Lecture 20: Microscopic Particle Image Velocimetry technique (Micro-PIV - Part 01)

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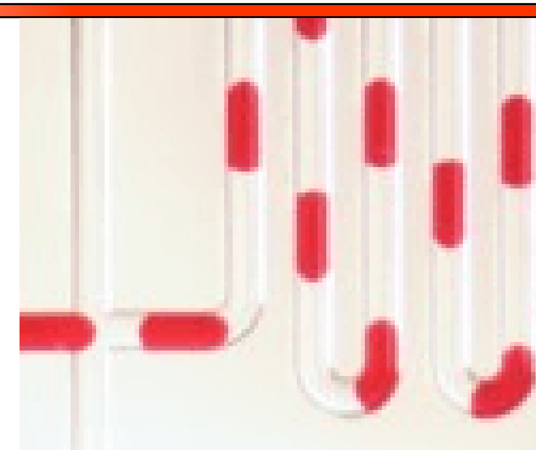
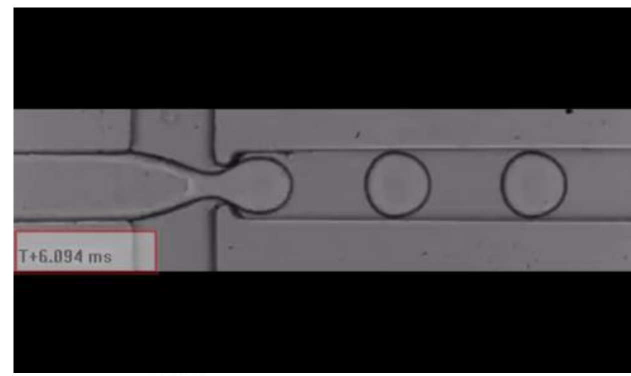
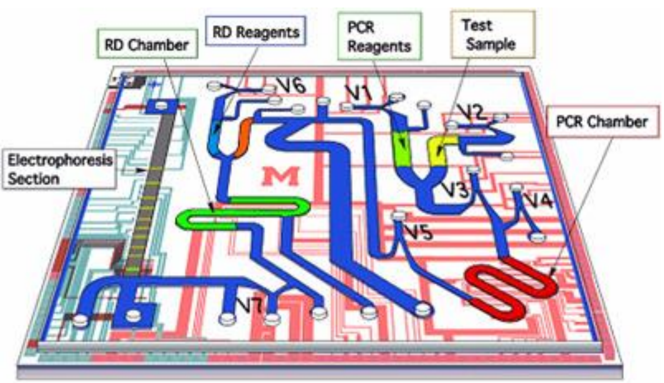
MEMS and Microfluidics

- *Micro-Electro-Mechanical Systems (MEMS) is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through microfabrication technology.*

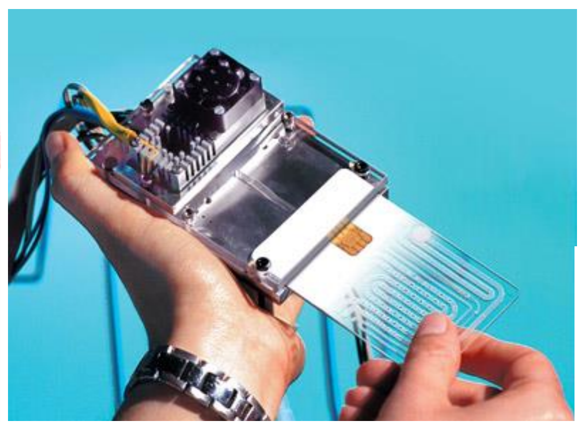


- *Lab-on-a-Chip and mcirofluidic devices for Chemical and biological applications:*





Lab-on-a-Chip for Fast Diagnosis of the Flu

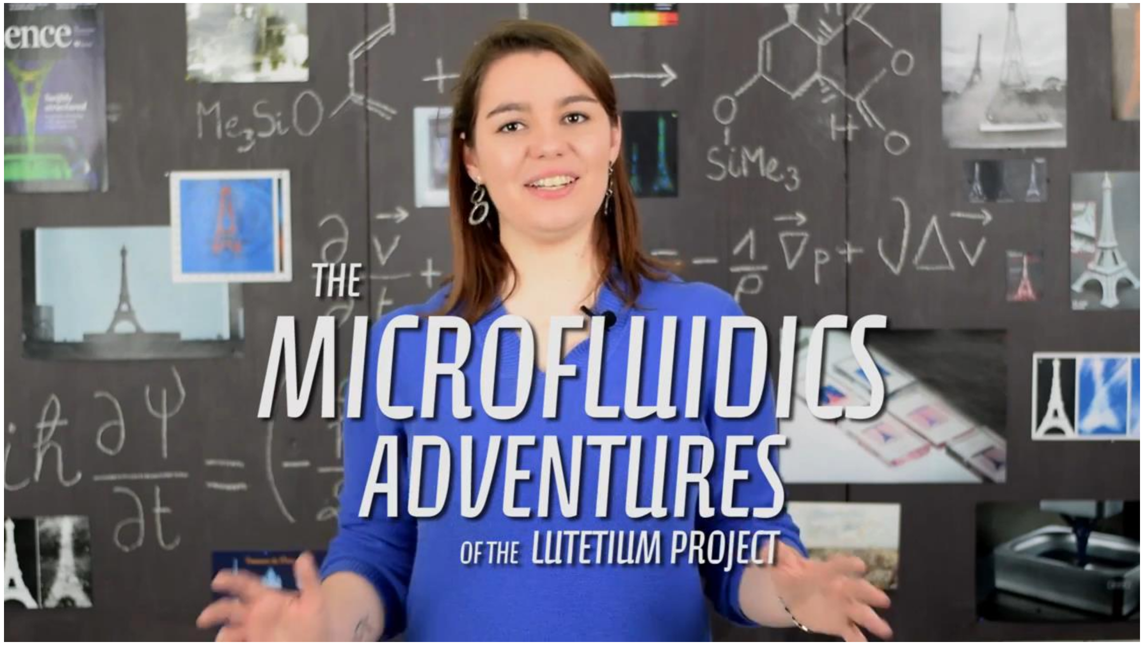


Siemens Quicklab for clinical routine diagnostics

Reasons for Fluid Behavioral Changes in Microscale

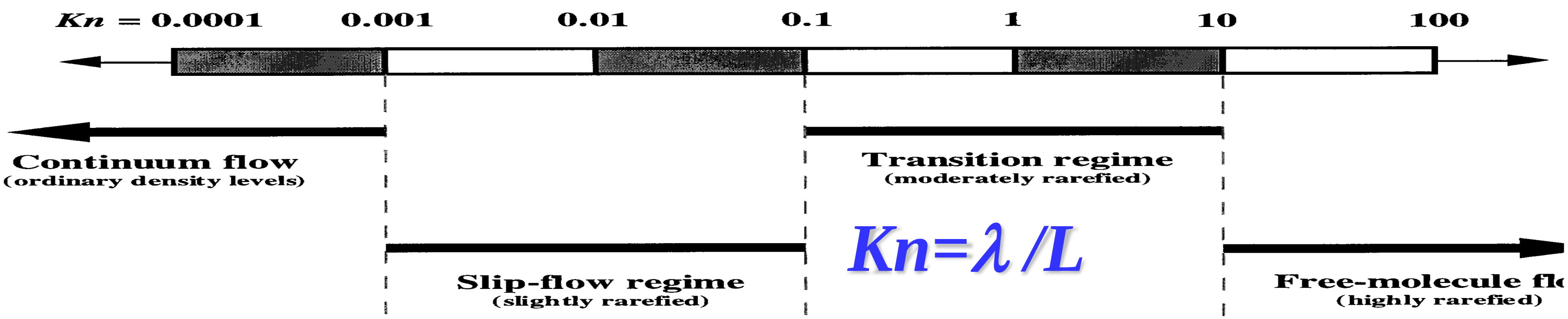
- *Cube-Square Law*
  - *Quantities $\propto L^3$*
    - *inertia, buoyancy, etc.*
  - *Quantities $\propto L^2$*
    - *drag, surface charge, etc.*
  - *Quantities $\propto L^1$*
    - *surface tension*

https://www.youtube.com/watch?v=b8zE2i755-k



- *Non-continuum effects*
  - *gases: Kn=λ /L, no slip, continuum approximation*
  - *liquids: complex boundary conditions*

Knudsen Number Regimes

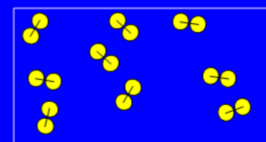
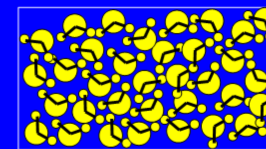


$$Kn = \lambda / L$$

Liquid and Gases Fluids

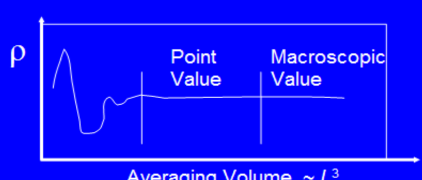
- *Continuum mechanics deals with physical properties of solids and fluids which are independent of any particular coordinate system in which they are observed.*
  - *Fluid Mechanics*
  - *Solid Mechanics*

The Smallest Length Scale of a Continuum
(Deen, Analysis of Transport Phenomena, 1998)

Gases (STP)		Liquids	
			
Molecular diameter	0.3 nm	Molecular diameter	0.3 nm
Number density (m^{-3})	3 E25	Number density (m^{-3})	2 E28
Intermolecular spacing	3 nm	Intermolecular spacing	0.4 nm
Displacement distance	100 nm	Displacement distance	1 pm
Molecular Velocity	500 m/s	Molecular Velocity	10^3 m/s

The Smallest Length Scale of a Continuum
(Deen, Analysis of Transport Phenomena, 1998)

Average over sufficient number of molecules
- Point quantities, ρ, ***u***, *T*



- Random process theory
  - $N \sim 10^4$ molecules $\sigma_\mu = \frac{\sigma_x}{N^{1/2}}$
- ***L* ~ 70 nm** (gases at STP)
- ***L* ~ 8 nm** (liquids)

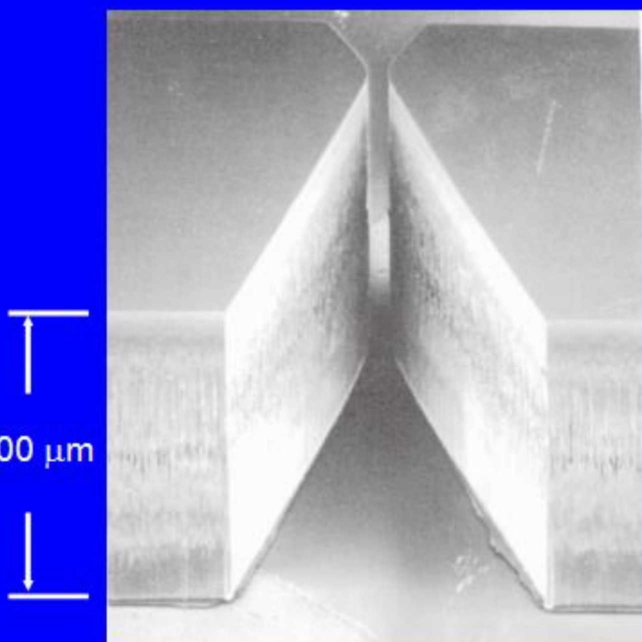
The Smallest Length Scale of a Continuum
(Deen, Analysis of Transport Phenomena, 1998)

Length scale of molecular interactions (transport properties, μ, κ, *D*)
- Gases: mean free path ~ 100 nm
- Liquids: molecular diameter ~ 0.3 nm

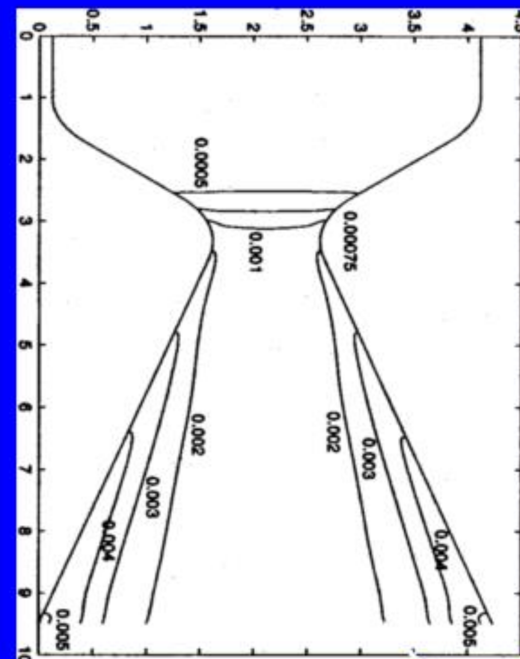
Average over ~ 10^3 interaction length scales
- ***L* ~ 1 μm** (gases)
- ***L* ~ 3 nm** (liquids)

MEMS –based Supersonic Microthruster

MEMS-based Supersonic Microthruster Example



(End View)



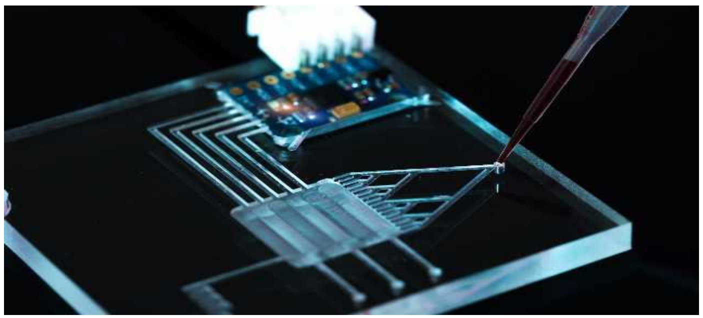
(Top View)

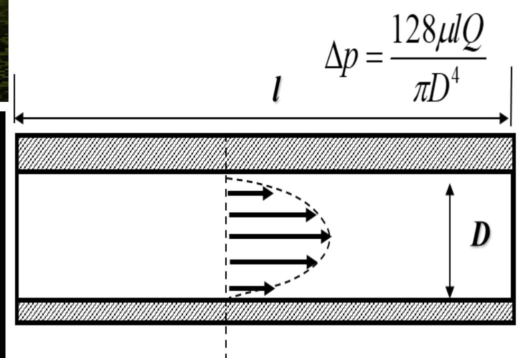
contours of Kn

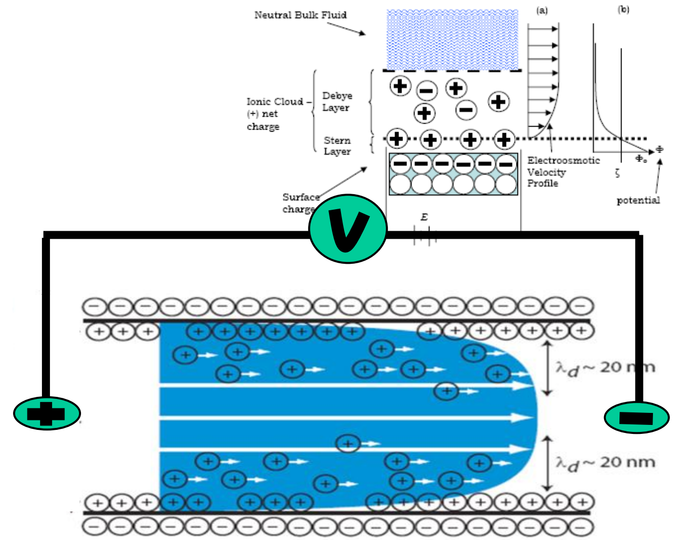
$$Kn = \sqrt{\frac{\pi\gamma}{2}} \cdot \frac{M}{Re}$$

(Courtesy: Bayt and Breuer, MIT)

Electro Osmosis Flow (EOF)



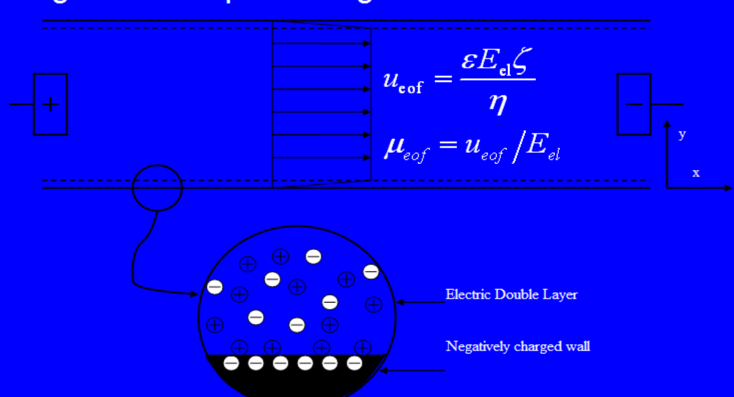




- *Pressure driven flow*
- *Electroosmotic driven flow*

Electroosmosis

- Apply electrical field across channel
- EDL drawn toward electrode pulling bulk along
- "Plug flow" if no pressure gradient

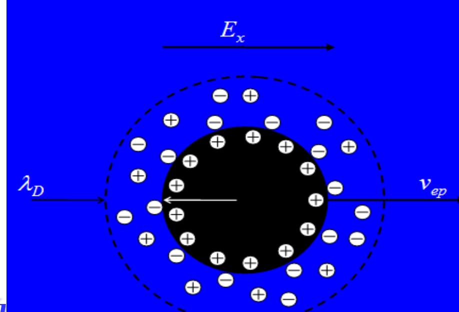


$$u_{eof} = \frac{\varepsilon E_{el} \zeta}{\eta}$$

$$\mu_{eof} = u_{eof} / E_{el}$$

Electrophoresis

- Particle/ion manipulation using EDL and electrical field
  - Common technique called 'capillary electrophoresis' (CE) used to sequence DNA, ala OJ Simpson or Human Genome Project



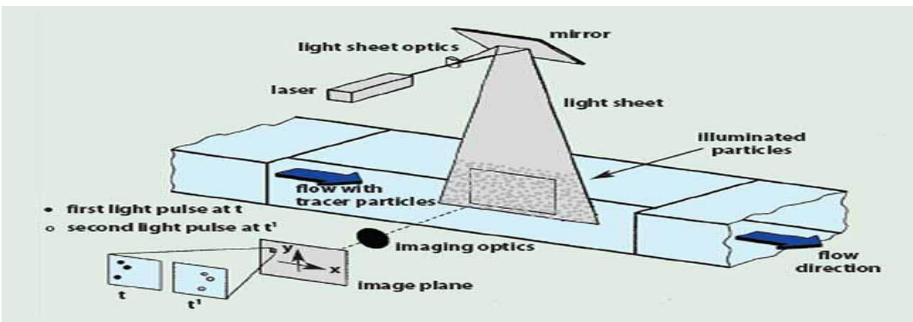
$$u_{ep} = \frac{2}{3}\frac{\varepsilon \zeta E_{el}}{\mu}, \lambda_D \gg d_p$$

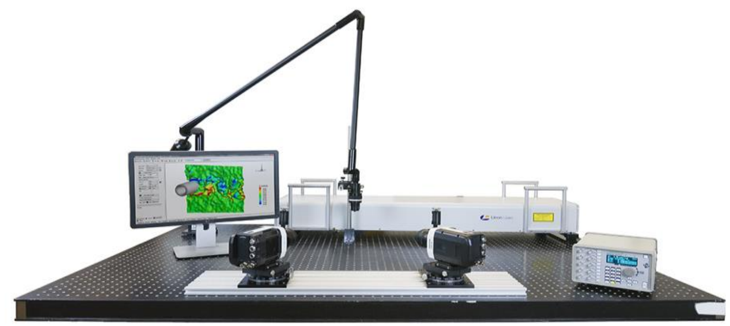
$$u_{ep} = \frac{\varepsilon \zeta E_{el}}{\mu}, \lambda_D \ll d_p$$

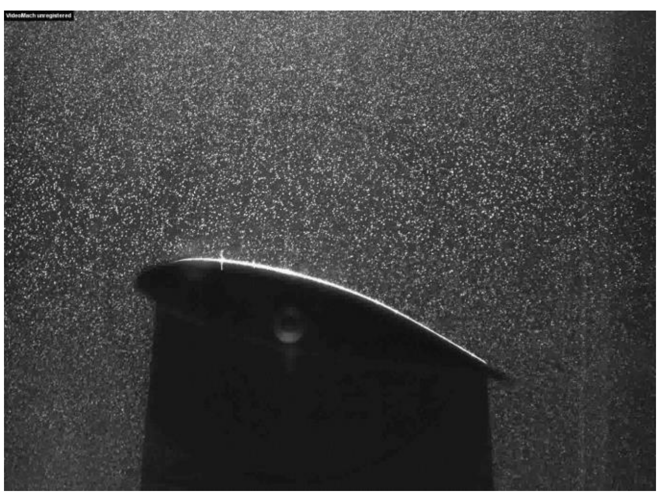
$$\mu_{ep} = u_{ep} / E_{el}$$

System Setup of a conventional PIV system

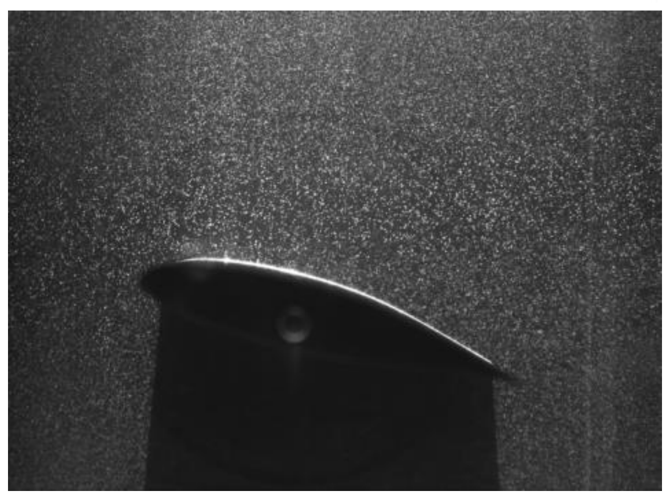
- *Particle tracers:* *to track the fluid movement.*
- *Illumination system:* *to illuminate the flow field in the interest region.*
- *Camera:* *to capture the images of the particle tracers.*
- *Synchronizer:* *to control the timing of the laser illumination and camera acquisition.*
- *Host computer:* *to store the particle images and conduct image processing.*



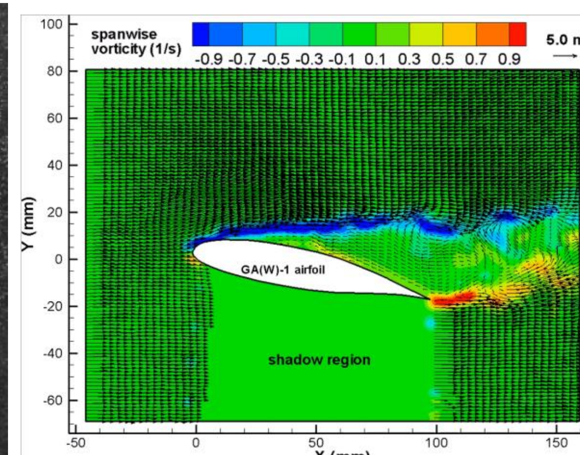




a. T=t0

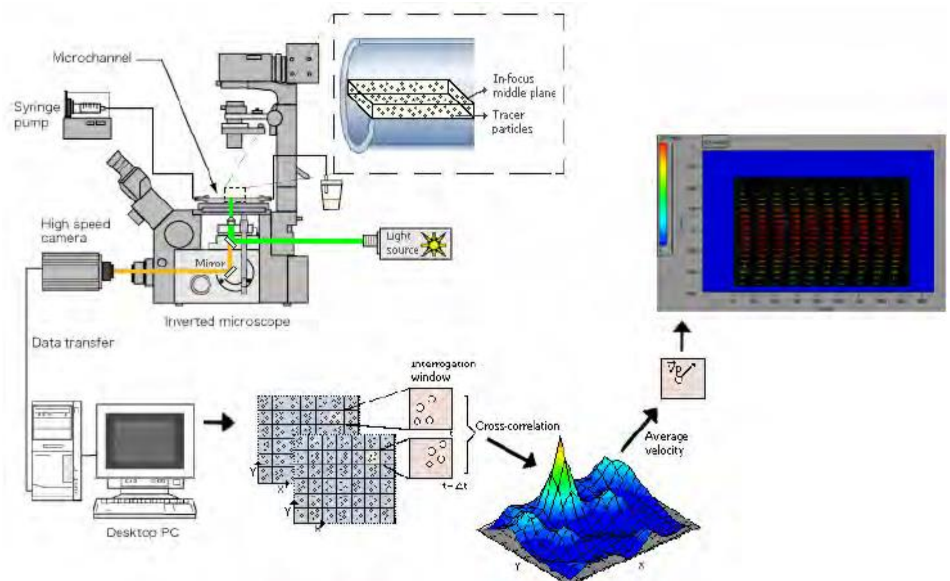


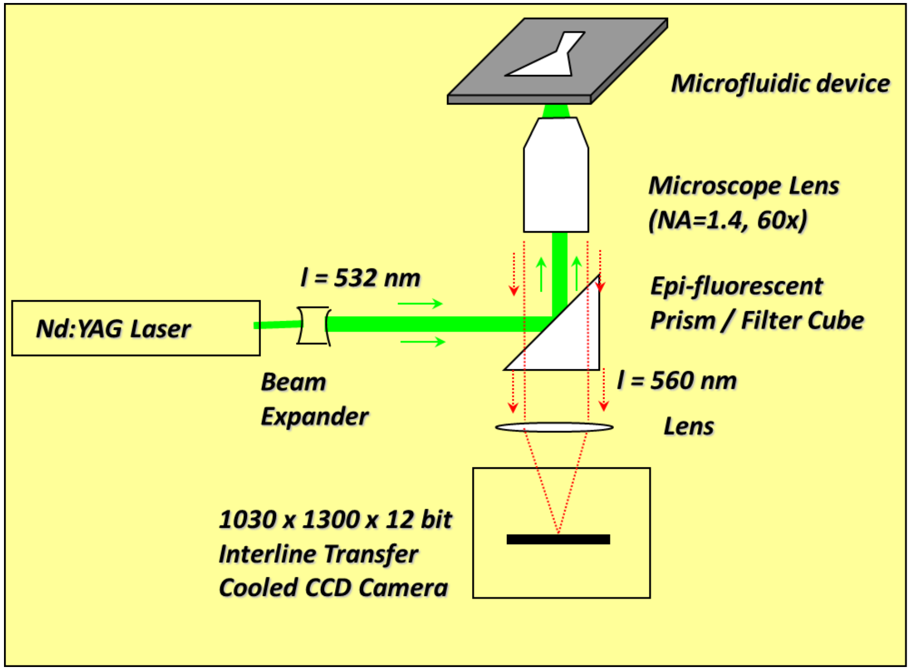
b. T=t0+10μs

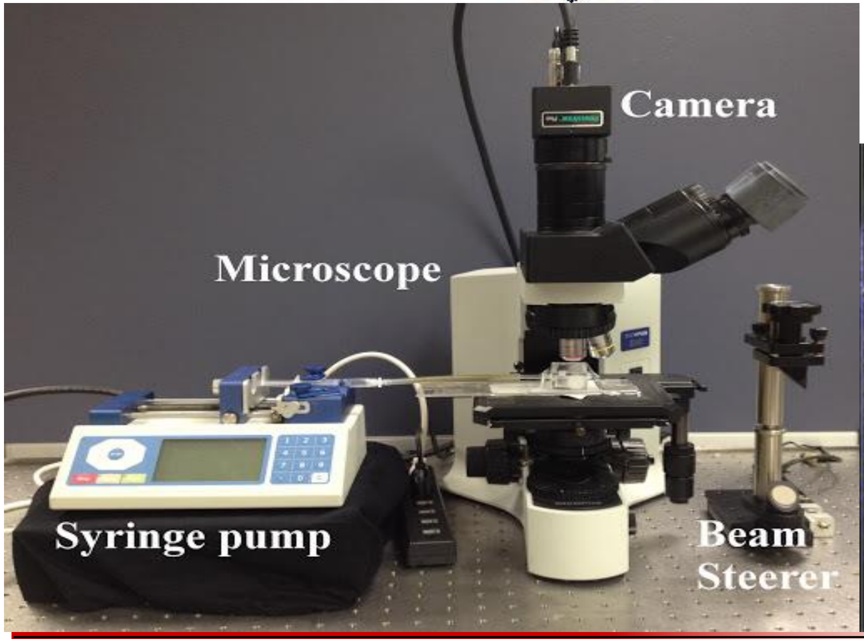


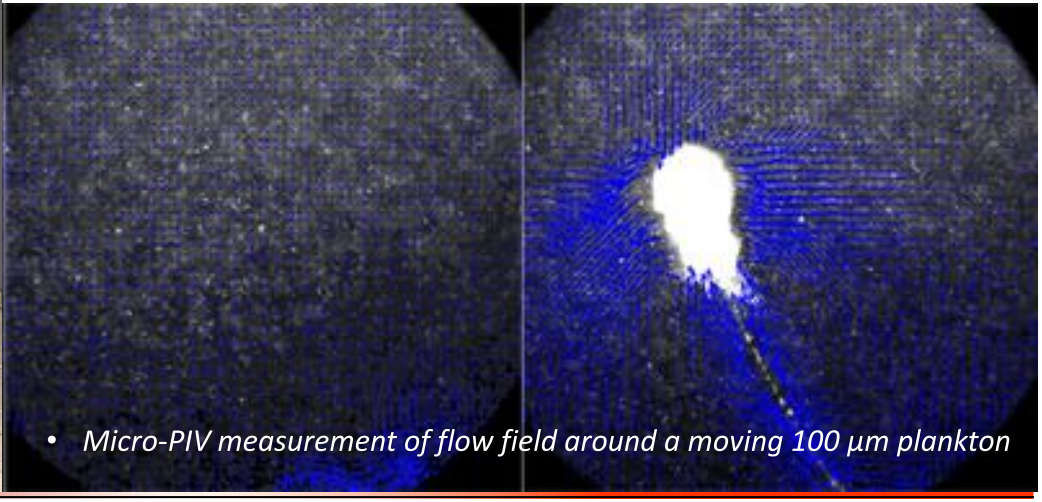
Corresponding Velocity field

System Setup of a Typical Micro- PIV system





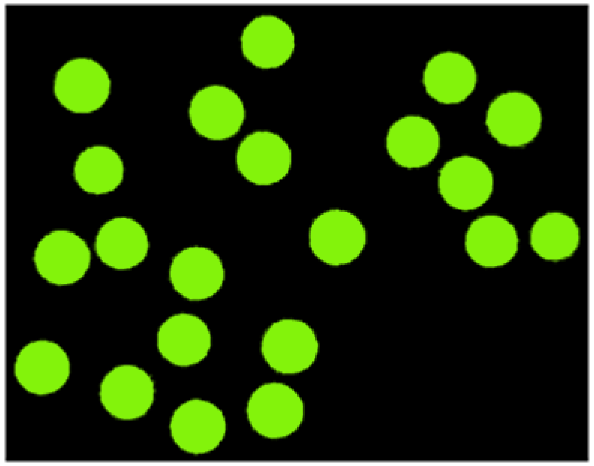




- *Micro-PIV measurement of flow field around a moving 100 μm plankton*

Differences between conventional PIV and Micro-PIV

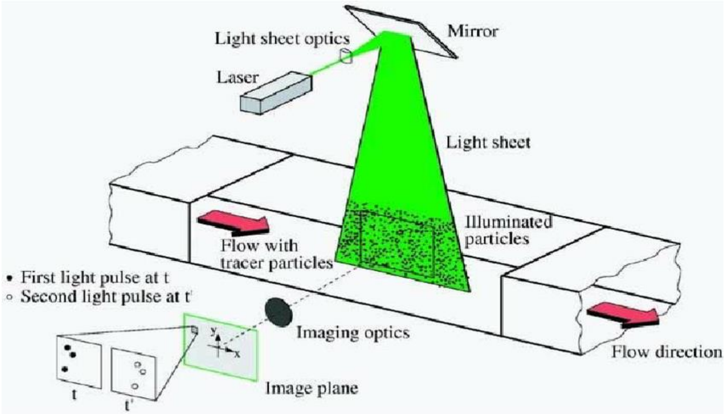
- *Particle tracers:*
  - *Conventional PIV:*
    - *Tracer particle size is about ~1 μm for gaseous flows and ~ 10 μm for liquid flows*
    - *To detect scattering light signal*
  - *Micro-PIV:*
    - *Coated fluorescent particles.*
    - *Particle size is much smaller 200 nm ~1000 nm for liquid flows*
    - *To detect fluorescent light signal*



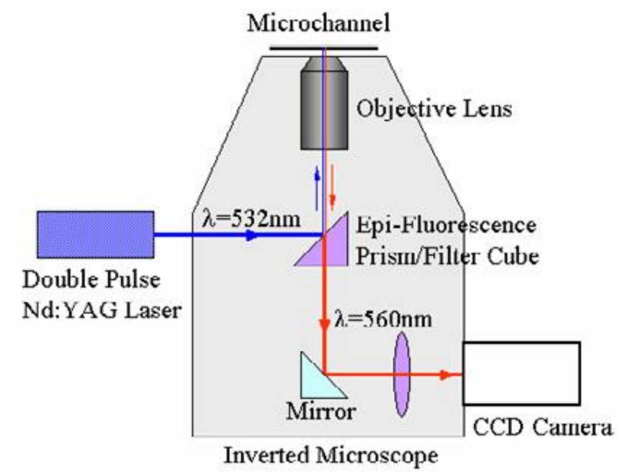
Spectral Properties of Standard Fluorescent Microspheres :

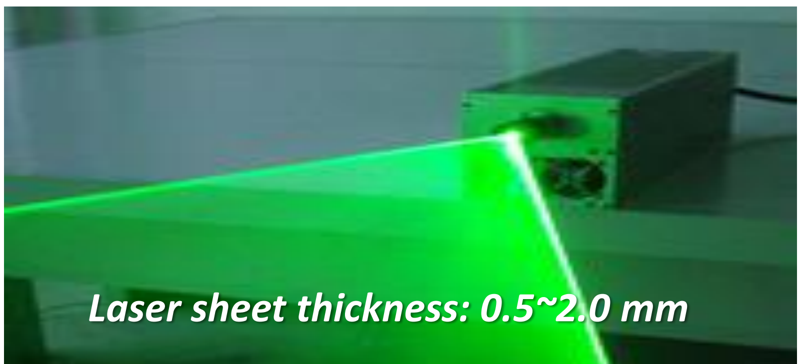
Color	Excitation Maxima (nm)	Emission Maxima (nm)	Stokes Shift (nm)
Green	469 (blue)	509 (green)	40
Red	541 (green) 365 (UV)	611 (red) 446 (blue)	70 81
Blue	388 (UV-violet) 412 (violet)	446 (blue) 473 (blue)	58 61

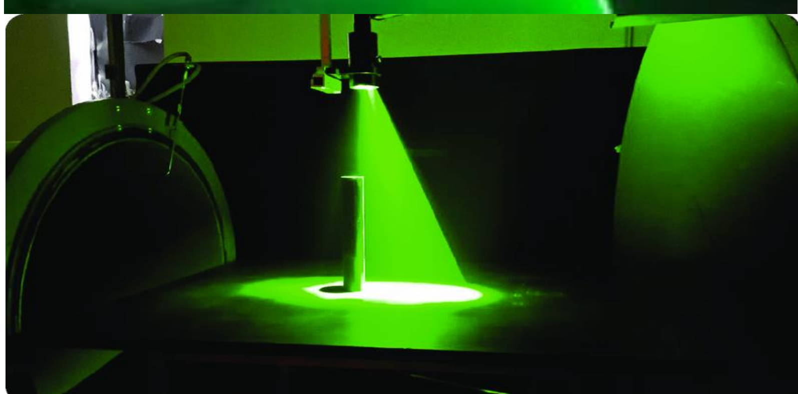
Volume illumination for Micro-PIV Measurements

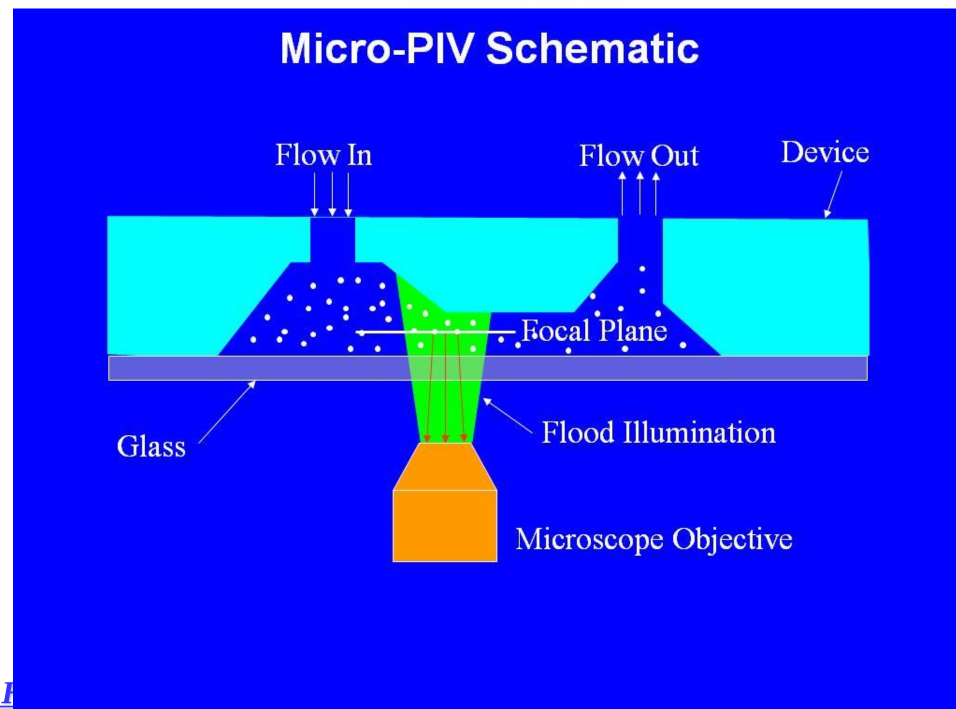


- *Conventional PIV measurements*







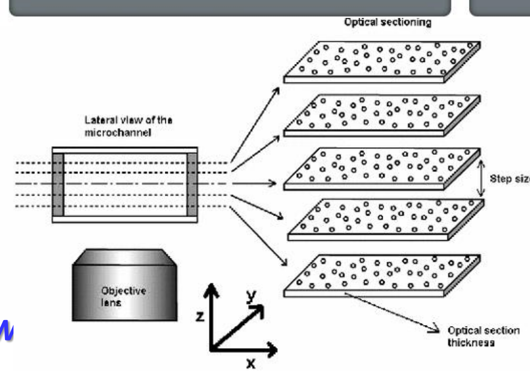


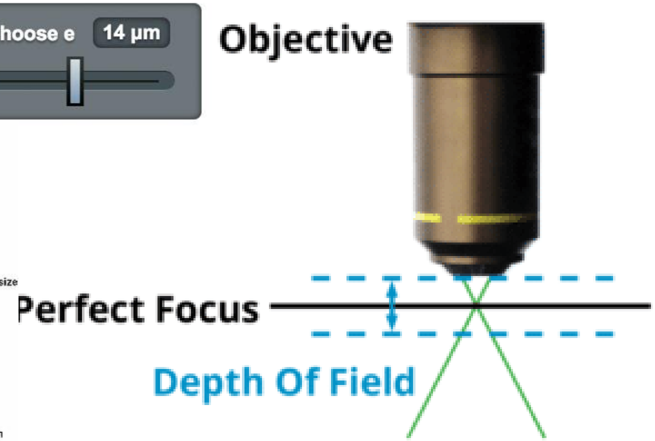
Microscope and Objective Lenses

$$90.00000\ \mu m = \frac{550nm \cdot 1.0}{0.10 \cdot 0.10} + \frac{1.0}{4.0x \cdot 0.10} \cdot 14\ \mu m$$

Depth of Field

$$d_{tot} = \frac{\lambda \cdot n}{NA^2} + \frac{n}{M \cdot NA} \cdot e$$



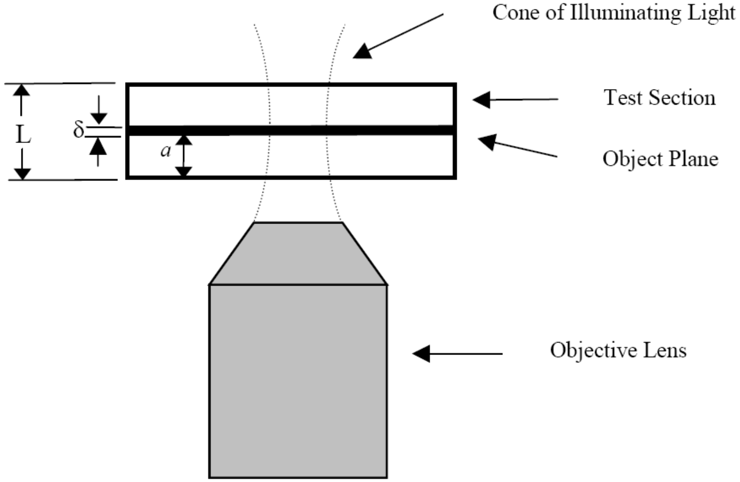


- *https://www.youtube.com/watch?v=lfqh2kNW*

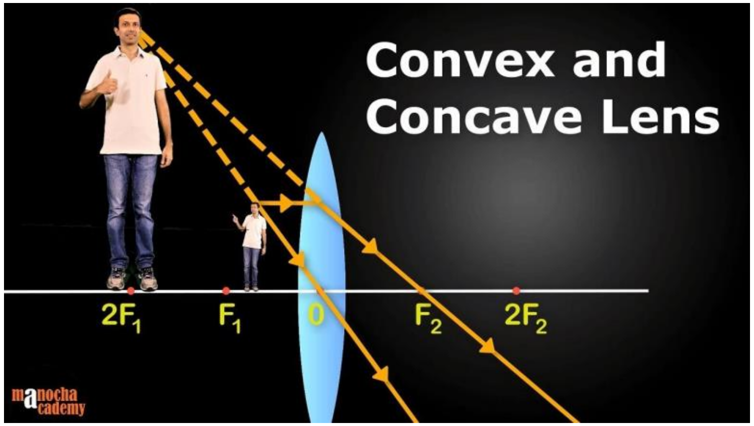
Out-of-Plane Spatial Resolution for Micro-PIV

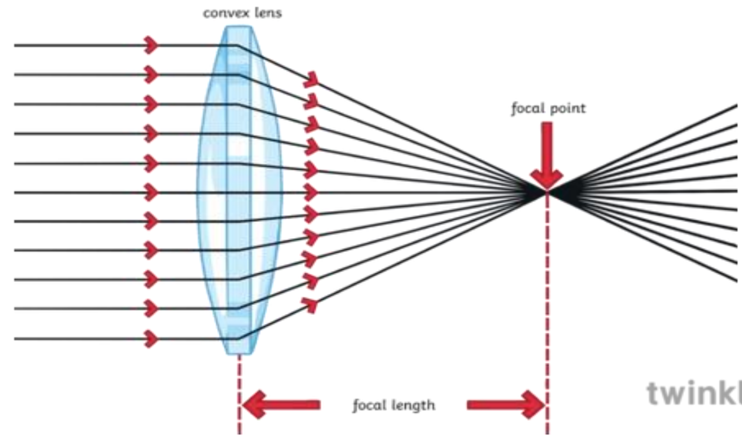
- ***Conventional "Macro"-PIV measurements:***
  - ***The light sheet illuminates only particles contained within the depth of focus of the recording lens, providing high quality in-focus particle images to be recorded with low levels of background noise being emitted from the out-of-focus particles.***
  - ***The out-of-plane spatial resolution of the velocity measurements is defined clearly by the thickness of the illuminating light sheet.***

- ***Micro-PIV measurements:***
  - ***Due to the small length scales associated with μ-PIV, it is difficult if not impossible to form a light sheet that is only a few microns thick, and even more difficult to align a light sheet with the object plane of an objective lens.***
  - ***It is common practice in μ-PIV to illuminate the test section with a volume of light, and rely on the depth of field of the lens to define the out-of-plane thickness of the measurement plane.***



Diameter of Particle Images for Micro-PIV



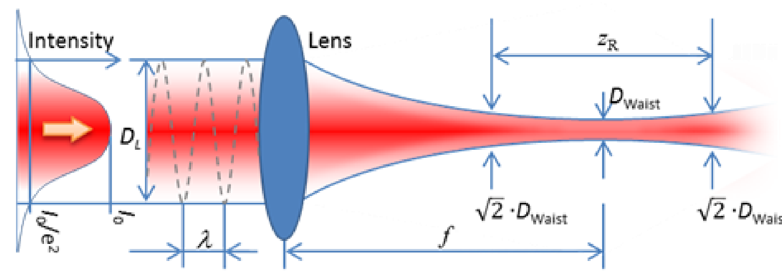


- ***Diffraction-limited spot size:***

$$d_s = 2.44\,(M+1)\,\frac{\lambda}{2NA}$$

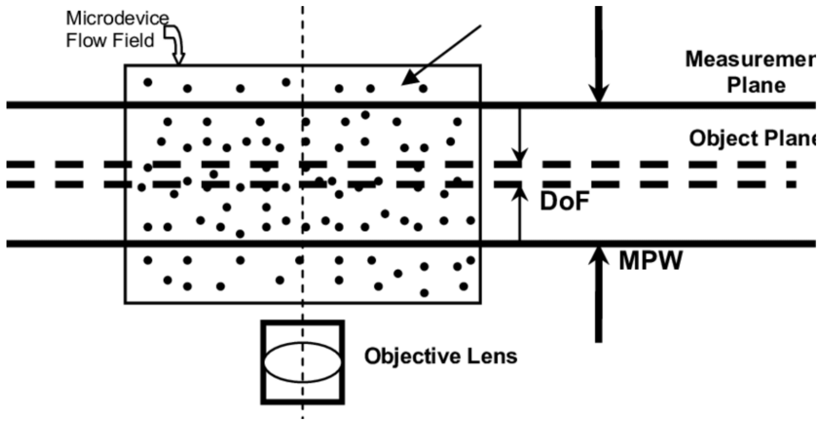
- ***Effective size of the tracer particles:***

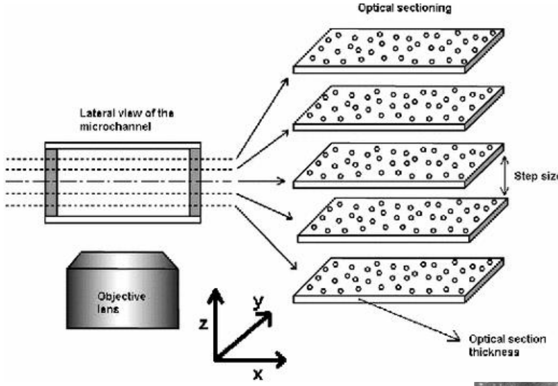
$$d_e = \left[d_s^2 + M^2 d_p^2\right]^{1/2}$$

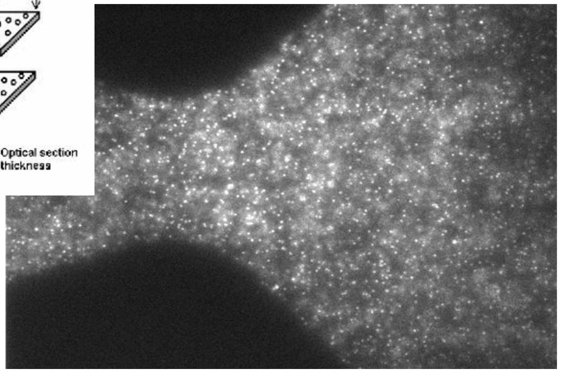


Particle Size d_p	Microscope Objective Lens Characteristics				
	$M = 60$, $NA = 1.4$	$M = 40$, $NA = 0.75$	$M = 40$, $NA = 0.6$	$M = 20$, $NA = 0.5$	$M = 10$, $NA = 0.25$
0.01 µm	0.50	0.93	1.20	1.40	3.00
0.10 µm	0.50	0.94	1.20	1.40	3.00
0.20 µm	0.53	0.95	1.20	1.40	3.00
0.30 µm	0.58	0.98	1.20	1.50	3.00
0.50 µm	0.70	1.10	1.30	1.50	3.00
0.70 µm	0.86	1.20	1.40	1.60	3.10
1.00 µm	1.10	1.40	1.50	1.70	3.20
3.00 µm	3.00	3.10	3.20	3.30	4.20

Out-of-Plane Spatial Resolution for Micro-PIV

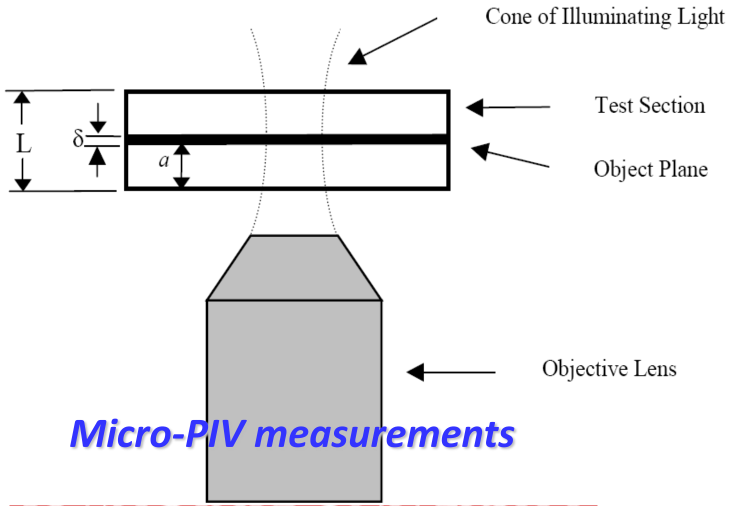






$$z_{corr} = \frac{1}{2}\left[\frac{\left(1-\sqrt{\varepsilon}\right)}{\sqrt{\varepsilon}}\left(\frac{n^2}{NA^2}-1\right)\left(d_p^2 + \frac{1.49\left(M+1\right)^2 \lambda^2}{M^2\, NA^2}\right)\right]^{1/2}$$

$$\varepsilon = \frac{d_e^4(0)}{d_e^4\left(z_{corr}\right)}$$

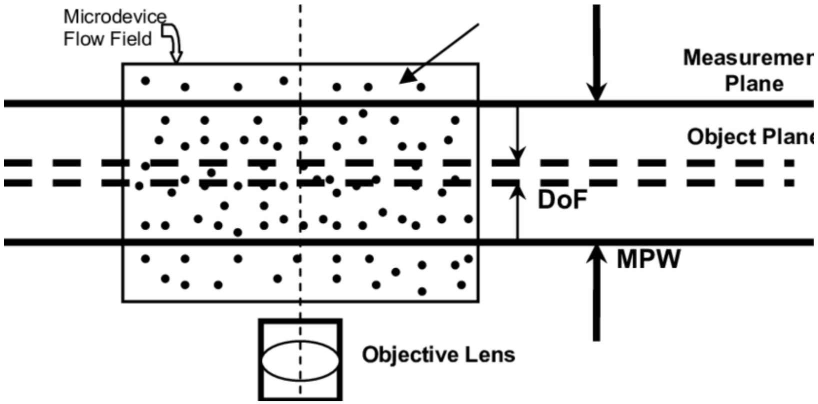


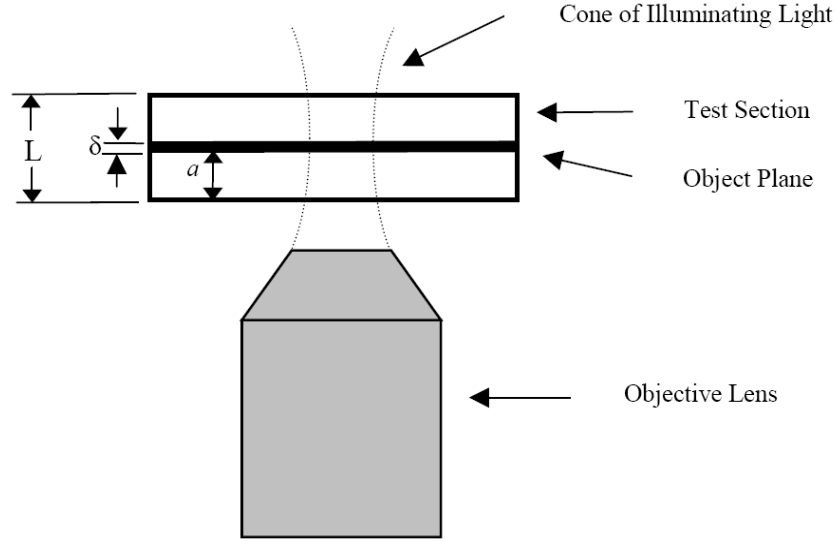
Micro-PIV measurements

Table 2. Thickness of the measurement plane for typical experimental parameters, $2z_{corr}$ (μm).

Particle Size d_p	Microscope Objective Lens Characteristics				
	$M = 60$ $NA = 1.4$	$M = 40$ $NA = 0.75$	$M = 40$ $NA = 0.6$	$M = 20$ $NA = 0.5$	$M = 10$ $NA = 0.25$
0.01 μm	0.62	2.47	4.67	7.46	34.95
0.10 μm	0.63	2.49	4.69	7.48	34.97
0.20 μm	0.66	2.53	4.74	7.53	35.02
0.30 μm	0.72	2.60	4.82	7.62	35.12
0.50 μm	0.87	2.80	5.08	7.90	35.43
0.70 μm	1.06	3.09	5.45	8.30	35.88
1.00 μm	1.39	3.62	6.15	9.09	36.83
3.00 μm	3.77	8.31	12.88	17.28	49.36

Visibility of Particles tracers





$$V = \frac{I(0,0)}{I_B} = \frac{4M^2\beta^2(s_o - a)(s_o - a + L)}{\pi C L s_o^2\left(M^2 d_p^2 + 1.49(M+1)^2\lambda^2 / NA^2\right)}$$

- ***For a given set of recording optics, particle visibility can be increased :***
  - ***By decreasing particle concentration, C,***
  - ***By decreasing test section thickness, L.***

- ***For a fixed particle concentration, the visibility can be increased by***
  - ***By decreasing the particle diameter,***
  - ***By increasing the numerical aperture of the recording lens.***

- ***Visibility depends only weakly on magnification, and object distance.***

Table 3. Maximum percent volume fraction of particles, V_{fr}, while maintaining an in-focus visibility, $V = 1.5$, for imaging the center of an $L = 100$ μm deep device.

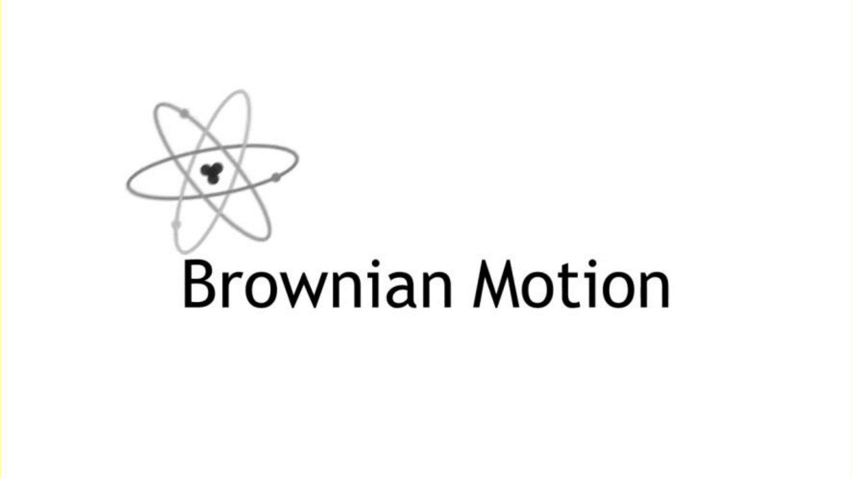
Particle Size d_p	Microscope Objective Lens Characteristics				
	$M = 60$ $NA = 1.4$ s_o=0.38 mm	$M = 40$ $NA = 0.75$ s_o=0.89 mm	$M = 40$ $NA = 0.6$ s_o=3 mm	$M = 20$ $NA = 0.5$ s_o=7 mm	$M = 10$ $NA = 0.25$ s_o=10.5 mm
0.01 μm	6.50E-6	1.86E-6	1.20E-6	7.91E-7	1.80E-7
0.10 μm	6.25E-3	1.84E-3	1.19E-3	7.88E-4	1.80E-4
0.20 μm	4.50E-2	1.43E-2	9.29E-3	6.21E-3	1.44E-3
0.30 μm	1.29E-1	4.56E-2	3.03E-2	2.50E-2	4.83E-3
0.50 μm	4.04E-1	1.81E-1	1.26E-1	8.80E-2	2.19E-2
0.70 μm	7.47E-1	4.09E-1	3.02E-1	2.19E-1	5.87E-2
1.00 μm	1.29E-0	8.68E-1	6.90E-1	5.33E-1	1.62E-1
3.00 μm	4.68E-0	4.45E-0	4.25E-0	3.98E-0	2.44E-0

Effect of Brownian Motion on micro-PIV measurements

Particle response time: $\tau_p = (1 + 2.76\, Kn_p)\, d_p^{\,2}\, \rho_p/(18\mu_f)$

For 300 nm diameter polystyrene latex spheres immersed in water, the particle response time is ~10^{-9} s.

- *Brownian motion is the random thermal motion of a particle suspended in a fluid. The motion results from collisions between fluid molecules and suspended particles.*
- *The velocity spectrum of a particle due to Brownian motion consists of frequencies too high to be resolved fully and is commonly modeled as Gaussian white noise.*
- *A quantity more readily characterized is the particle's average displacement after many velocity fluctuations.*
- *For time intervals Δt much larger than the particle inertial response time, the dynamics of Brownian motion are independent of inertial parameters such as particle and fluid density.*
- *The mean square distance of diffusion is proportional to DΔt, where D is the diffusion coefficient of the particle.*
- *For a spherical particle subject to Stokes drag law, the diffusion coefficient D was first given by Einstein (1905) as:*



$$D = \frac{\kappa T}{3\pi\mu d_p}$$

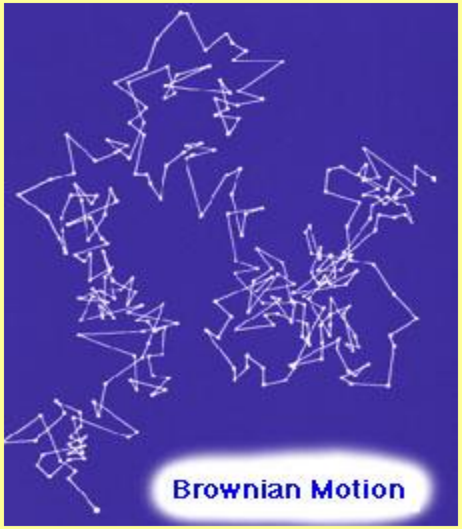
where d_p is the particle diameter, κ is Boltzmann's constant, T is the absolute temperature of the fluid, and μ is the dynamic viscosity of the fluid.

Effect of Brownian Motion on Micro-PIV measurements

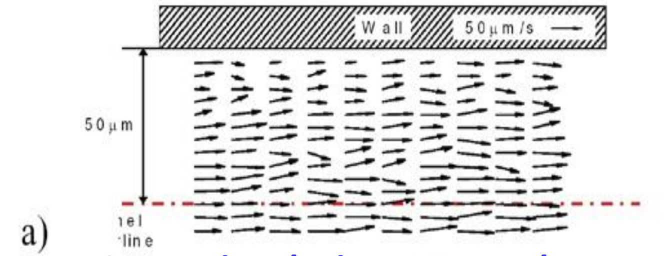
$$\Delta x = u\,\Delta t$$
$$\Delta y = v\,\Delta t$$

$$\varepsilon_x = \frac{\sigma_x}{\Delta x} = \frac{1}{u}\sqrt{\frac{2D}{\Delta t}}$$
$$\varepsilon_y = \frac{\sigma_y}{\Delta y} = \frac{1}{v}\sqrt{\frac{2D}{\Delta t}}$$

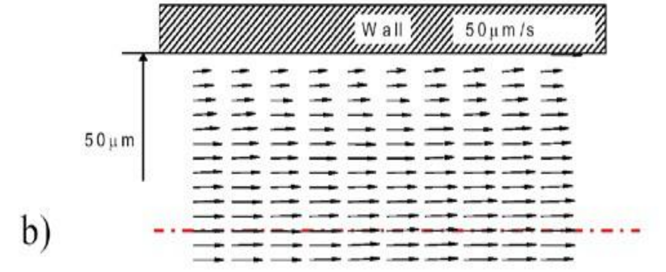
$$D = \frac{\kappa T}{3\pi\mu d_p}$$



- *The errors estimated by above Equations show that the relative Brownian intensity error decreases as the time of measurement increases. Larger time intervals produce flow displacements proportional to Δt while the root mean square of the Brownian particle displacements grow as $\Delta t^{1/2}$.*
- *In practice, Brownian motion is an important consideration when tracing 50 to 500 nm particles in flow field experiments with flow velocities of less than about 1 mm/s.*
- *For a velocity on the order of 0.5 mm/s and a 500 nm seed particle, the lower limit for the time spacing is approximately 100 µs for a 20% error due to Brownian motion.*
- *This error can be reduced by both averaging over several particles in a single interrogation spot and by ensemble averaging over several realizations.*
- *The diffusive uncertainty decreases as 1/√N, where N is the total number of particles in the average*



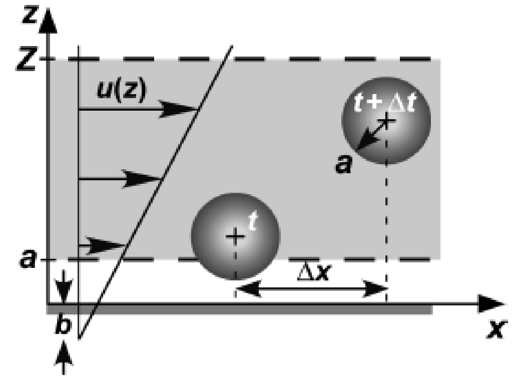
- *Convectional micro-PTV results*



- *Correlation based micro-PIV results*

Particle in Shear Flows - Saffman effect

- *Particles are found to intend to stay away from the regimes with high velocity gradient .*
- *Poiseuille (1836) is generally acknowledged to be the first modern scientist who recorded evidence of particle migration with his observations that blood cells flowing through capillaries tended to stay away from the walls of the capillaries.*
- *Taylor (1955) scanned the cross-section of a tube carrying a suspension and noticed areas of reduced cell concentration not only near the walls, but also near the center of the channel.*
- *Segré and Silberberg (1962) systematically performed experiments that confirmed both observations—migration away from the walls and migration away from the center of the channel and determined that migration rate was proportional to the square of the mean velocity in the channel as well as the fourth power of the particle radius.*
- *Saffman (1965) analytically considered the case of a rigid sphere translating in a linear unbounded shear field.*



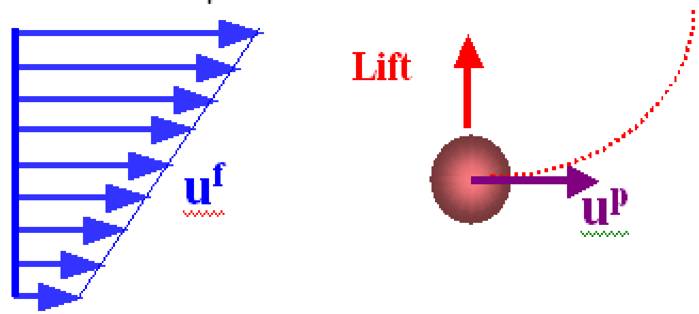
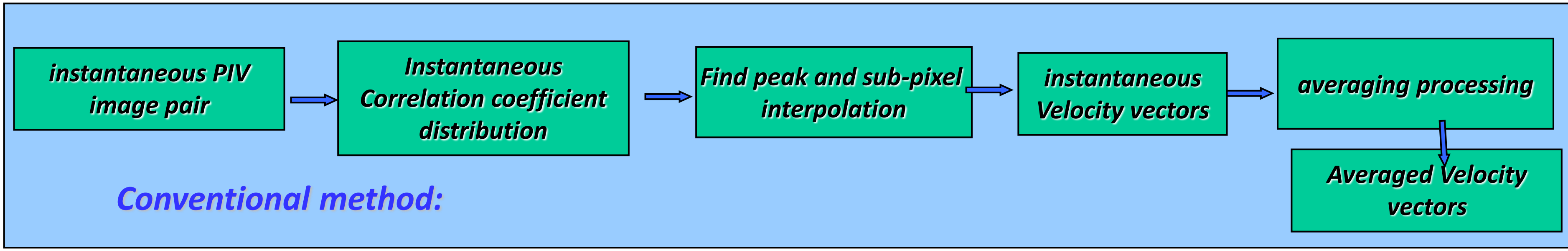


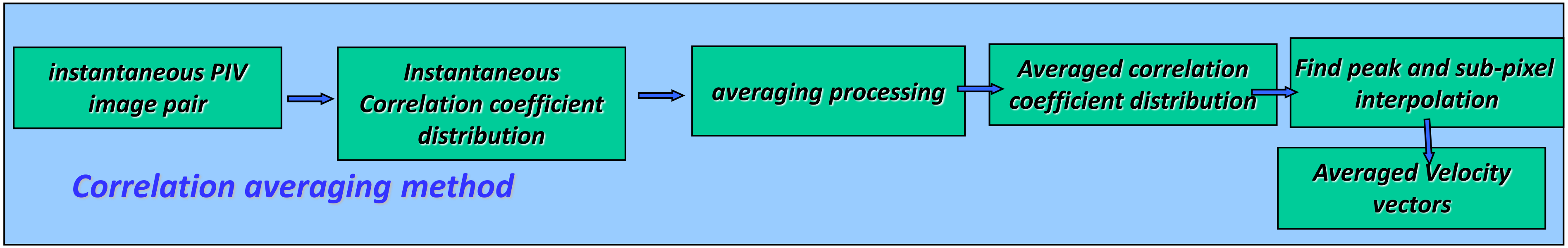
Figure 1. Schematics of a particle in a shear flow.

$$\frac{V_m}{V_s} = 0.343a\sqrt{\frac{G}{\nu}} .$$

G : *velocity gradient*
Vs : *is slip velocity*
Vm: *migration velocity*

Image Processing Algorithms for Micro-PIV Measurements





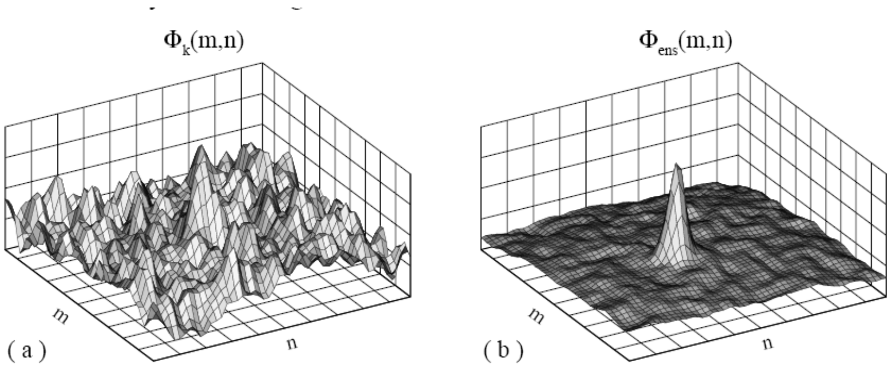


Figure 5. Effect of ensemble correlation: (a) results with conventional correlation for one of the PIV recording pairs; (b) results with ensemble correlation for 101 PIV recording pairs (Wereley, et al., 2001).

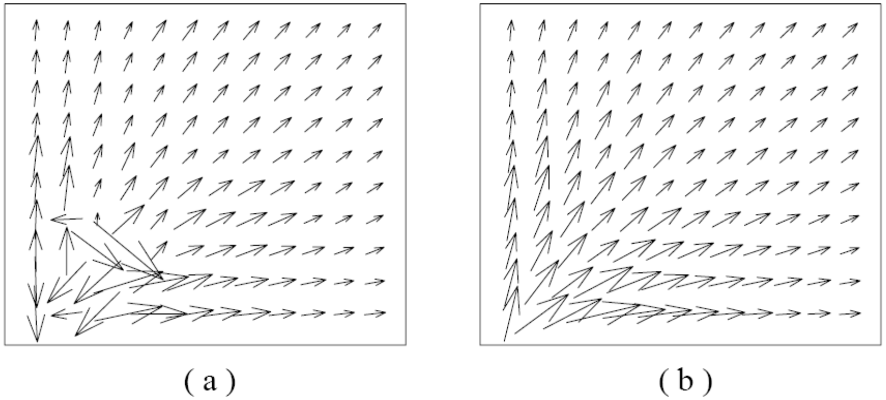
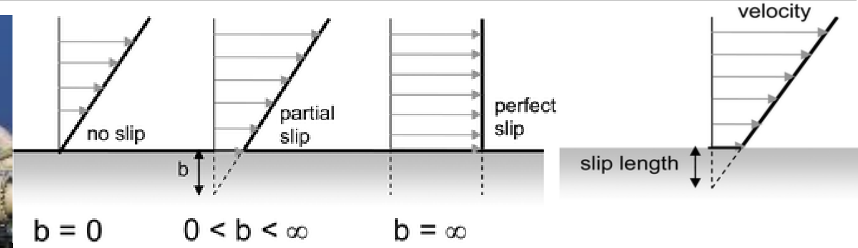
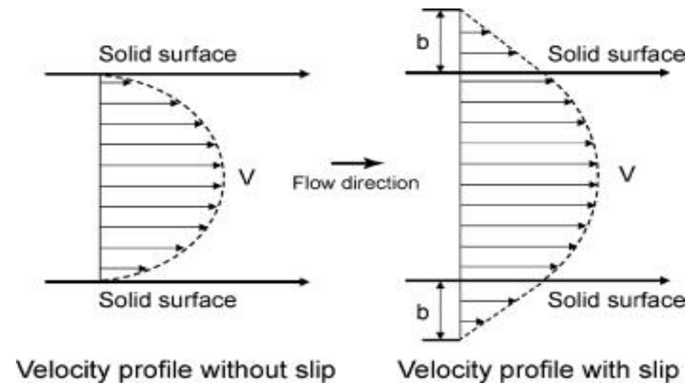
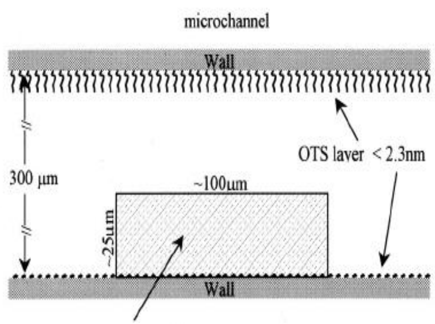


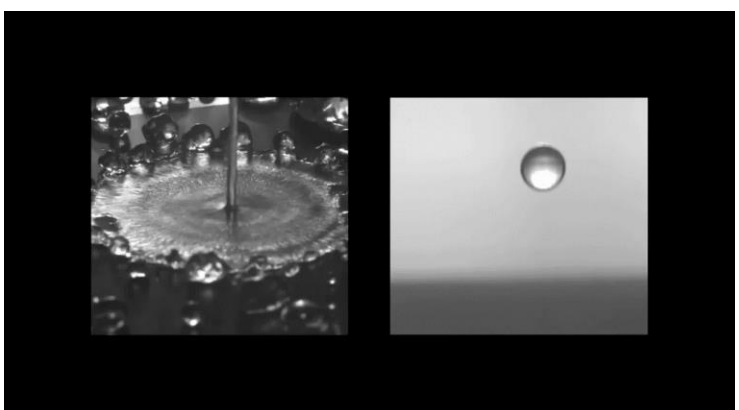
Figure 6. Comparison of the evaluation function of (a) a single PIV recording pair with (b) the average of 101 evaluation functions (Wereley, et al., 2001).

Micro-PIV Application: Near Wall Flow Velocity Measurements









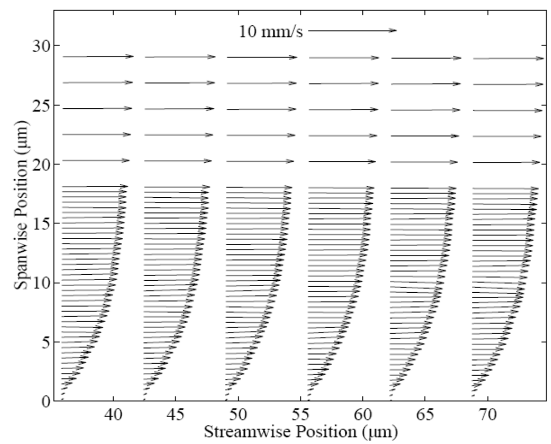


Figure 12b. Near wall view of boxed region from Figure 12a (Meinhart, et al., 1999).

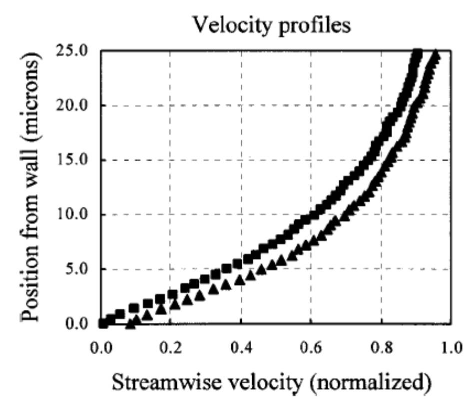
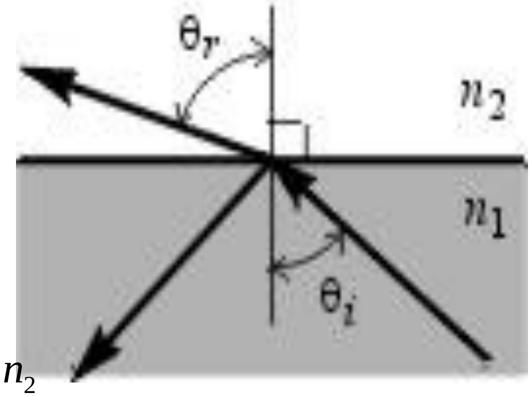


FIG. 3. Velocity profiles for flow over a hydrophilic (square) and hydrophobic (triangle) microchannel surface. The velocity profiles are normalized by the free-stream velocity.

Micro-PIV Application: Near Wall Flow Velocity Measurements

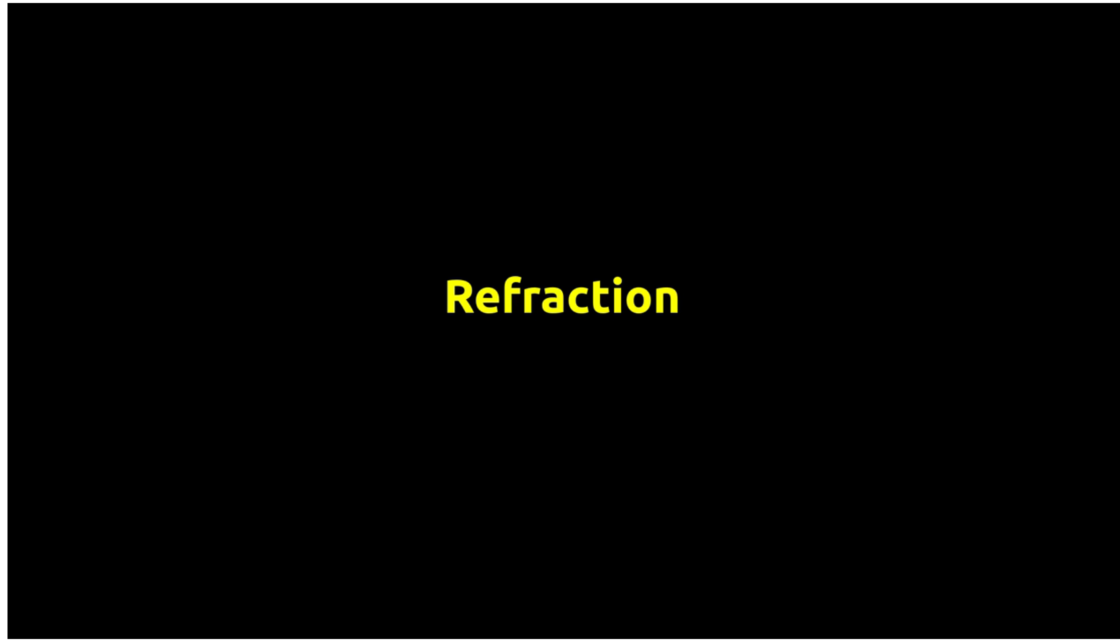
Total Internal Reflection

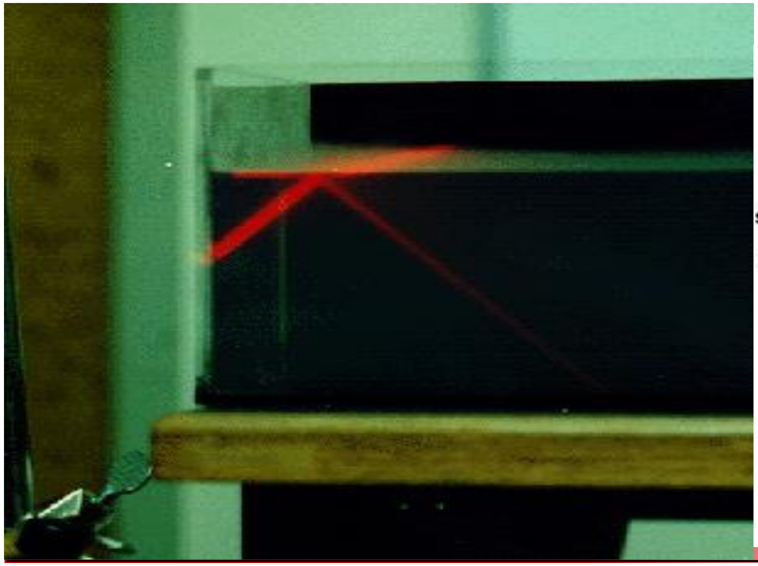


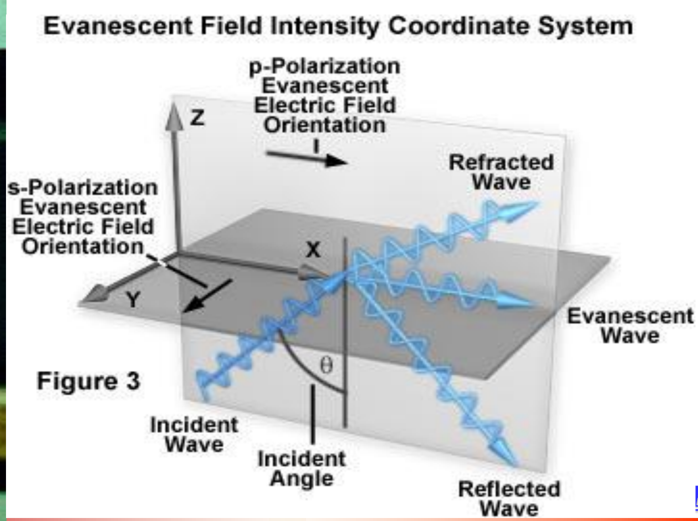
$$\frac{\sin\varphi_1}{\sin\varphi_2}=\frac{n_2}{n_1}$$

$$n_1 > n_2 \Rightarrow \varphi_2 > \varphi_1$$

$$\varphi_{2\max} = \pi/2 \Rightarrow \varphi_{1cri} = \sin^{-1}(n_2/n_1)$$







Reserved!

Aerospace Engineering

Evanescent-Wave Based Nano-Particle Image Velocimetry Technique.