第九讲：流动显示与测量技术

Chapter 21 Flow Visualization and Measurement Technique

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Content

- Visualization by smoke, dye, bubble（烟雾）
- Visualization by shadowgraphy（阴影）
- Particle Image Velocimetry (PIV粒子图像)
- Lagrangian Particle Tracking (LPT粒子追踪)

Flow Visualization

Most fluids, gas or liquid, are transparent media, and their motion remains invisible to the human eye during direct observation 流体对肉眼透明.

Techniques are able to make fluid flows visible, usually referred to as flow visualization 流动显示可使流动可视化.

These techniques rely mostly on the addition of a tracer material to the flowing fluid, e.g. dye or smoke, and what is then observed is merely the motion of the tracer 向流动流体中添加示踪剂（如染料或烟雾等）.

Visualization by Smoke

Visualization: make the flow patterns visible, in order to get qualitative or quantitative information on them.

使流动模式可见，以便获得有关它们的定性或定量信息。

Visualization by Smoke

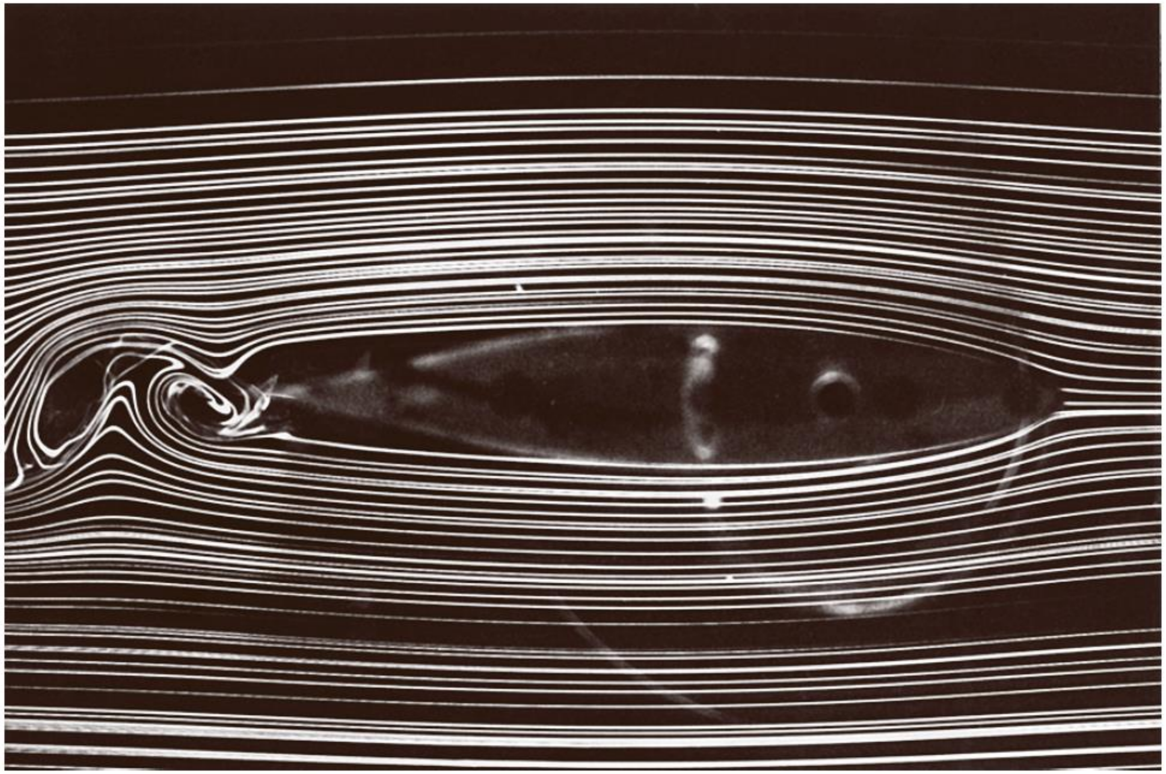
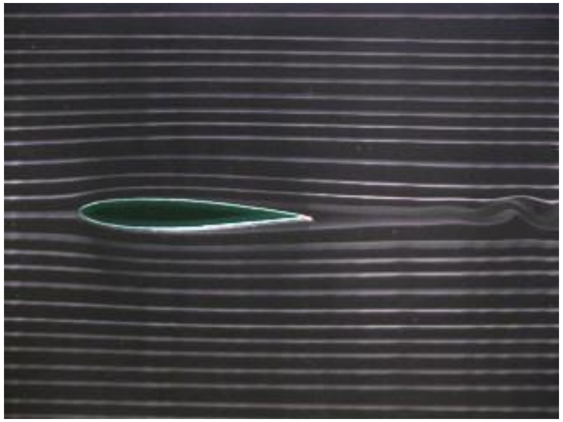


Fig. 11.8 Smoke lines around a model airfoil in a low-Reynolds-number wind-tunnel flow (courtesy of Prof. T. J. Mueller, University of Notre Dame, USA)

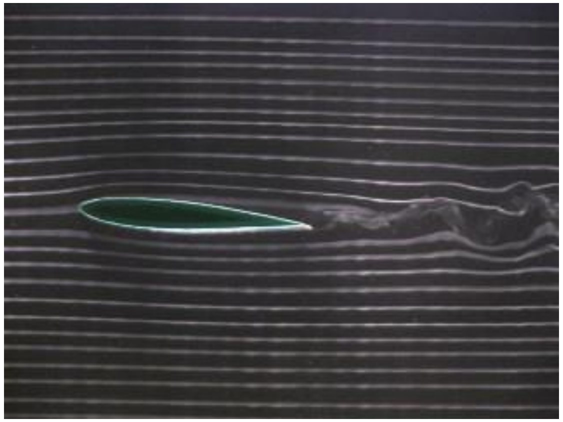
To visualize the streamline of the flow around a airfoil

Visualization by Smoke

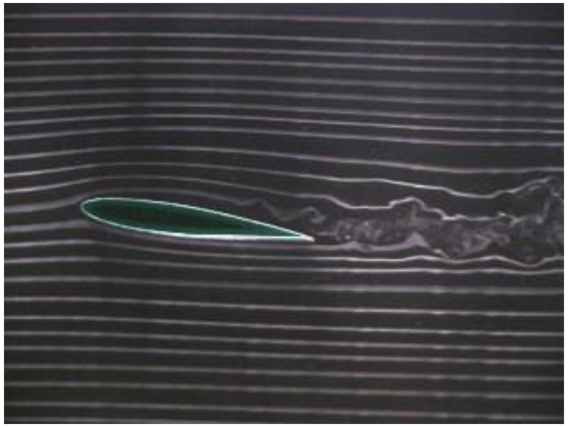
To visualize the streamline of the flow around a airfoil



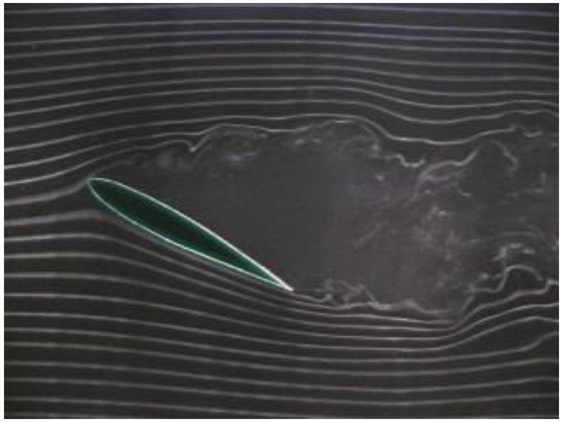
Angle of attack = 0°



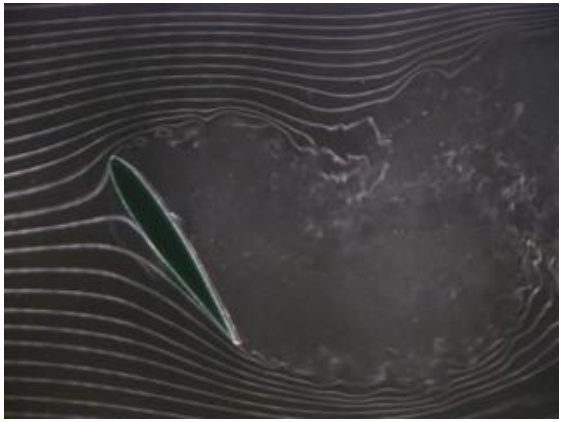
5°



10°

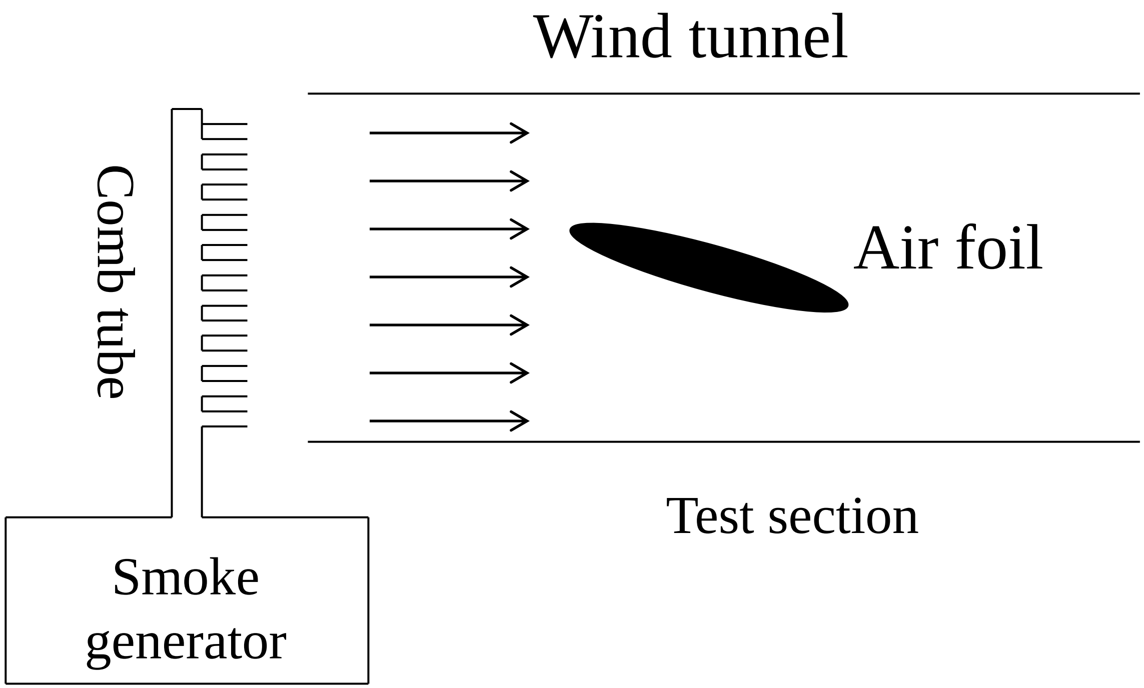


30°



60°

Visualization by Smoke



Put at the inlet of the contraction

Visualization by Smoke

How to generate smoke?

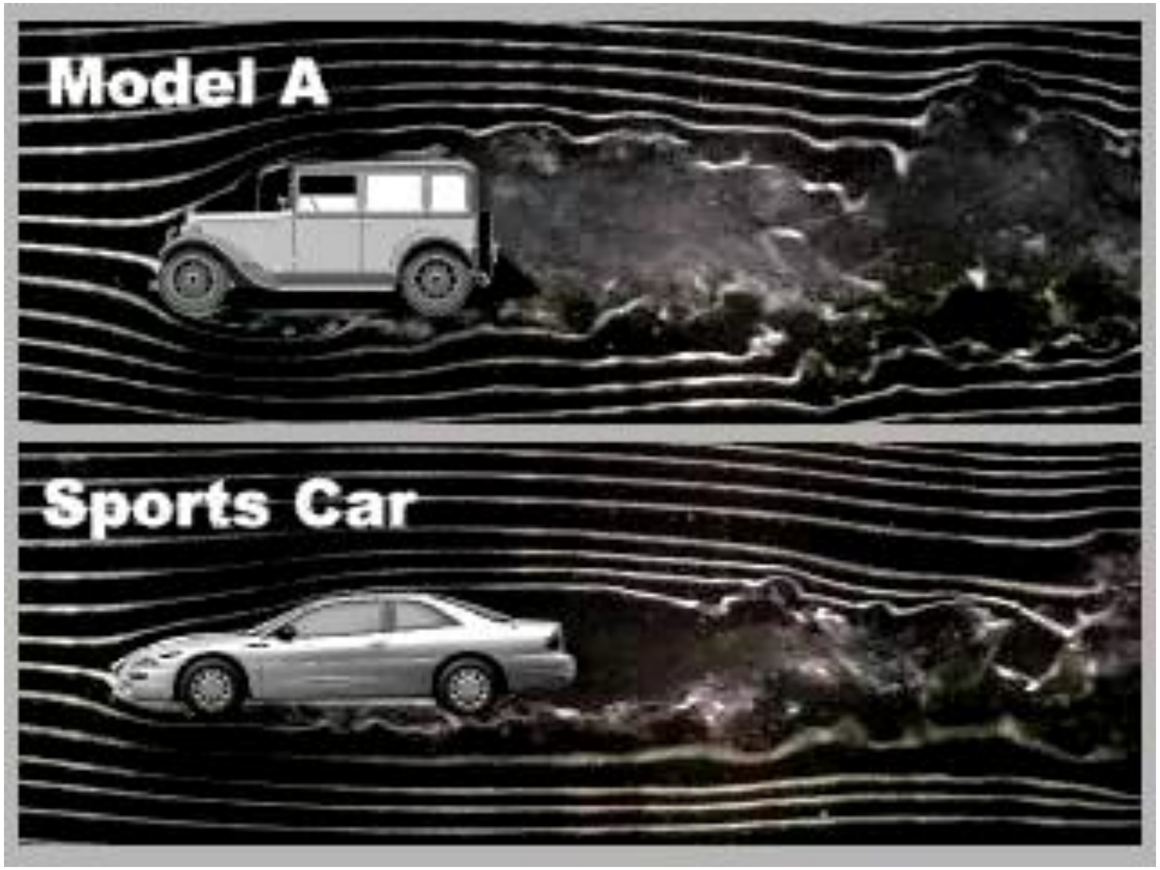
- Burning or smoldering tobacco, wood, or straw
- Vaporizing mineral oils
- Producing mist as the result of the reaction of various
- chemical substances
- Condensing steam to form a visible fog

The most popular smoke generator is based on vaporization of hydrocarbon oils, particularly kerosene（煤油）. It consists of a heating facility and a device in which the kerosene vapor is mixed with an airstream to form the appropriate mist.

Visualization by Smoke

Fig. 11.4 Smoke line visualization of the flow over a car body in a full-scale wind tunnel (courtesy Volkswagen AG, Wolfsburg, Germany)

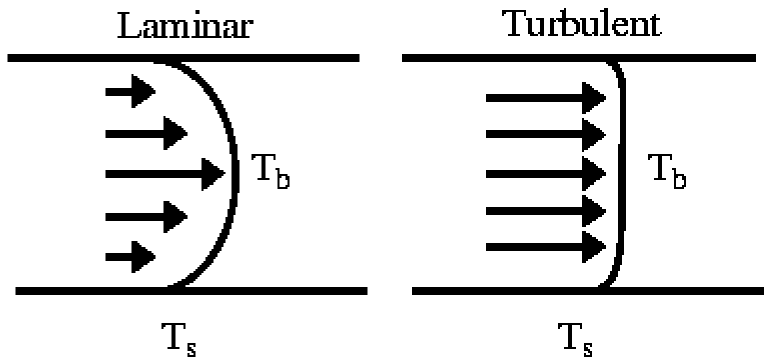
Visualization by Smoke

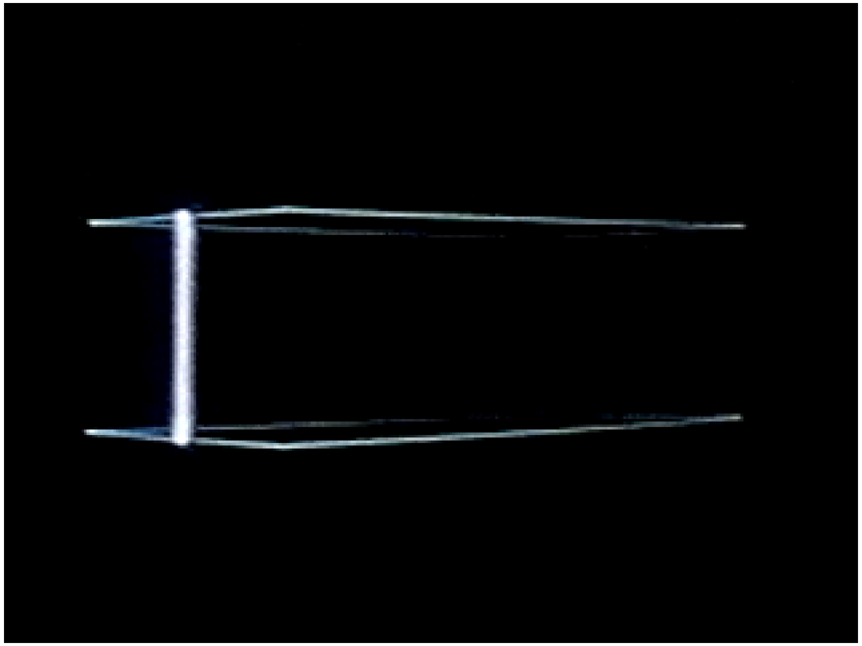


Visualization by Smoke

Fig. 11.10 Open field experiment: smoke visualization of vortex formation during the start of an airplane (courtesy Prof. Cam Tropea, Technische Universität Darmstadt, Germany)

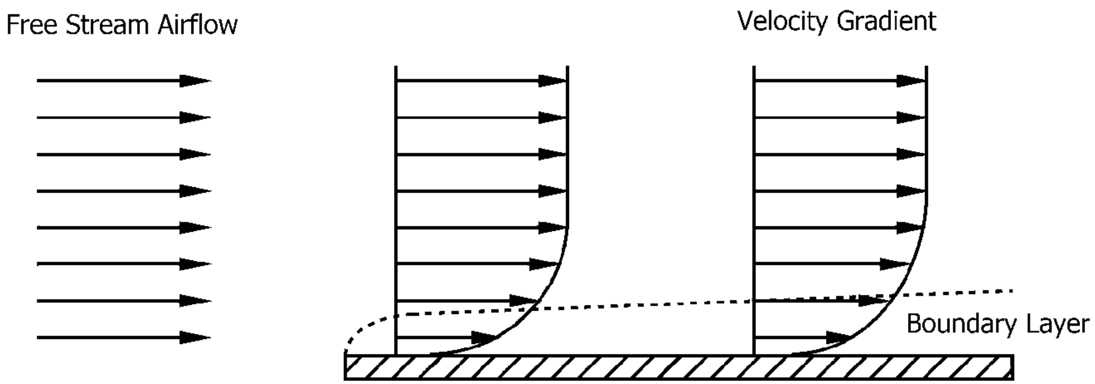
Visualization of the velocity profile

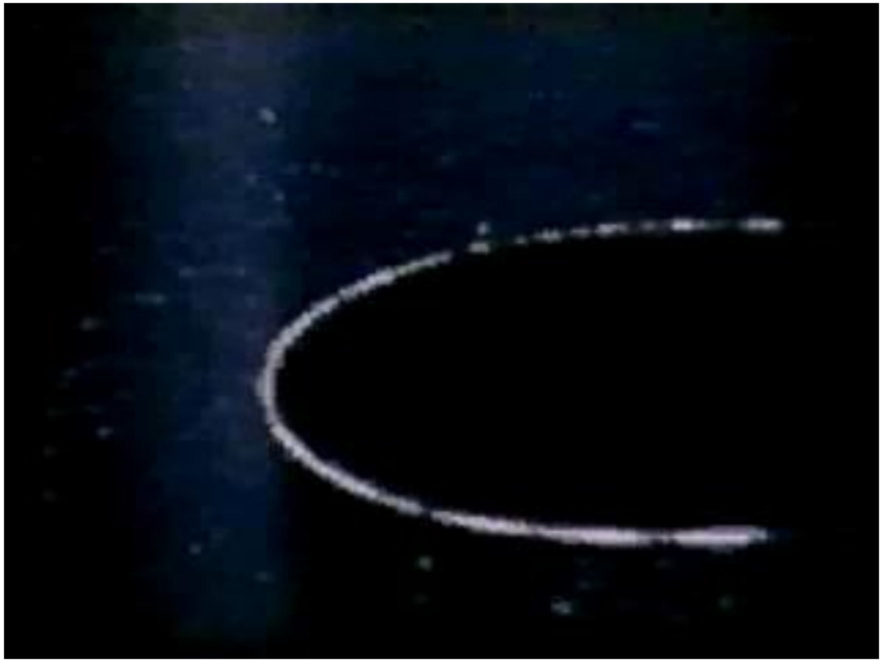




Visualization by Smoke

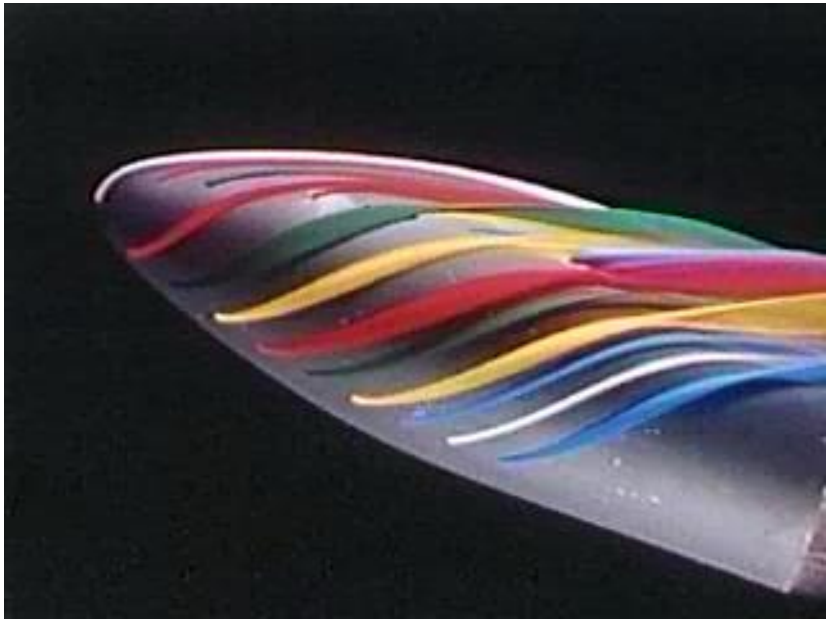
Visualization of the boundary layer





Visualization by Dye

In water flow smoke is not practicable, one needs to use other tracers like dye, or hydrogen bubble … …



Reynolds (雷诺) Experiment

http://www.youtube.com/watch?v=3na9oezJ_Yk&feature=related

Visualization by Hydrogen bubble

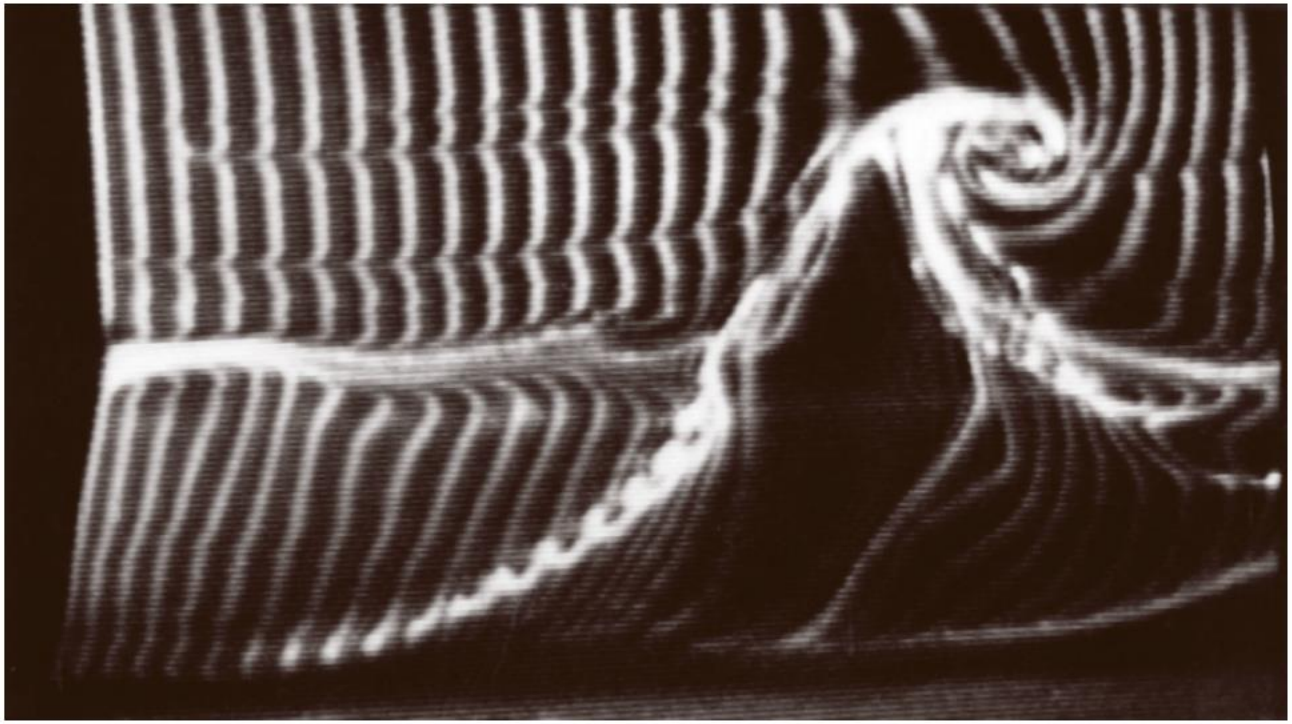


Fig. 11.15 Visualization of vortical structures in boundary layer flow by means of hydrogen-bubble time lines (courtesy Prof. C. R. Smith, Lehigh University, Bethlehem, PA, USA)

Visualization by Hydrogen bubble

It is based on the electrolysis of water, a fine wire as the cathode defines the straight line where the tracers are produced upon application of a dc voltage. 它是基于电解水，一根细线作为阴极，给定了一条直线，其中示踪剂是在直流电压作用下产生的。

Hydrogen bubbles are formed at the cathode and the oxygen bubbles at the anode that is placed somewhere else in the water flow. 氢气泡在阴极形成，而氧气泡则在阳极处，放置在水流中的其他地方。

By pulsing the voltage at a constant frequency, one can produce several successive rows of bubbles, which mark the flow curves separated by a constant flow time. 通过以恒定频率脉冲电压，可以产生连续几排气泡，这些气泡标志着由恒定流动时间分隔的流动曲线。

Summary 小结

Objective目的: visualize the flow structure: streamline, velocity profile, boundary layer ……

How如何做: water flow with dye, hydrogen bubble … air flow with smoke, mist, steam…

Requirements具备条件: Smoke generator, bubble generator, dye introducing system

Recording记录方式: naked eyes, images, videos …

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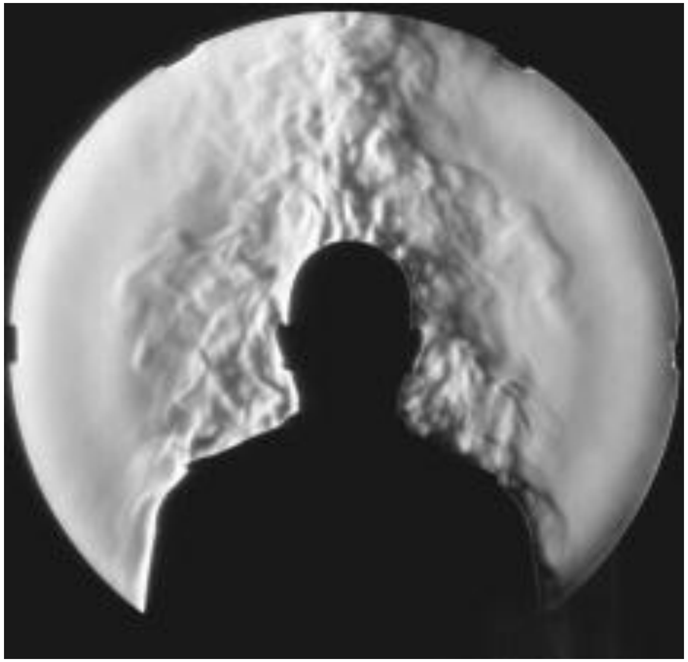
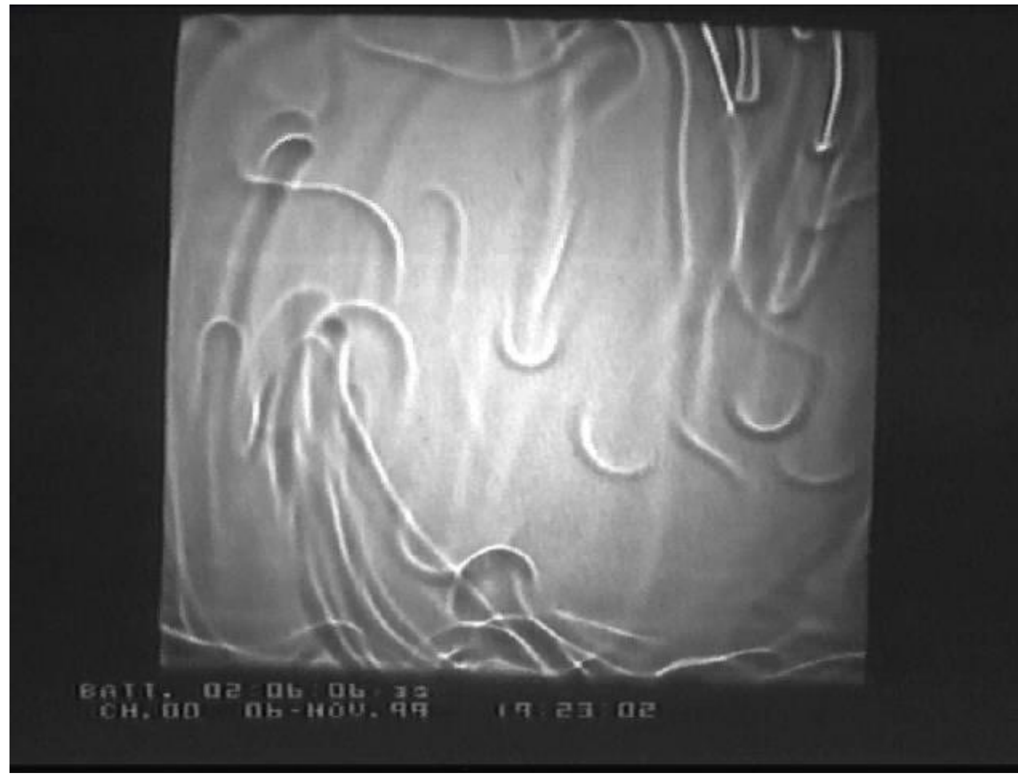
Shadowgraph

Thermal flow generated by a man



Thermal flow generated by a candle

The large-scale circulation in Rayleigh-Benard convection system

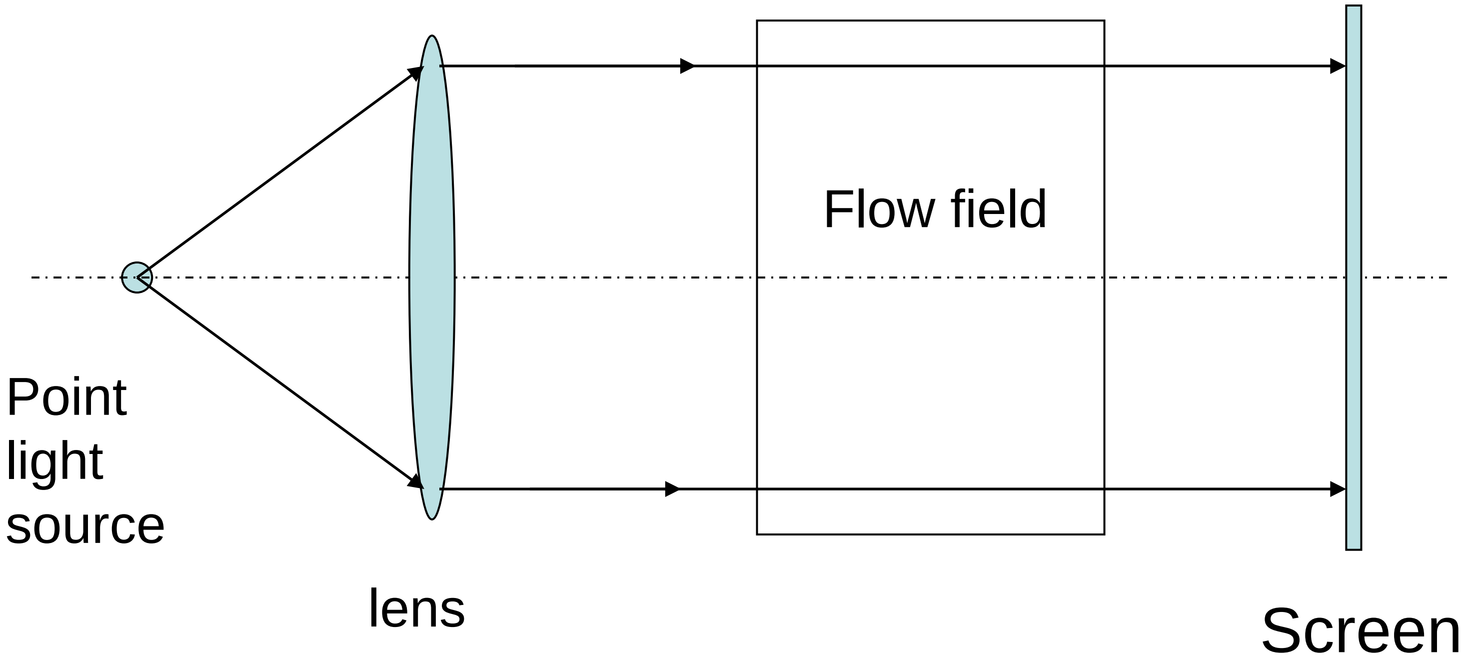


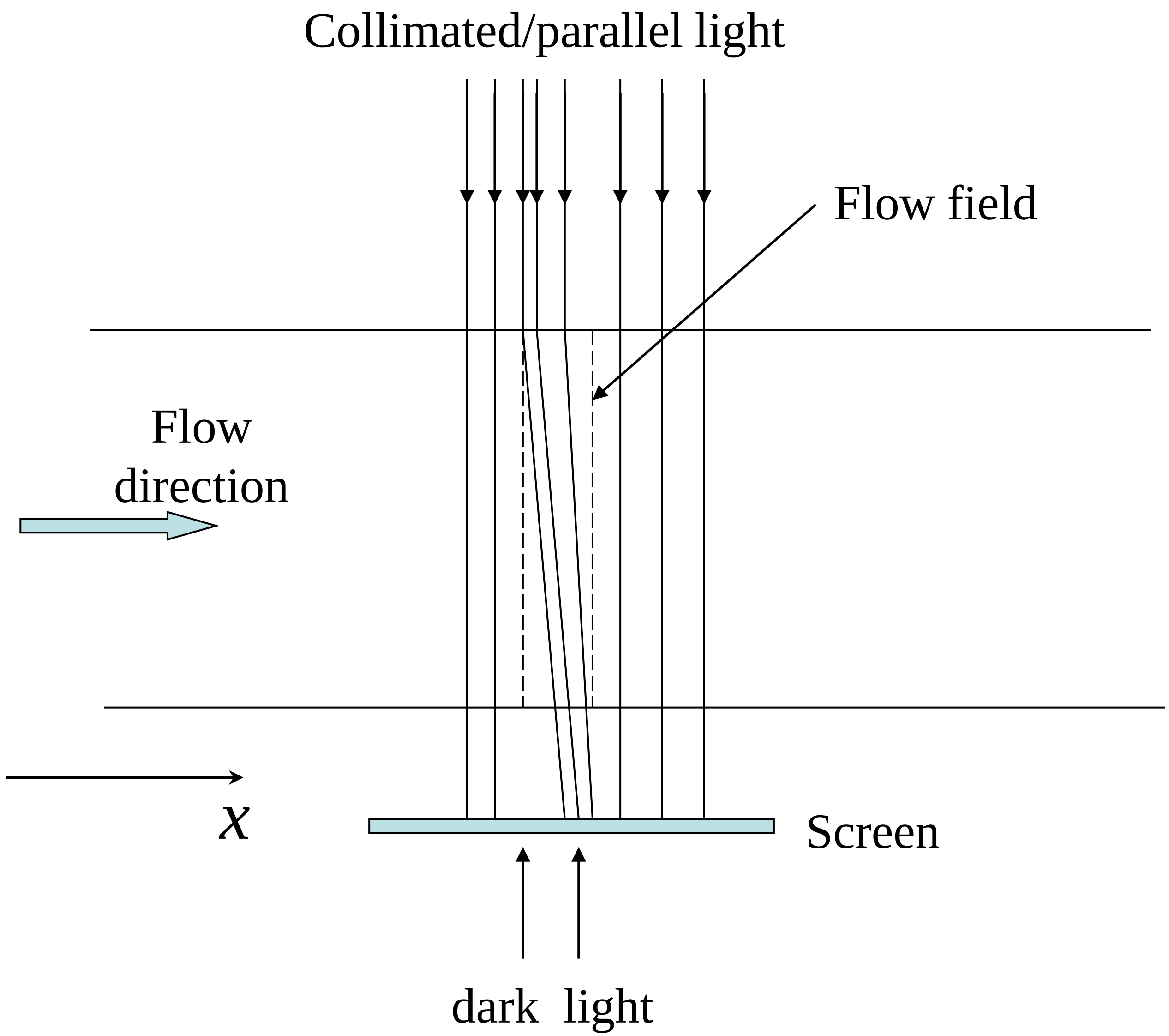
Xi and Xia, 2004 JFM

Visualization by shadowgraph

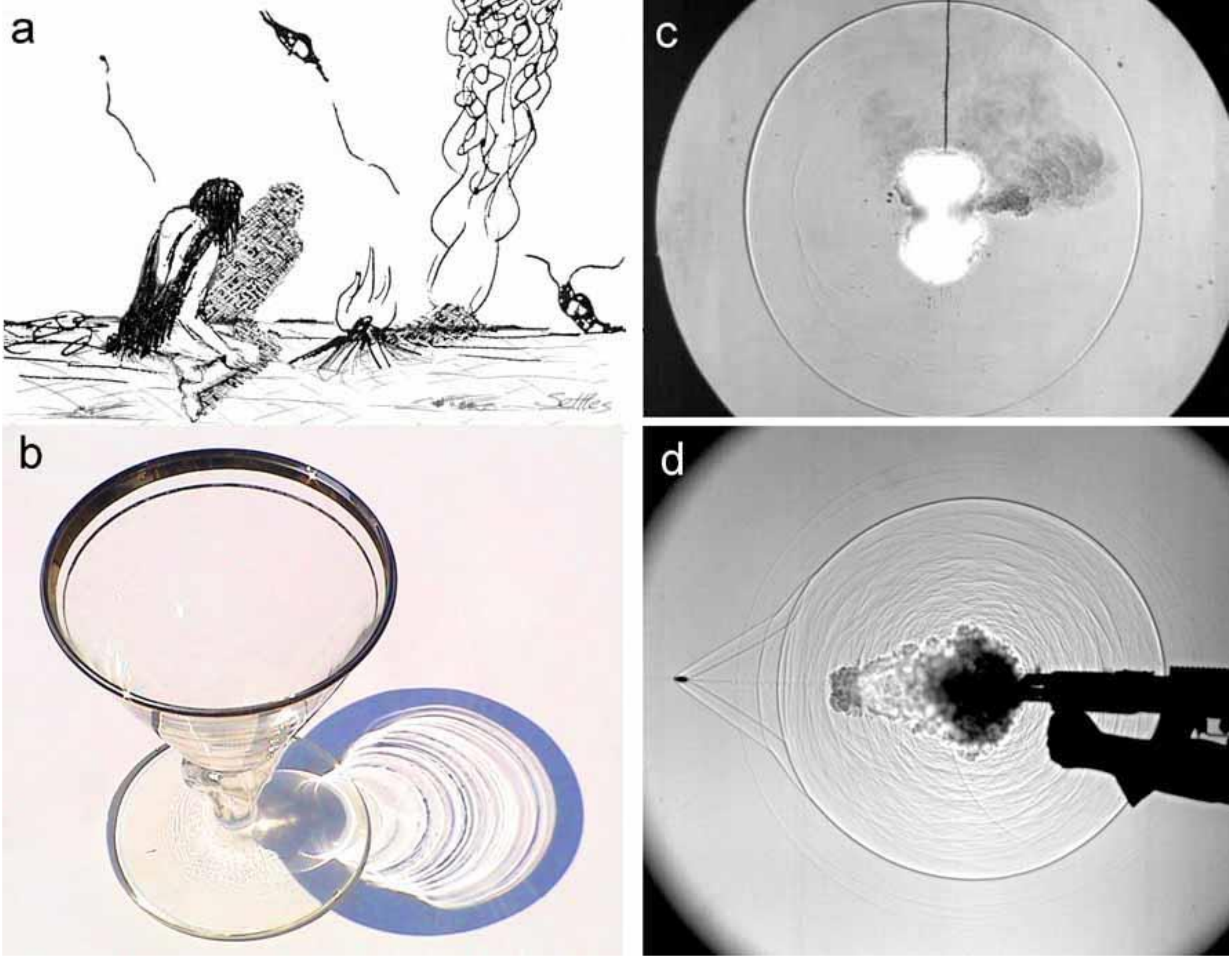
Shadowgraph is an optical method that reveals non-uniformities in transparent media like air, water, or glass. （光学测量方法）

In principle, we cannot directly see a difference in temperature, a different gas, or a shock wave in the transparent air. However, all these disturbances refract light rays （折射光线） , so they can cast shadows. The plume of hot air rising from a fire, for example, can be seen by the way of its shadow cast upon a nearby surface by the uniform sunlight.



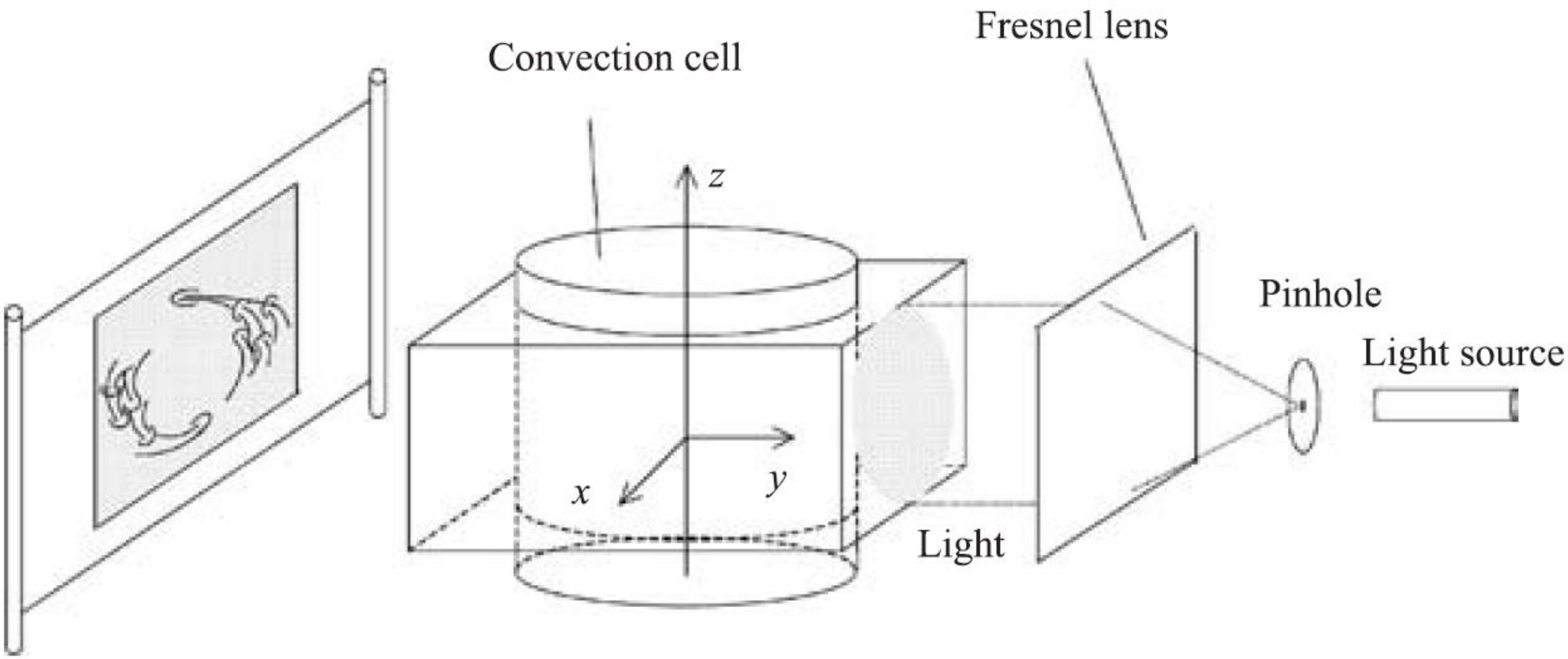


Working principle of Shadowgraphy



a) Prehistoric shadowgraphy, b) Sunlight shadowgram of a martini glass, c) "focused" shadowgram of a common firecracker explosion, d) "Edgerton" shadowgram of the firing of an AK-47 assault rifle

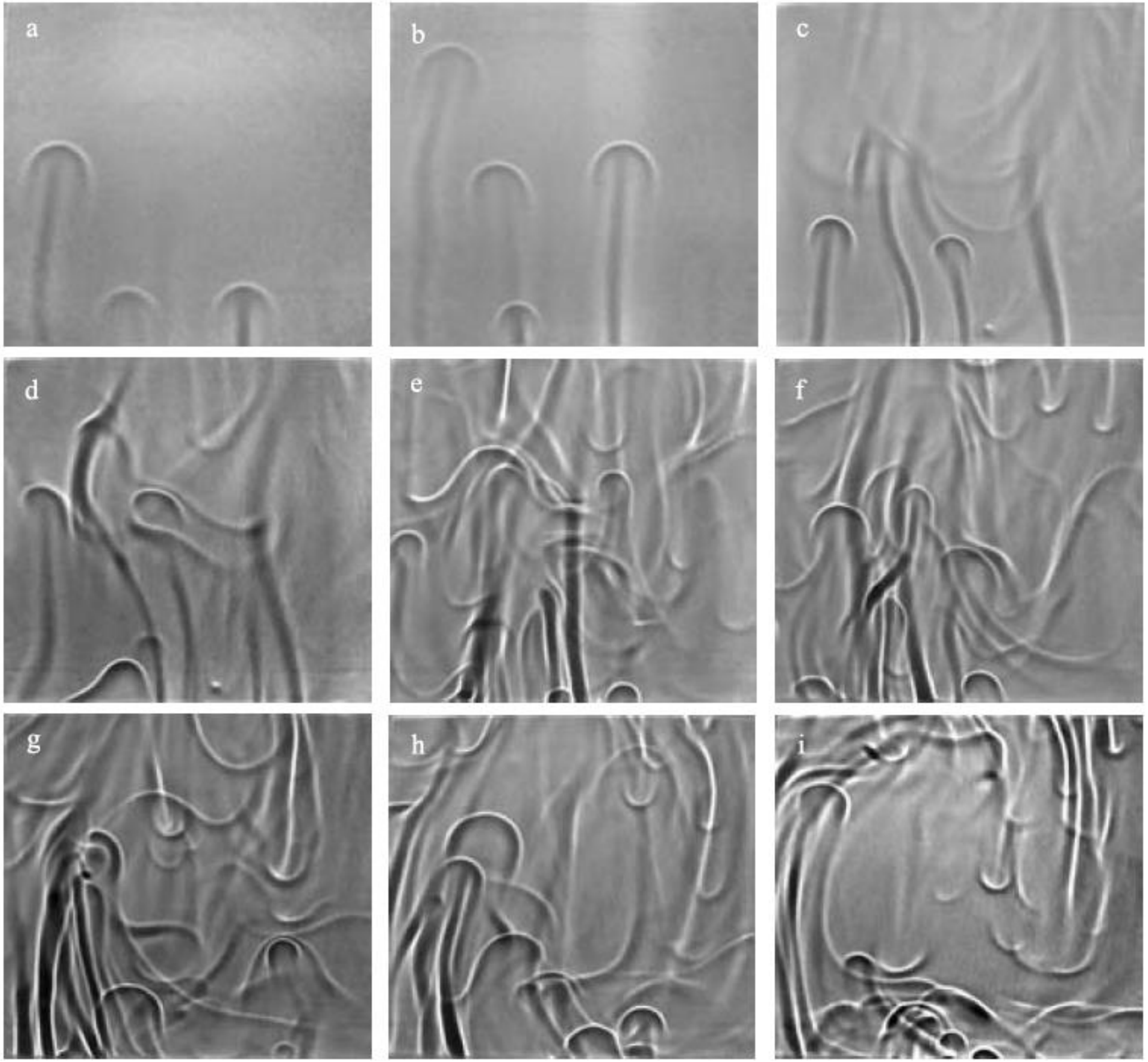
Shadowgraph



GURE 1. Schematic drawing of the experimental setup for shadowgraph visualizations.

Xi and Xia, 2004 JFM

The projected image on the screen is simply an integration of refractive index contrast along the light path.



Xi and Xia, 2004 JFM

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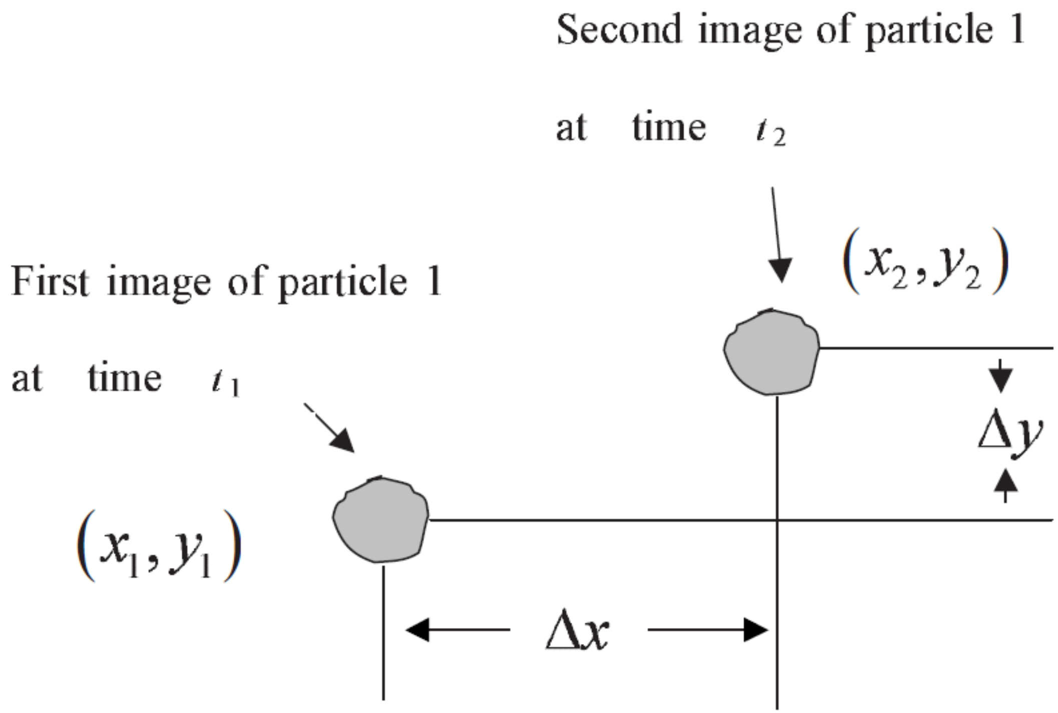
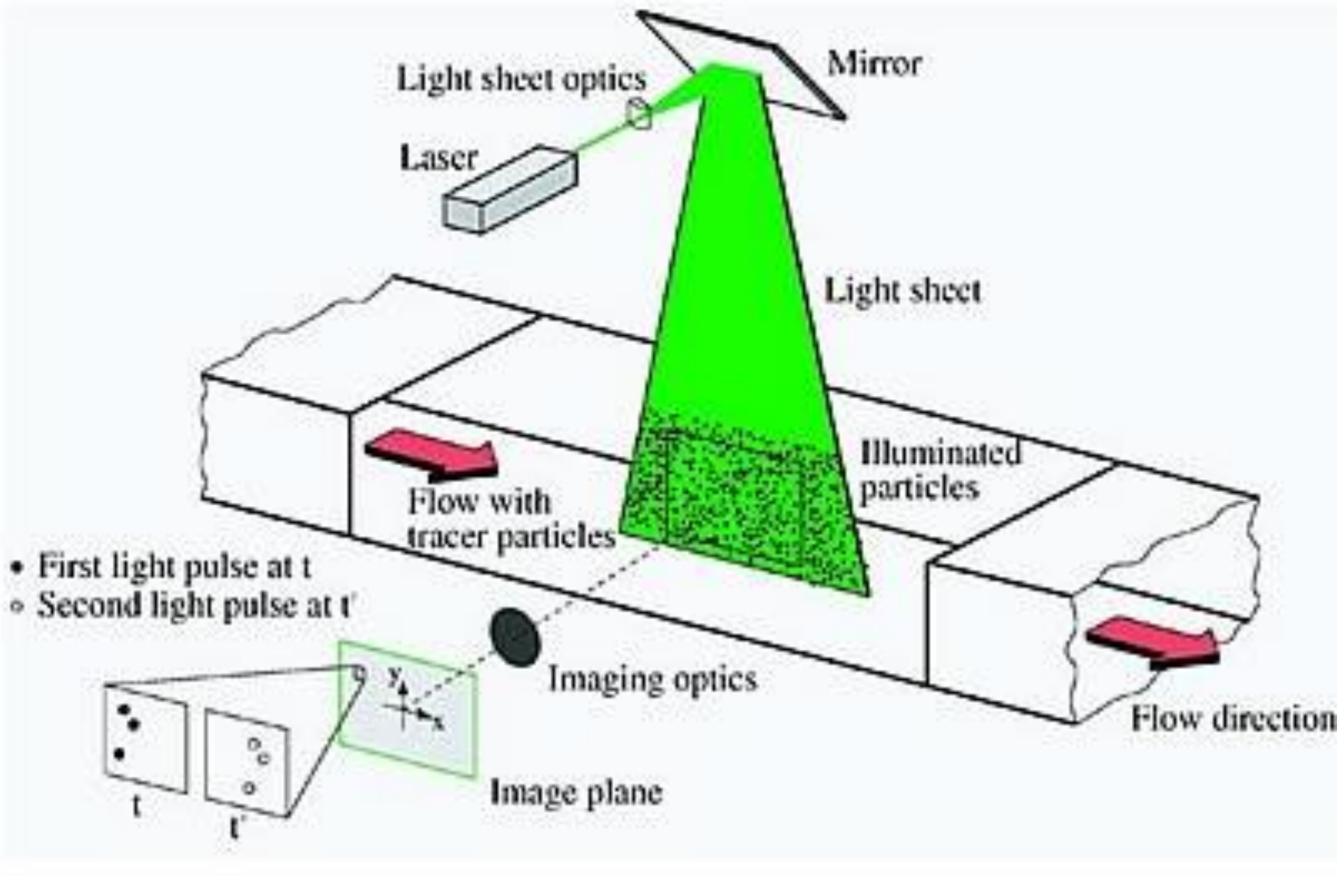
Particle Image velocimetry (PIV)



$$u = \lim_{t_2 \to t_1} \frac{x_2 - x_1}{t_2 - t_1} \qquad v = \lim_{t_2 \to t_1} \frac{y_2 - y_1}{t_2 - t_1}$$

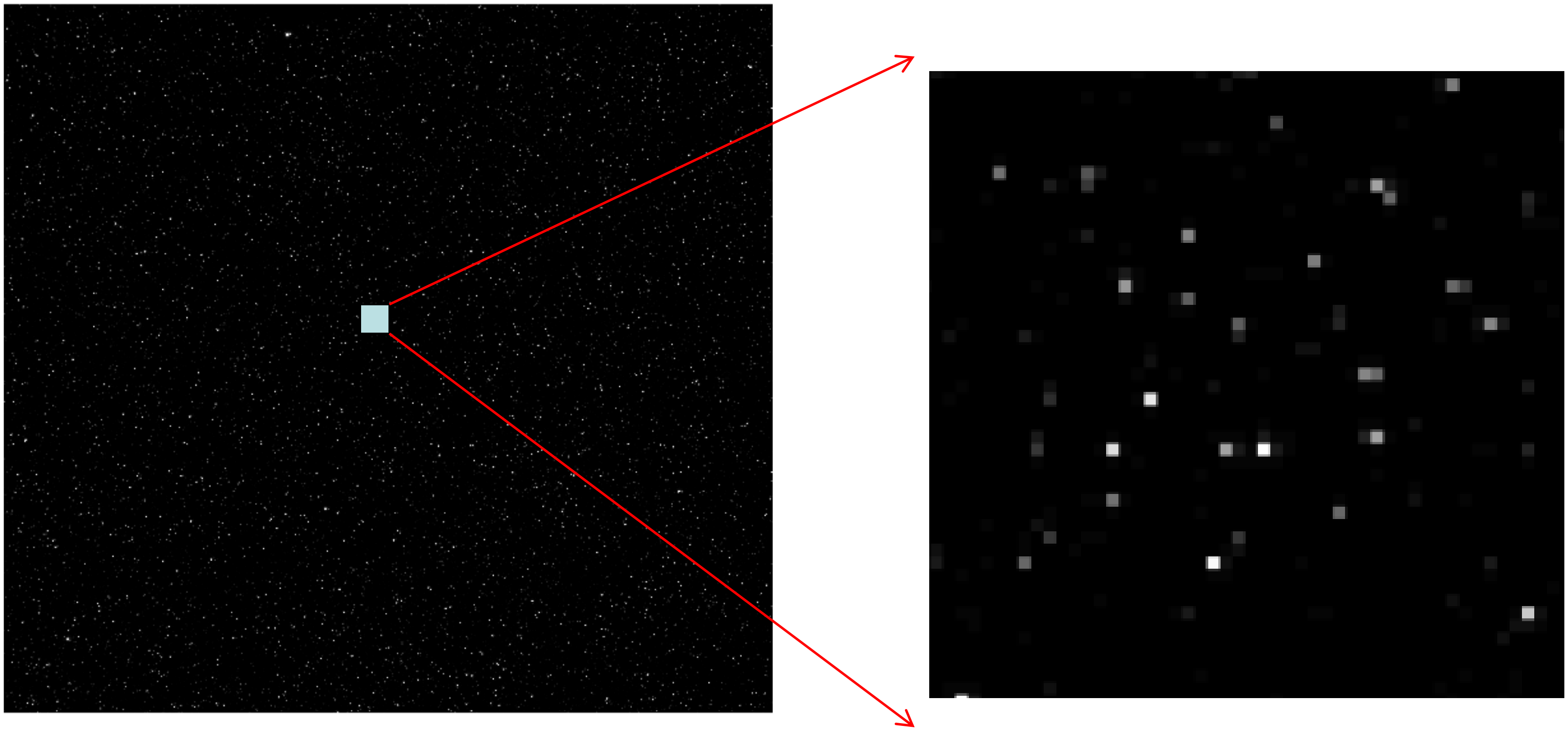
Particle Image velocimetry



Measuring velocity through the particle displacement

Particle Image velocimetry

A typical PIV image and typical interrogation window

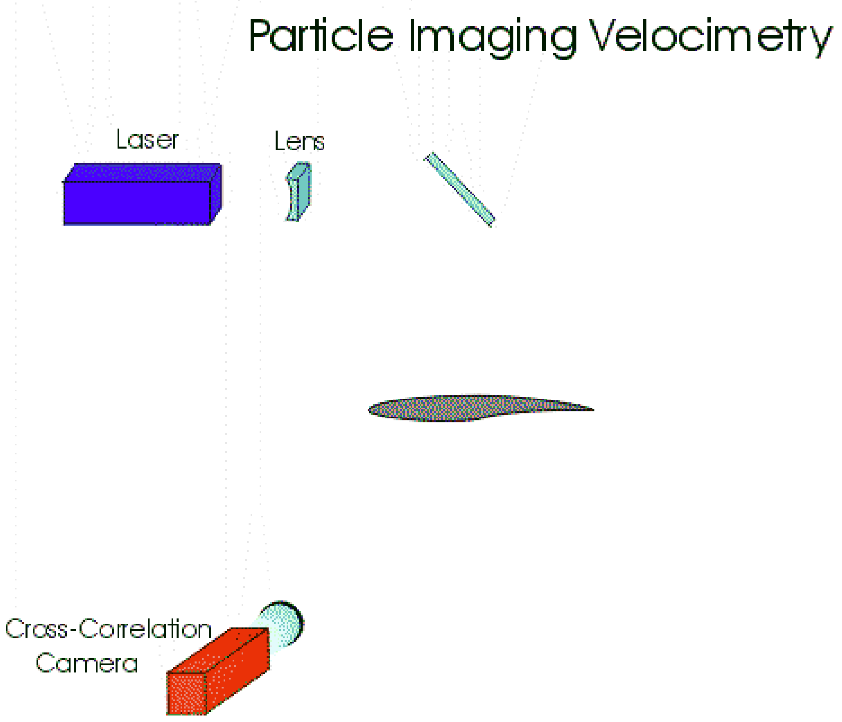


1280x1024 pixels

32x32 pixels

Xi 2003 Master Thesis

How PIV works

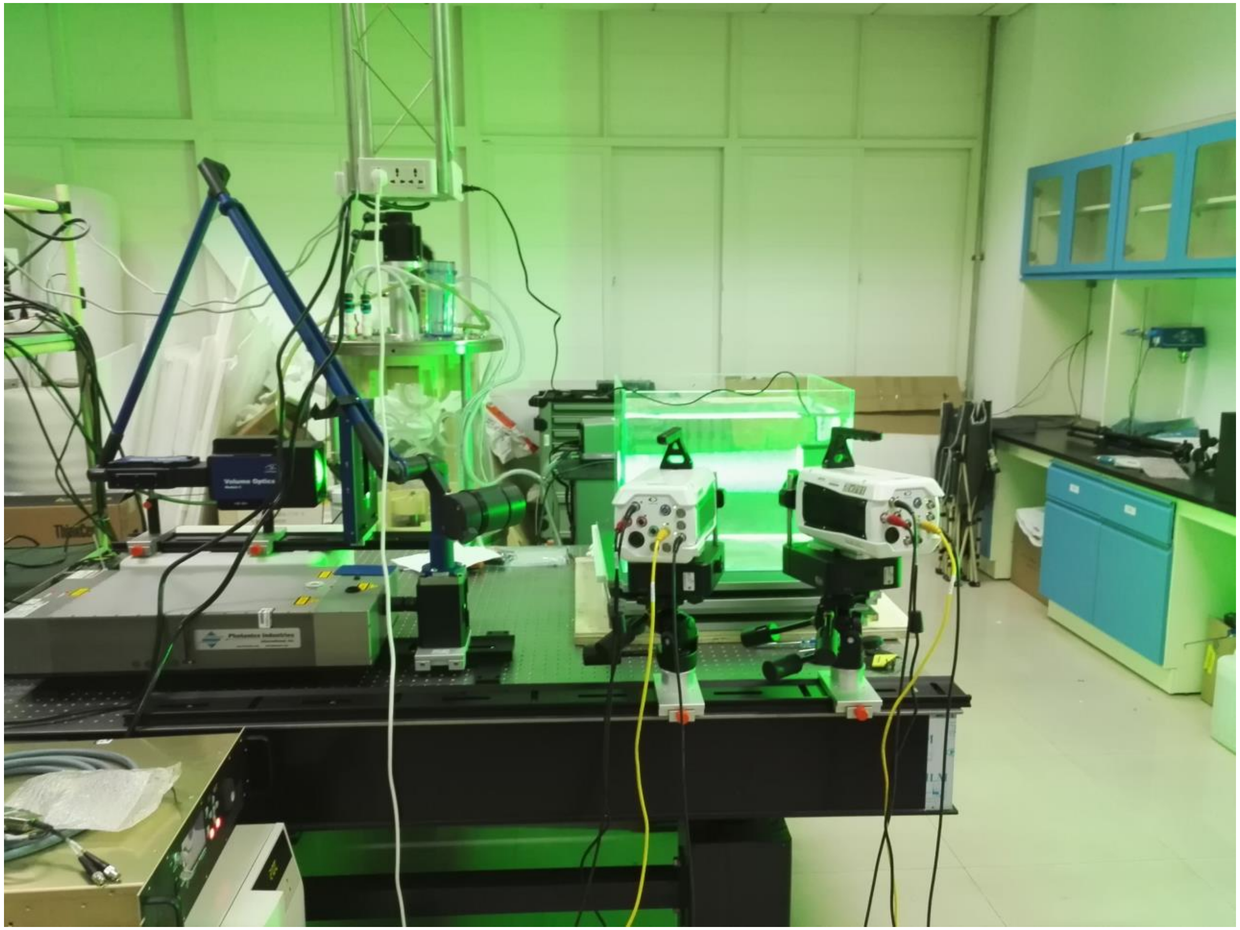


http://www.grc.nasa.gov/WWW/OptInstr/piv/pivdemo.htm

西工大航空学院湍流与复杂流动实验室

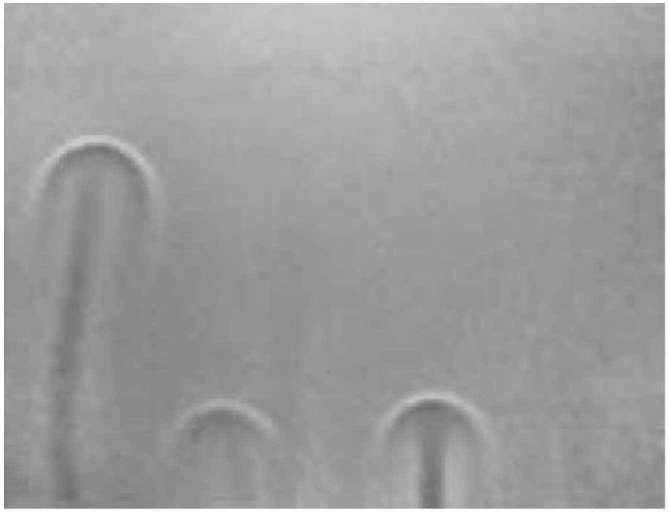
低速二维PIV 系统，激光15Hz，相机20帧/秒@2048x2048像素

西工大航空学院湍流与复杂流动实验室

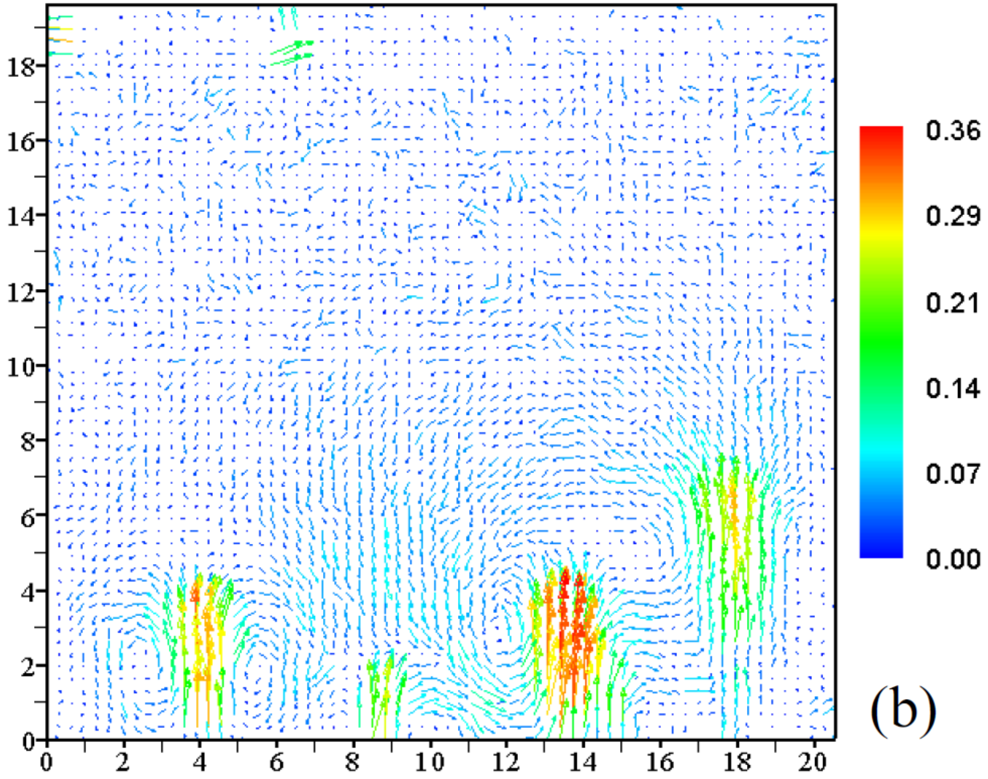


高速Stereo PIV 系统，激光20KHz，相机7500帧/秒@1280x800像素

Particle Image velocimetry



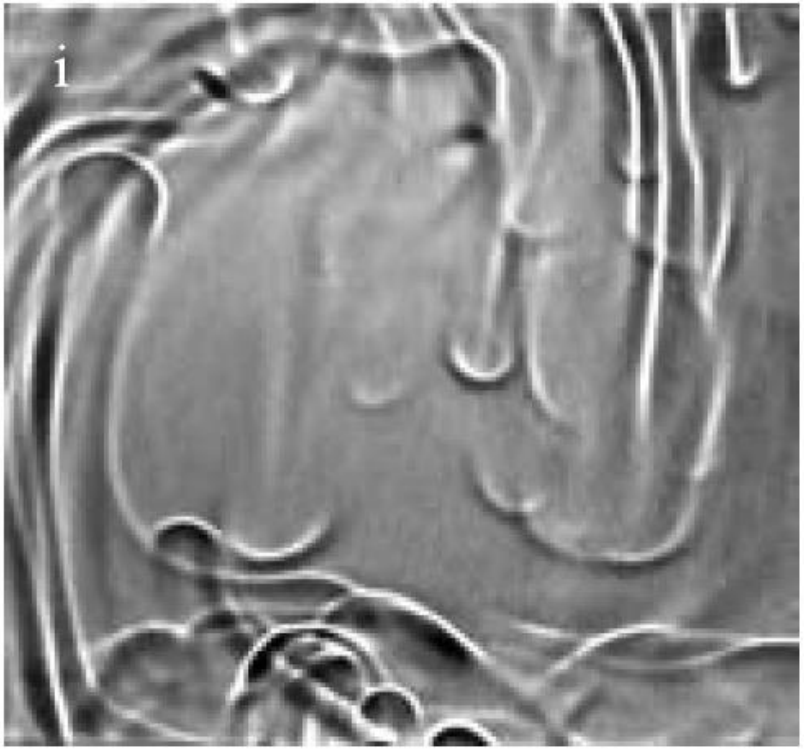
Shadowgraph

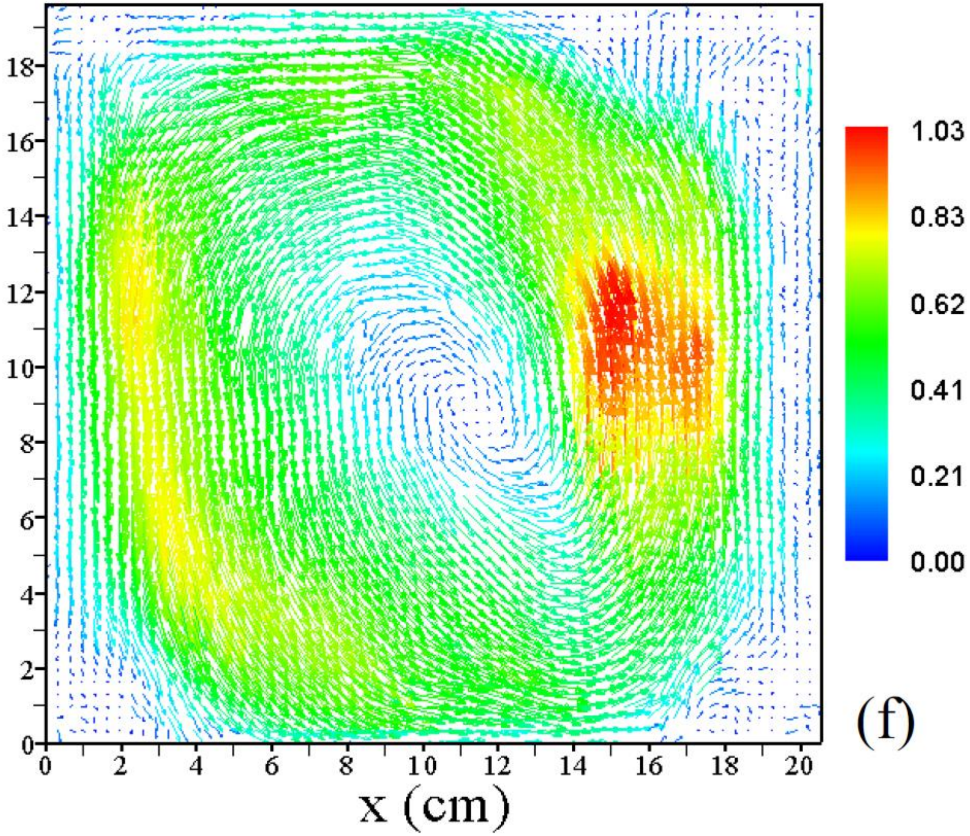


PIV

Xi and Xia, 2004 JFM

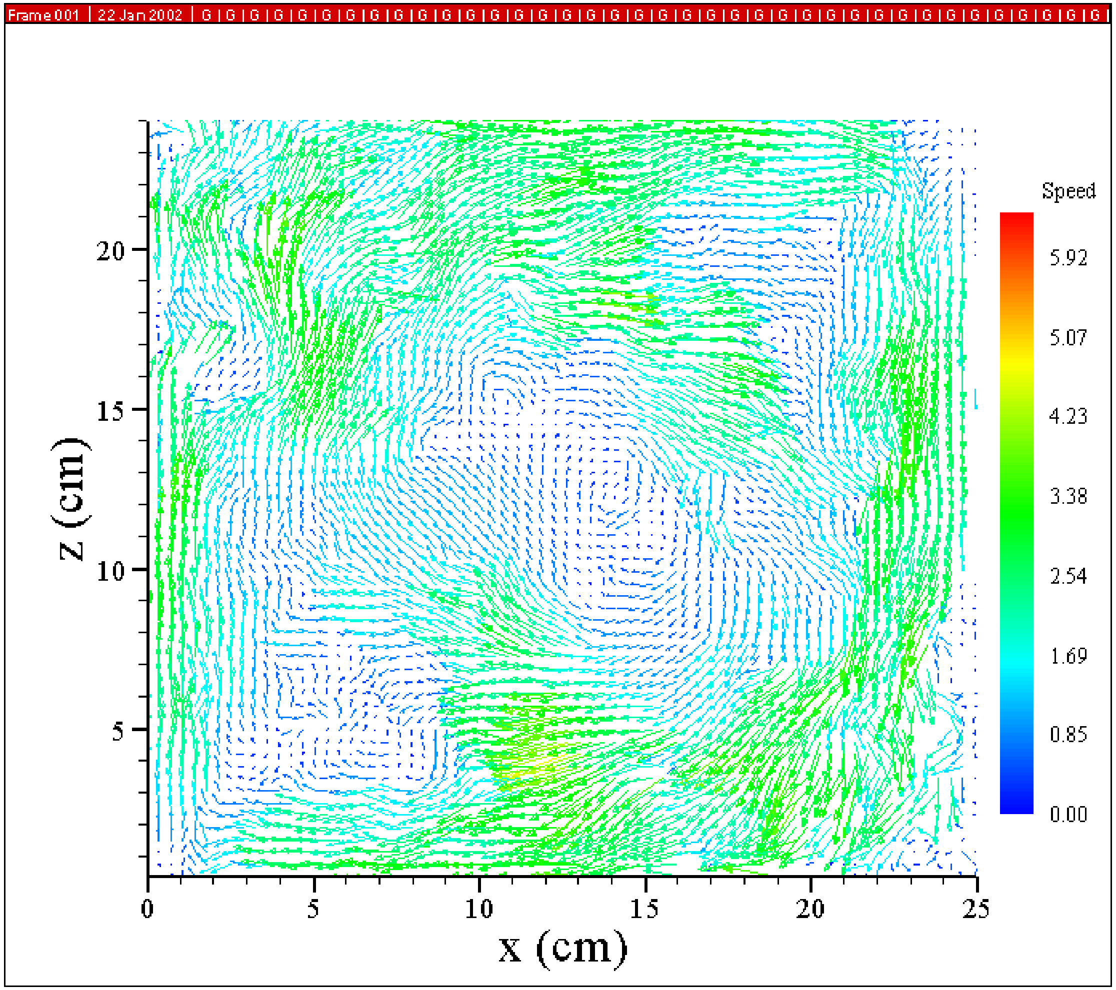
Particle Image velocimetry





Xi and Xia, 2004 JFM

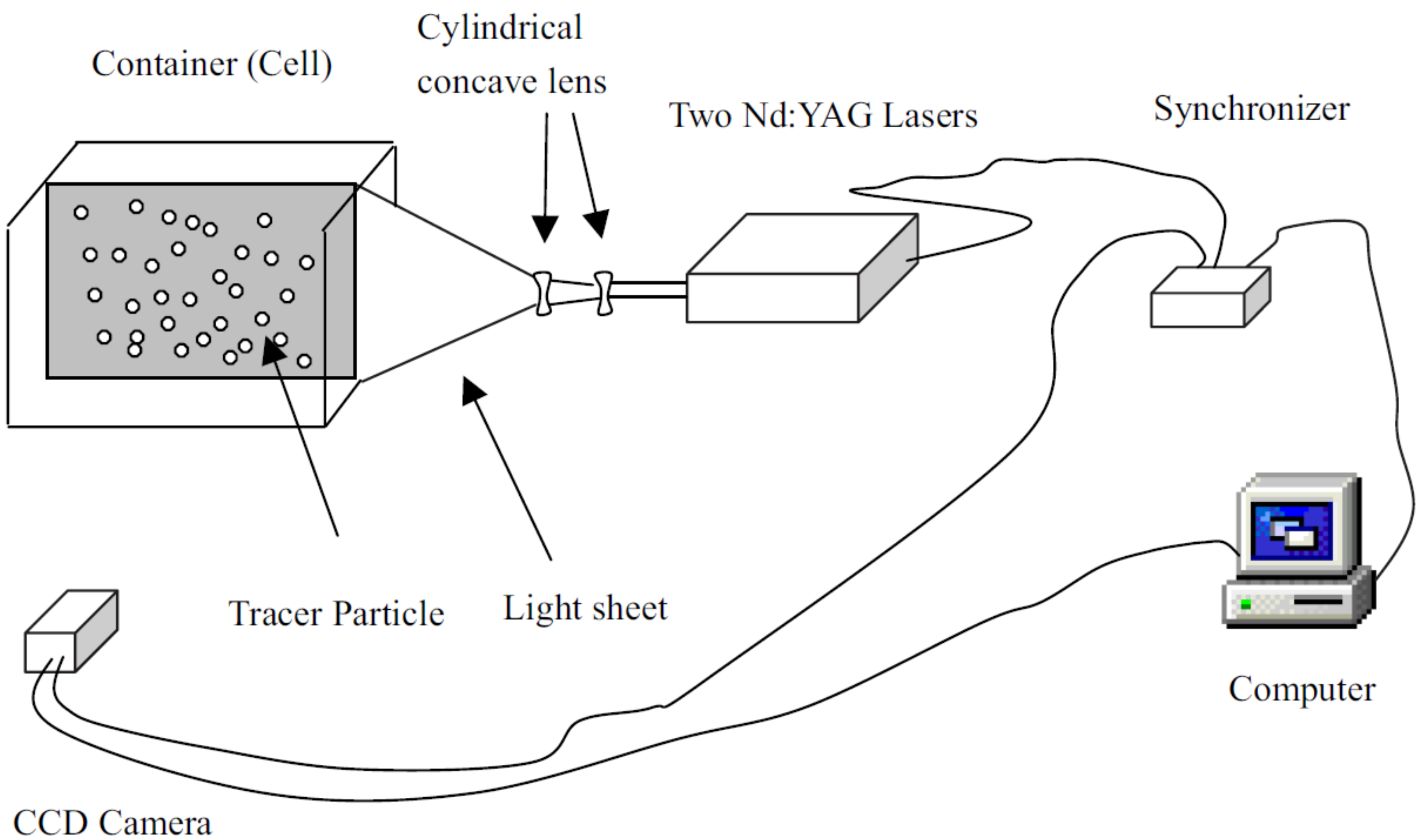
Particle Image velocimetry



Ra = 5×10^{10}

Sun, Xia and Tong, 2005 PRE

Particle Image velocimetry



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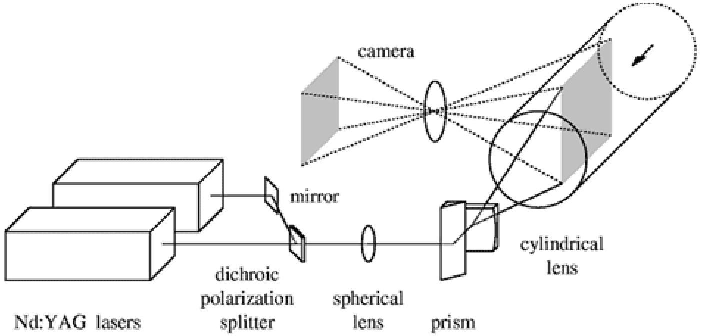
The key components for a PIV system

- Camera
- Lens
- Laser
- Synchronizer
- Optics

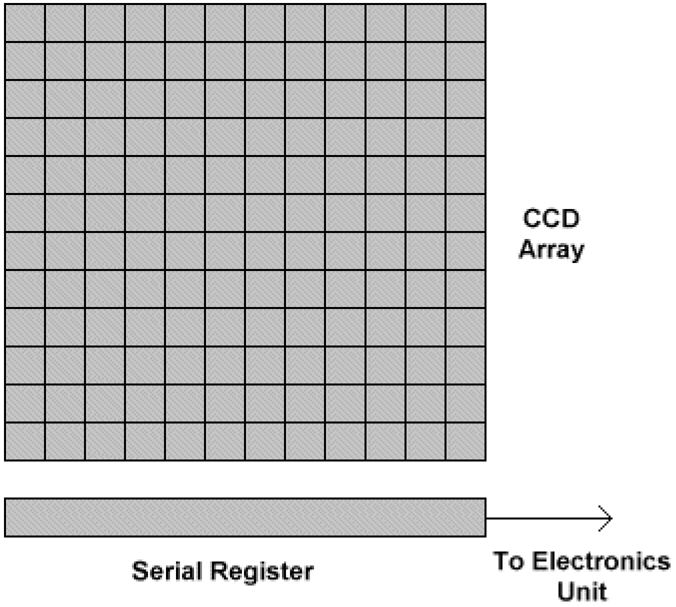


Camera

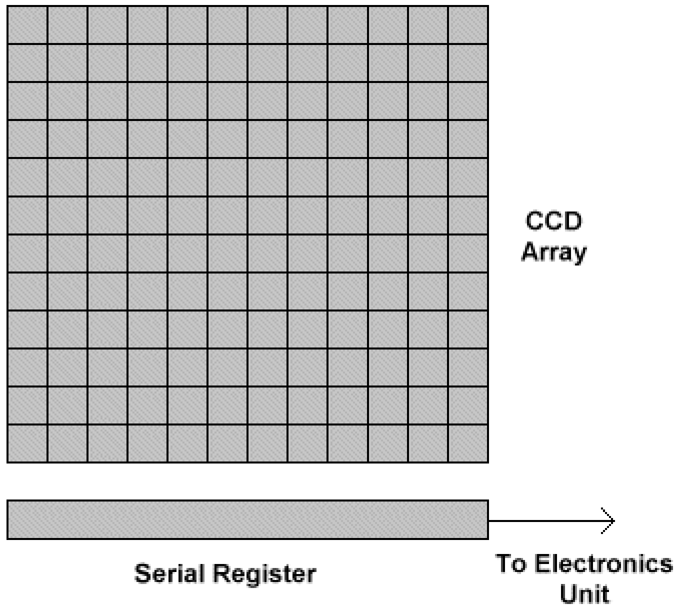
CCD vs CMOS

High signal to noise ratio
Low speed , typical frame rate:
Tens of frame/second @ 1024x1024 pixel

Low signal to noise ratio
High speed, typical frame rate:
7000 frame/second @ 1024x1024 pixels



Resolution and Dynamic range of the camera



X position	y position	Light intensity
1	1	5
…	…	…
1	1024	230
2	1	128
…	…	…
2	1024	255
3	1	245
…	…	…
3	1024	145
…		…
…		..
1024	1	68
…	…	…
1024	1024	32

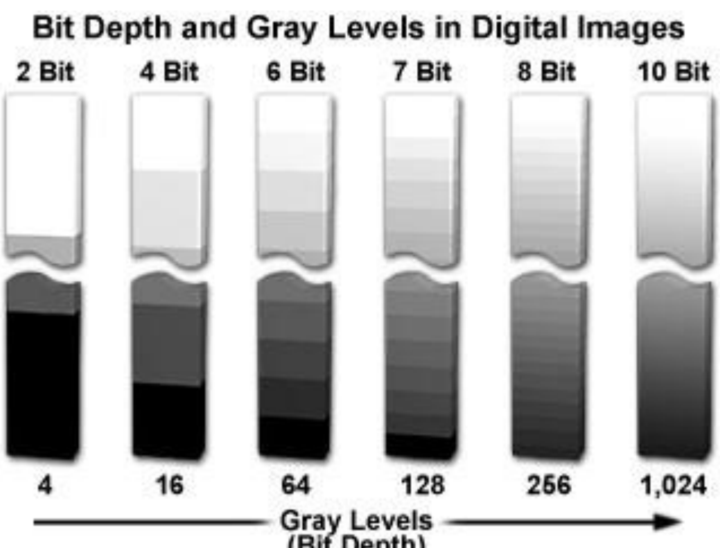


Figure 2

Light intensity is represented by values between 0-255 (2^8-1) if the dynamics range is 8 bit; between 0-1024 (2^{10}-1) if the dynamics range is 10 bit.

The PIV lens

Fixed focal length or changeable focal length

Focal length

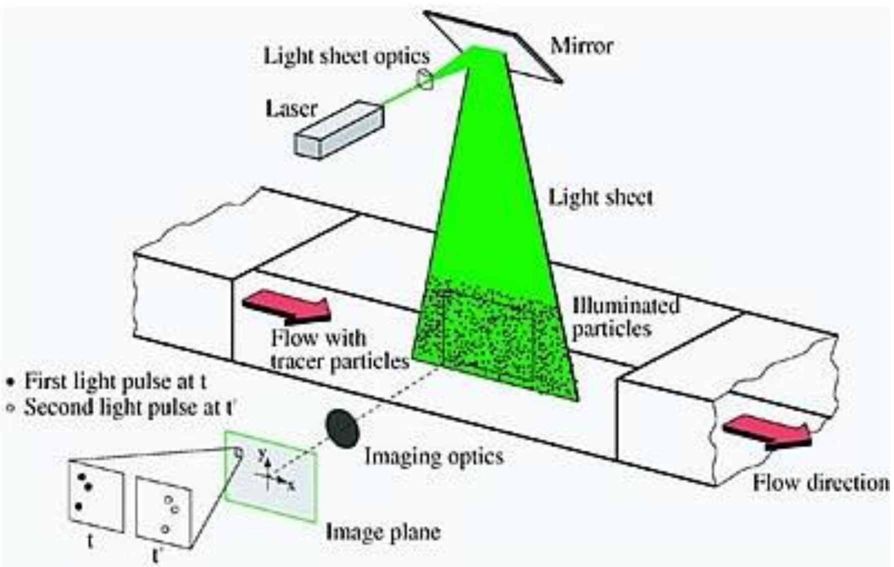
Aperture

Mount

Focal depth

Laser and illumination

- And there should be two lasers, which are synchronized.
- The laser should be powerful enough as the camera receives the 90 degree scattering.
- Laser should be pulsed laser.



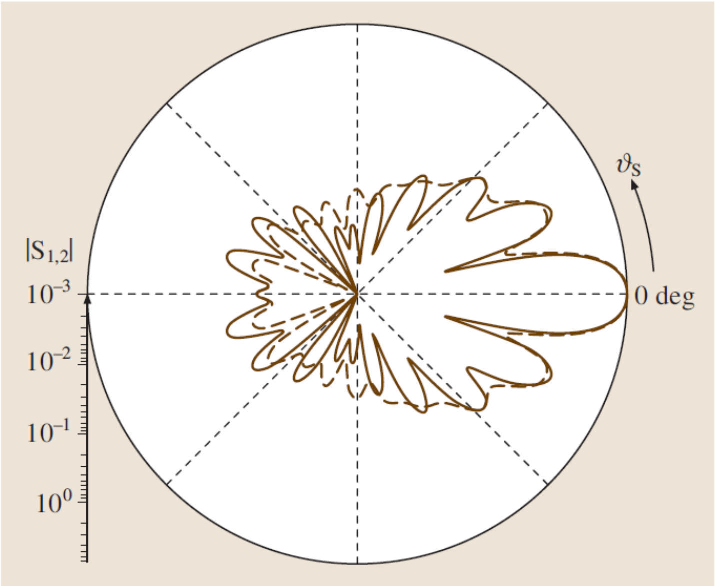


Fig. 5.61 Scattering function for a Mie parameter value of 10 computed for a water droplet in air ($m = 1.334$); *solid line*: perpendicular polarization, *dashed line*: parallel polarization (after *Albrecht* et al. [5.356])

Handbook of Experimental Fluid Mechanics, by Tropea et al, Springer, 2007

The synchronization between laser and camera

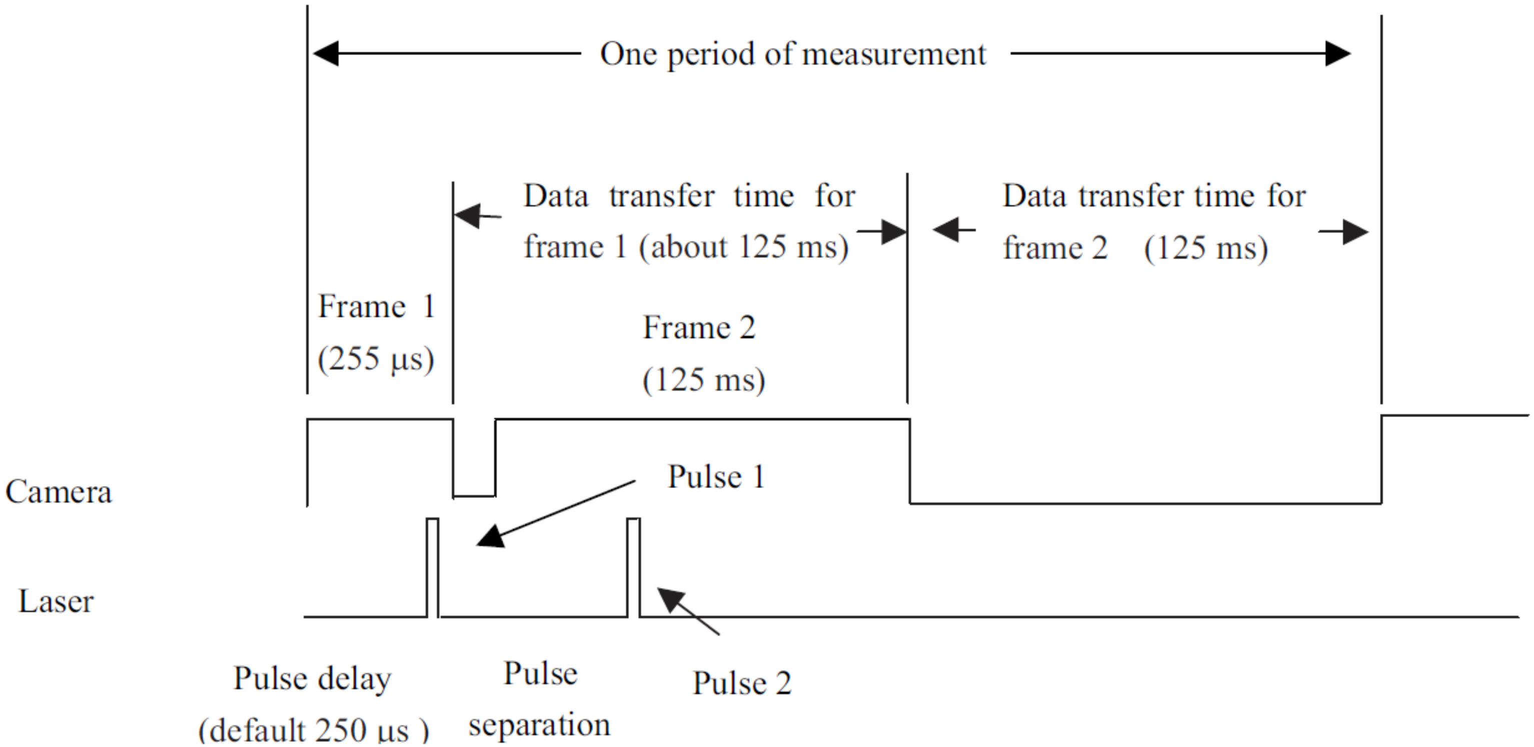


Figure 2.12: Timing diagram of the frame straddle technique for the CCD PIVCAM13-8.

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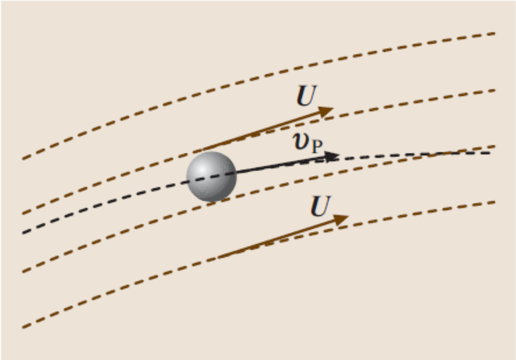
Tracer particle

Tracer particle should faithfully follow the flow.

- Oil droplet
- Smoke
- Hallow glass beads
- Polystyrene particles

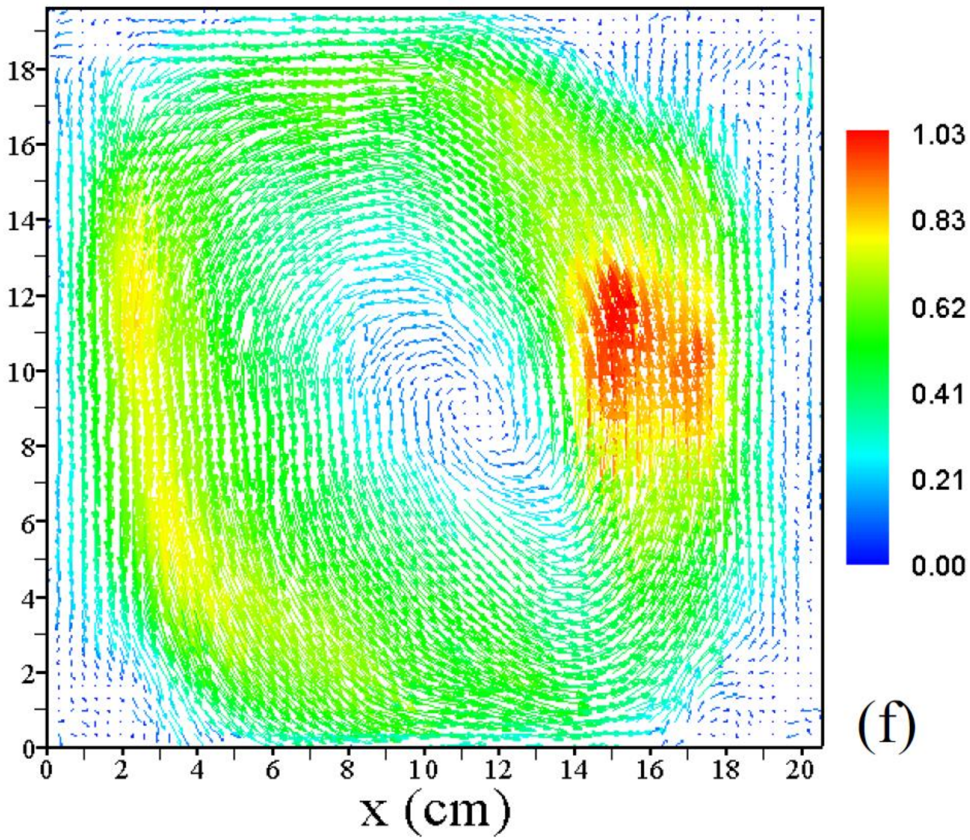


Handbook of Experimental Fluid Mechanics, by Tropea et al, Springer, 2007

Difference between particle velocity and fluid velocity (slip velocity):

$$U_l = U_p - U = d_p^2 \frac{\rho_p - \rho}{18\mu} a$$

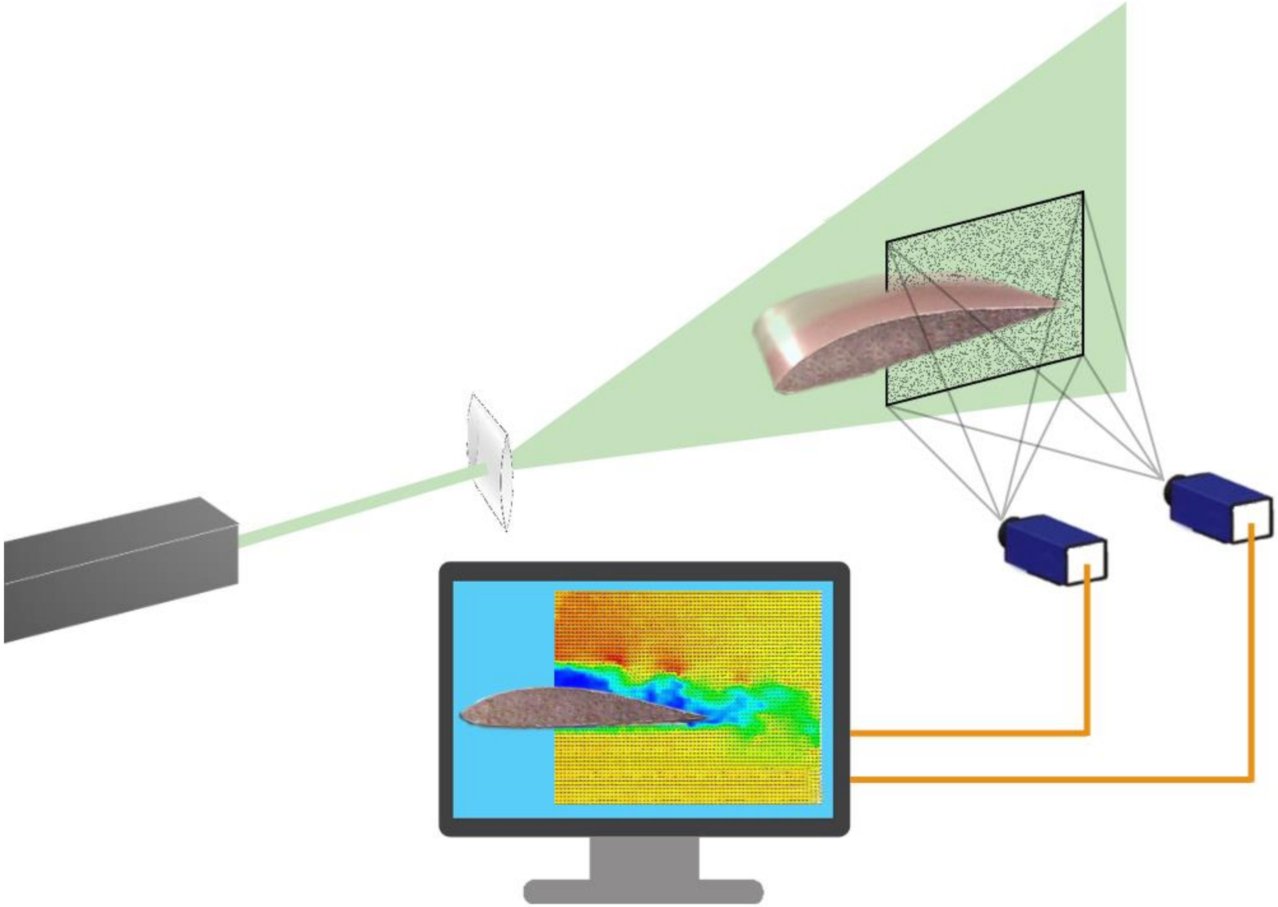
Particle Image velocimetry



From 2-D PIV one can compute: Vorticity, velocity gradient, velocity contour, vorticity contour …

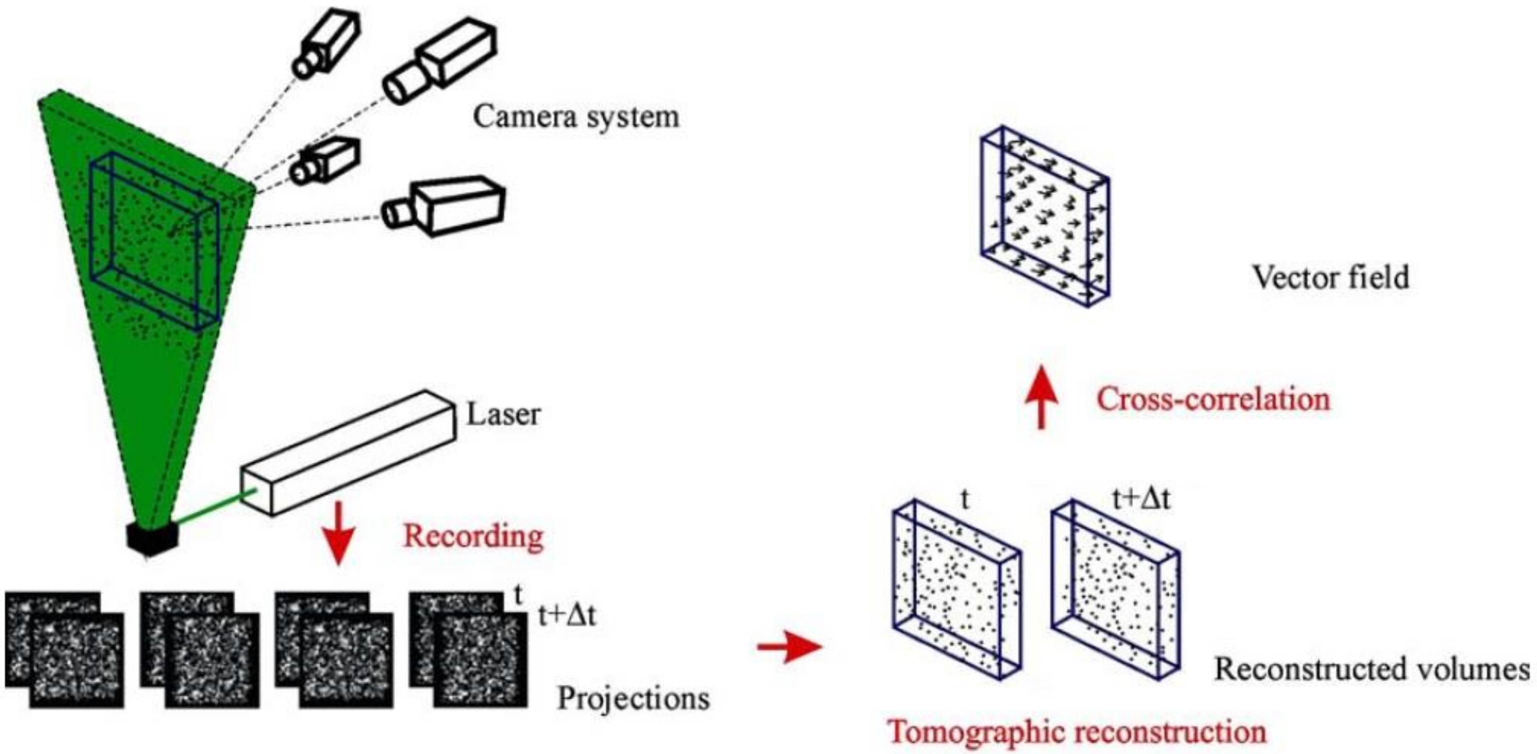
X position	**Y position**	**U (pixel/ second)**	**V (pixel/ second)**
1	1	8	2
…	…	…	…
1	30	7	8
2	1	3	5
…	…	…	
2	30	6	9
3	1	8	4
…	…	…	…
3	30	3	2
…	…	…	…
…	…	…	…
30	1	4	7
…	…	…	…
30	30	10	3

Stereo PIV



Two cameras and one laser, can offer 3 components of the velocity in 2-D plane

Tomographic PIV



Four cameras and one laser, can offer 3 components of the velocity in 3-D space

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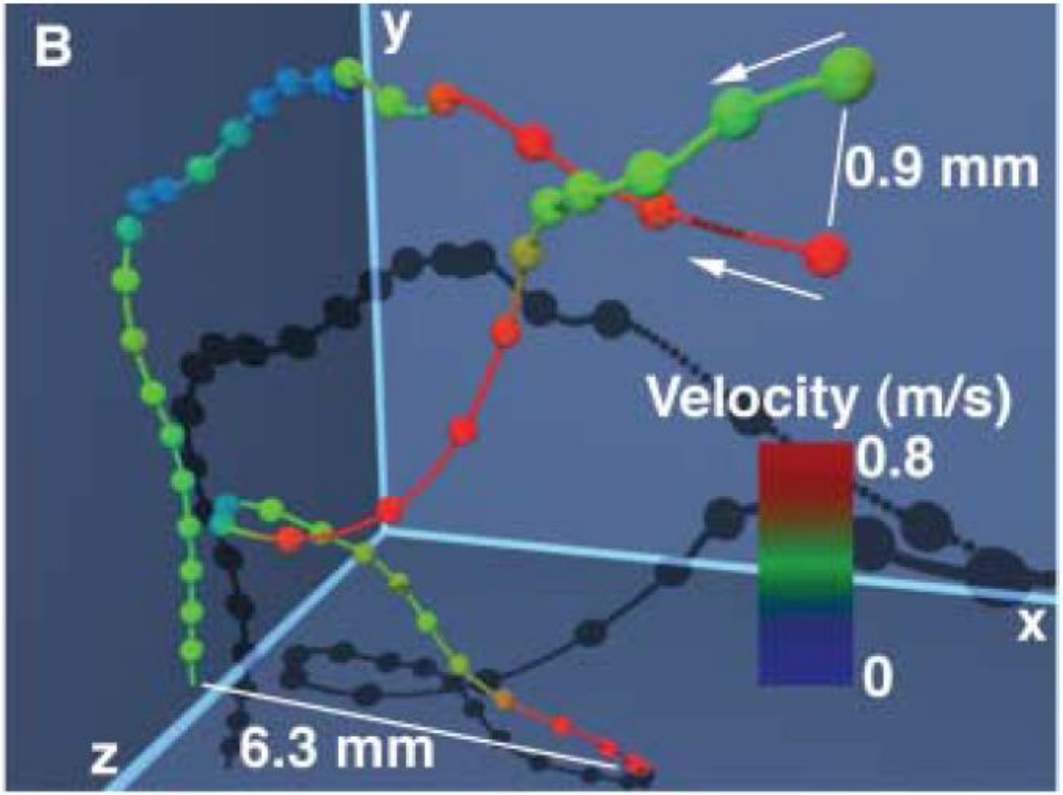
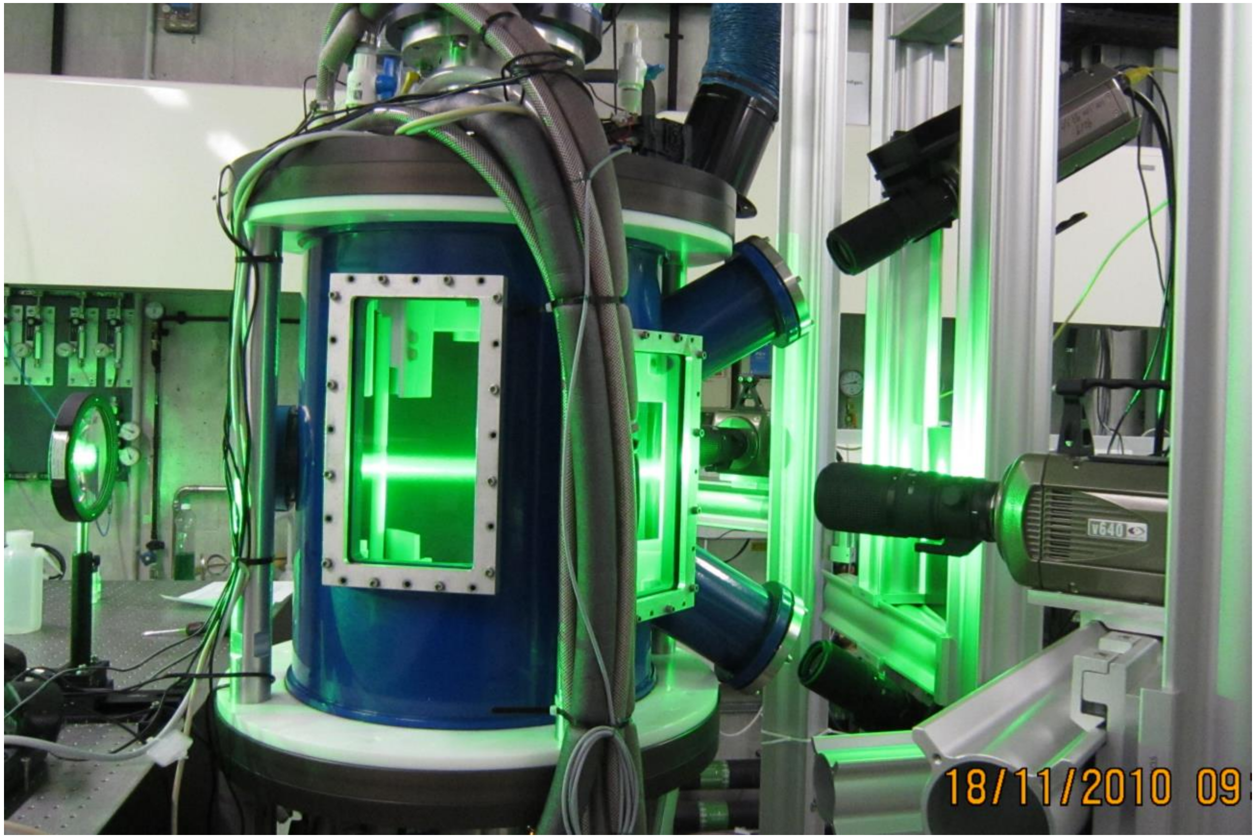
Eulerian frame vs Lagrangian frame



Bourgoin, Ouellette, Xu, Berg, and Bodenschatz**, Science** (2006)

Experimental setup

Von Karman Swirling flow system



3D Lagrangian Particle tracking system

Laser: frequency =10k-100kHz, power=60 W
High speed Camera: 20000 frame/second @512x512 pixels

Particle Tracking Algorithm

1. Particle finding 发现粒子:

   particle center on image plane

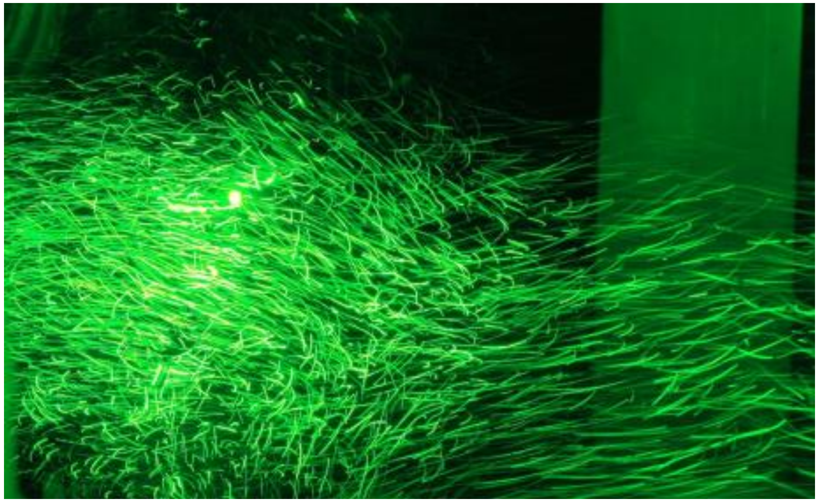
2. Stereoscopic matching 立体匹配:

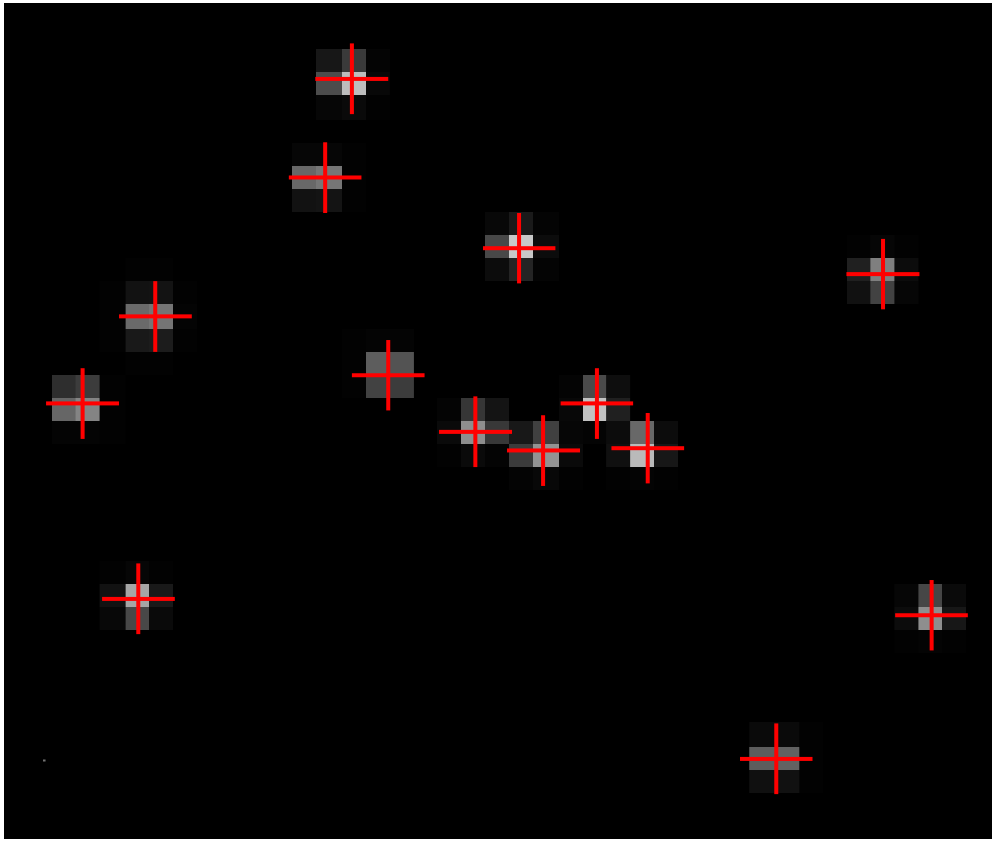
   2D image plane --> 3D laboratory frame

3. Tracking in time 及时跟踪:

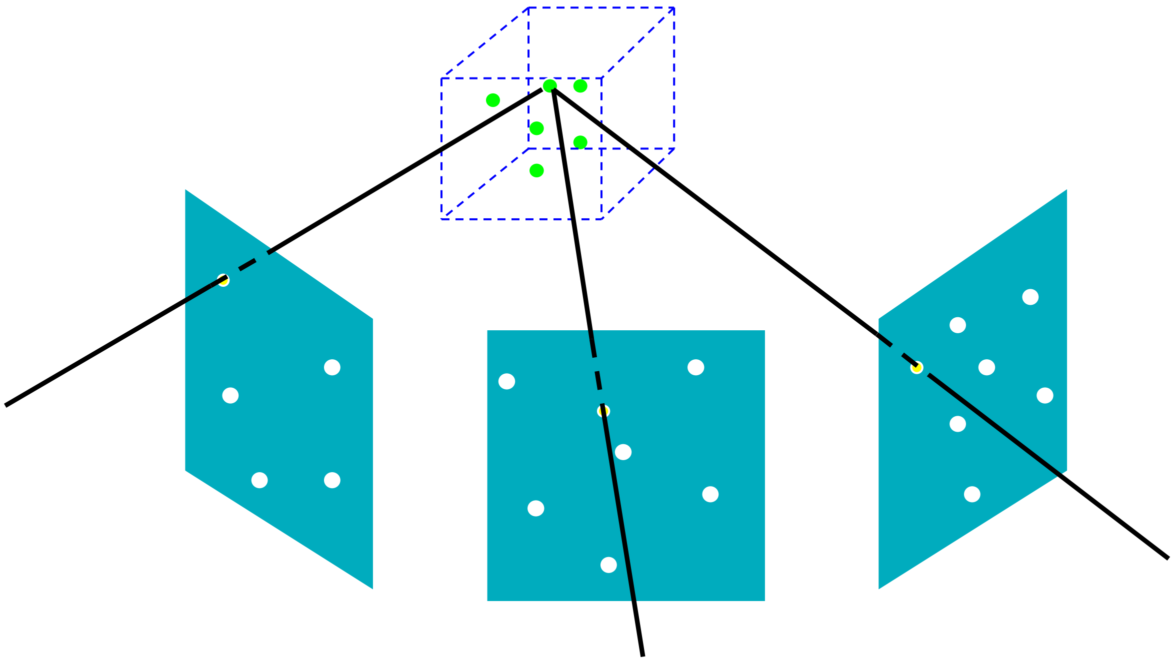
   Lagrangian trajectories

Particle Tracking (1) particle center finding

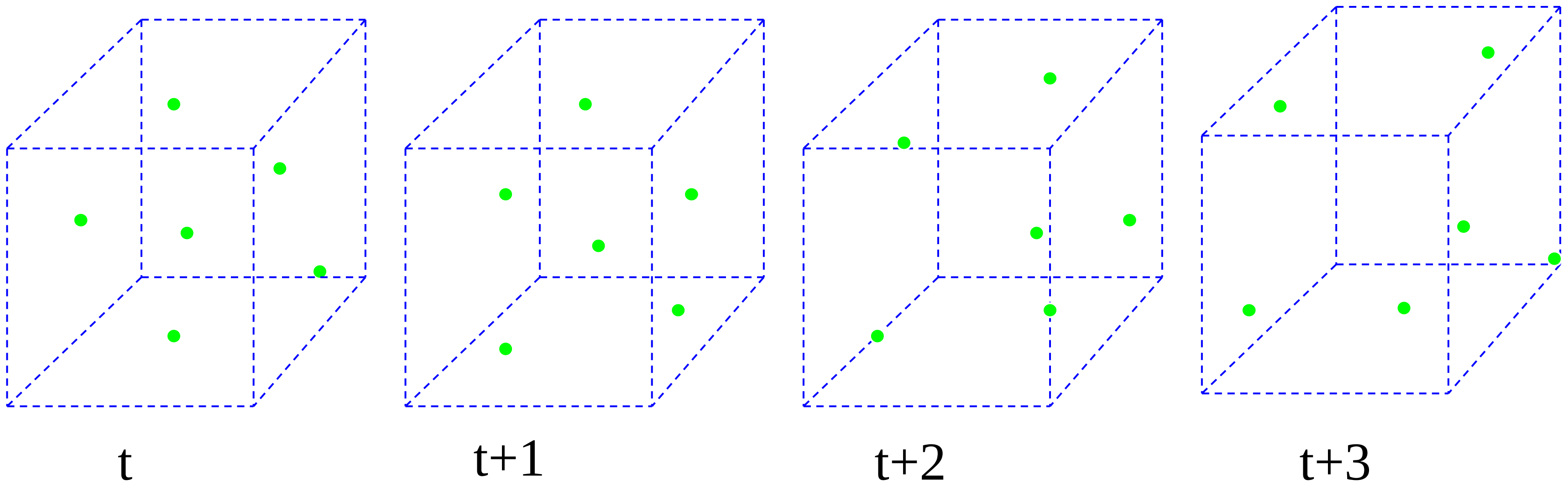


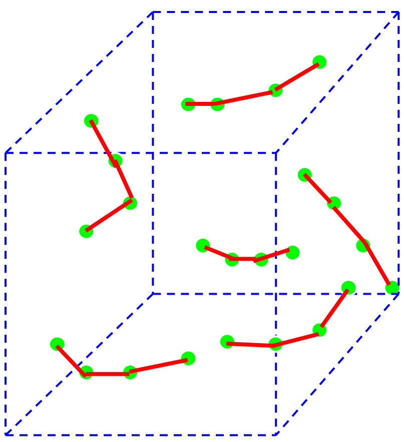


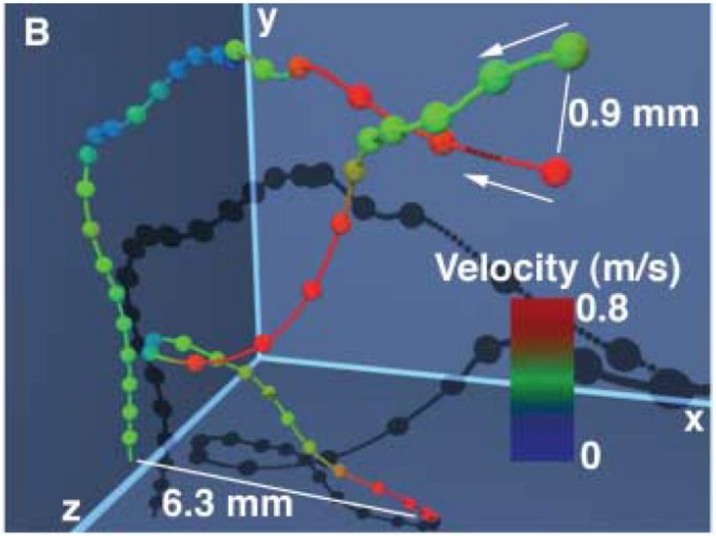
Particle Tracking (2) stereo matching



Particle Tracking (3) track the particles in time



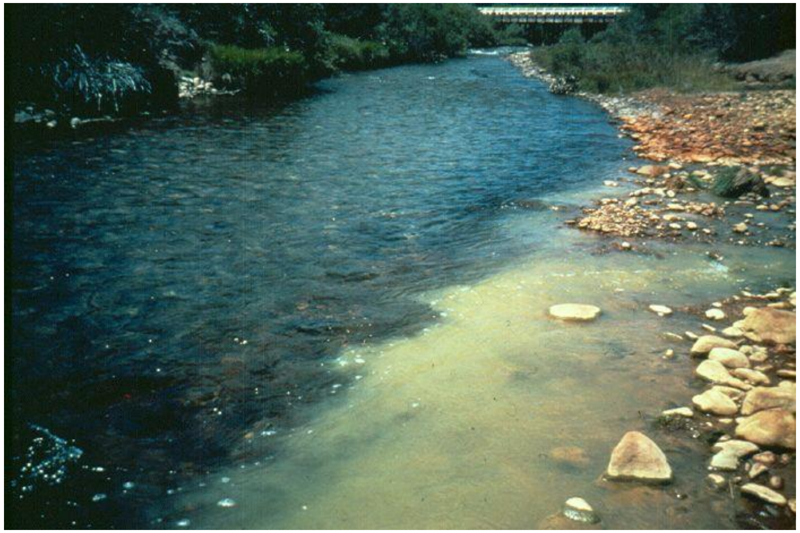


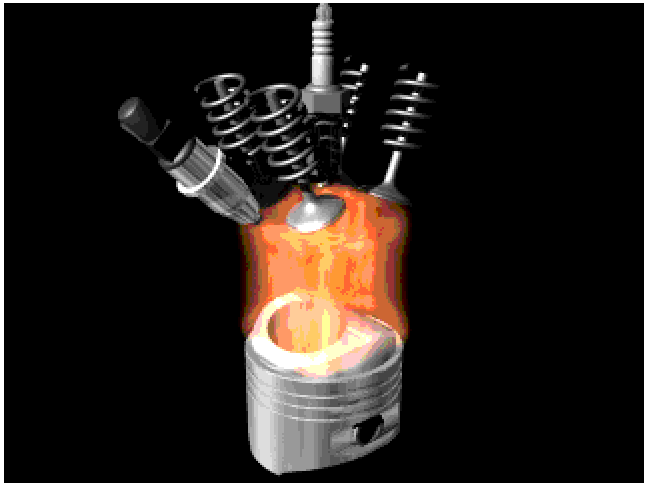


Ouellette, Xu and Bodenschatz (**Exp. Fluids**, 2006)

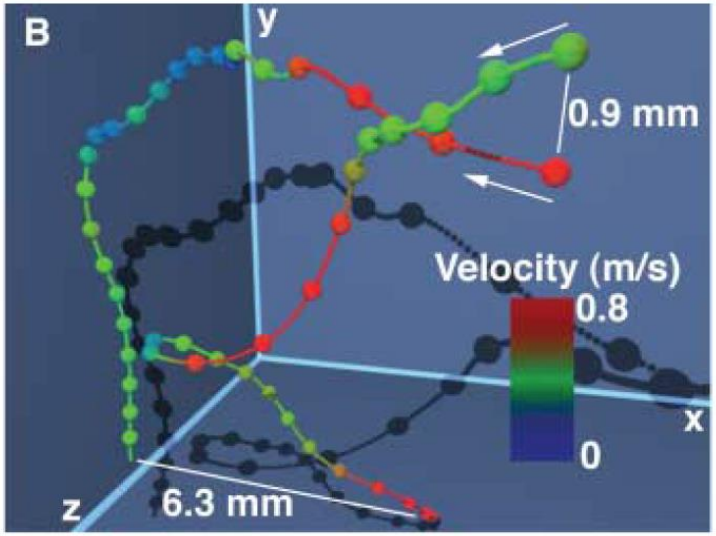
Bourgoin, Ouellette, Xu, Berg, and Bodenschatz**, Science** (2006)

The mixing problem in turbulence





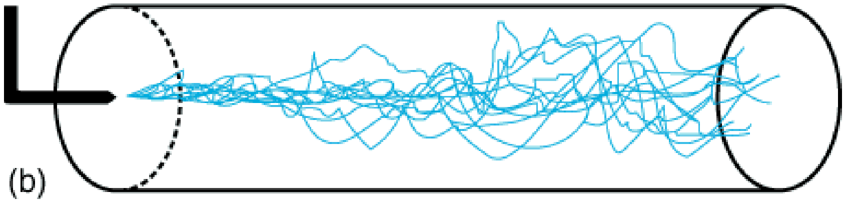
Dispersion of the particles in turbulent flows



Bourgoin, Ouellette, Xu, Berg, and Bodenschatz, **Science** (2006)

The dispersion of the particles in turbulent flow

湍流中颗粒的分散



The time evolution of the mean squared separation

System caliberation （系统校准）

System Caliberation

Fig. 10.13 Images of the calibration mask from each of the three cameras used in the particle tracking system

Handbook of Experimental Fluid Mechanics, by Tropea et al, Springer, 2007

Comparison between PIV and LPT

- Spatial resolution： LPT is much better than PIV

- Results: LPT offers Lagarangian information, PIV
- offers Eulerian information

- Set up: 2D and Stereo PIV are easy, 3D LPT is hard

- Computational cost: Tomographic PIV > 3D LPT > stereo PIV > 2D PIV