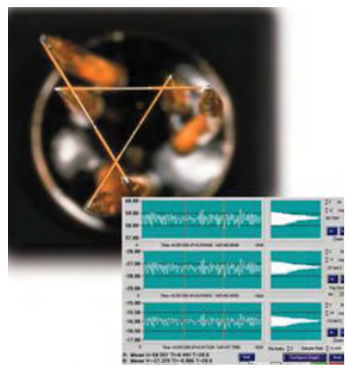
Configuration of the various sensor types



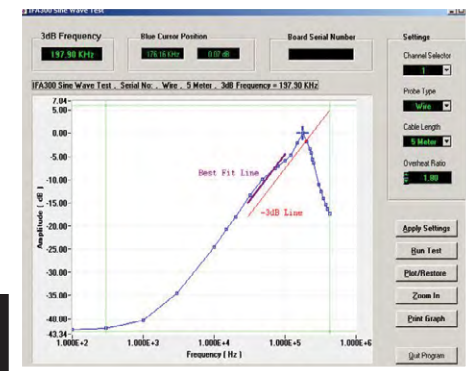
Picture of the different sensors, 1D, 2D and 3D sensors



Orientation of the sensor to the flow measurement



A typical result for a 3D sensor



Power spectrum plot of a typical measurement from a wire sensor in a wind tunnel flow

## About TSI

TSI designs and manufactures innovative precision instruments to measure flow, turbulence, temperature, particulate and many other key parameters. TSI serves the needs of industry, governments, research institutions, and universities, with applications ranging from pure research to primary manufacturing. Every TSI instrument is backed by our unique blend of technical expertise and outstanding quality.

TSI facilities total more than 425,00 square feet of space devoted to product development, manufacturing and customer support. Our work culture gets employees out from behind desks and into the field. We hold customer-training sessions, sponsor workshops and conduct product demonstrations, serve on standards committees relating to product usage, and participate in a wide variety of technical conferences.

TSI researchers and engineers have granted more than 50 patents and have a proven record of developing instruments that are the finest, often the only, and always the best of their kind. Our staff and products are involved in current global issues such as diesel exhaust reduction, biohazard protection, homeland security, environmental pollution, workspace comfort and facility monitoring. Data provided by our instruments are used in monitoring and research applications destined to have long-term impact on humankind and the world around us.

## Quality

TSI Inc. is ISO 9002 Certified meaning TSI's production, service, calibration, and checkout procedures comply with the requirements of ISO 9002 and are audited against those criteria.



UNDERSTANDING, ACCELERATED

**TSI Incorporated** - Visit our website **[www.tsi.com](http://www.tsi.com)** for more information.

<b>USA</b>	<b>Tel:</b> +1 800 874 2811	<b>India</b>	<b>Tel:</b> +91 80 67877200
<b>UK</b>	<b>Tel:</b> +44 149 4 459200	<b>China</b>	<b>Tel:</b> +86 10 8219 7688
<b>France</b>	<b>Tel:</b> +33 4 91 11 87 64	<b>Singapore</b>	<b>Tel:</b> +65 6595 6388
<b>Germany</b>	<b>Tel:</b> +49 241 523030		