

Lecture # 05: Velocimetry Techniques and Instrumentation

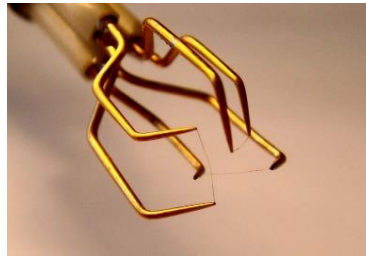
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☐ VARIOUS MEASUREMENT TECHNIQUES FOR THERMO-FLOW STUDIES

Velocity, temperature, pressure, density (concentration), etc...

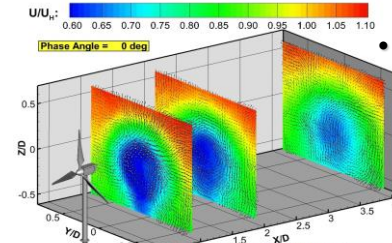
Thermo-Fluids measurement techniques



• Hotwire probe



• Thermocouples



• Stereoscopic PIV

Intrusive techniques

- Pitot probe
- hotwire, hot film
- thermocouples
- etc...

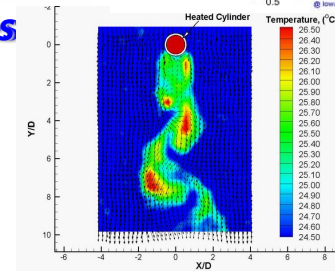
Non-intrusive techniques

particle-based techniques

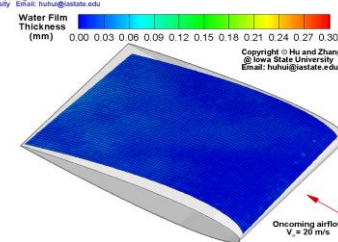
molecule-based techniques

Flow velocity
 V_f

= Velocity of particles or molecule Tracers, V_{tracer}



• MTV & MTT



• DIP measurements

- Laser Doppler Velocimetry (LDV)
- Planar Doppler Velocimetry (PDV)
- Particle Image Velocimetry (PIV)
- etc...

- Laser Induced Fluorescence (LIF)
- Molecular Tagging Velocimetry (MTV)
- Molecular Tagging Thermometry (MTT)
- Digital Image Projection (DIP)
- Pressure Sensitive Paint (PSP)
- Temperature Sensitive Paint (TSP)
- Quantum Dot Imaging
- etc ...



Methods to Measure Local Flow Velocity - 1

- *Mechanical methods:*

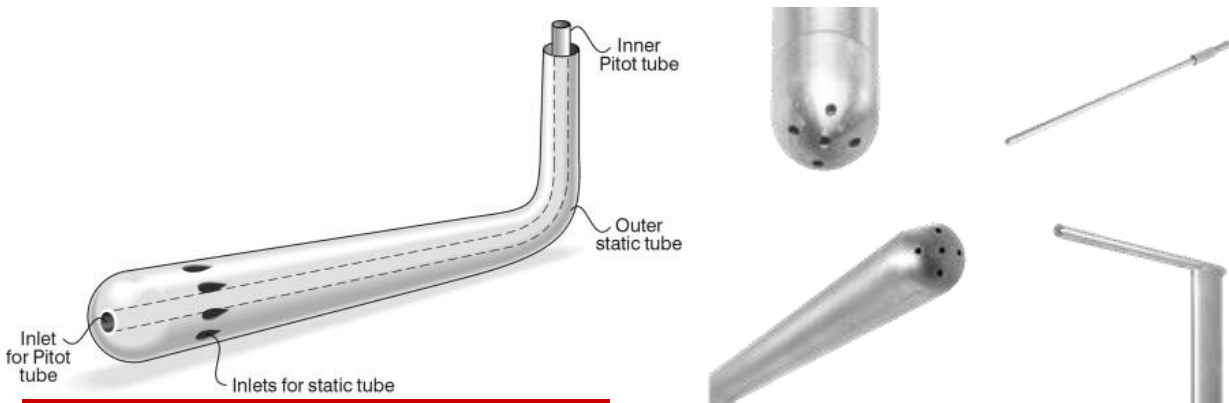
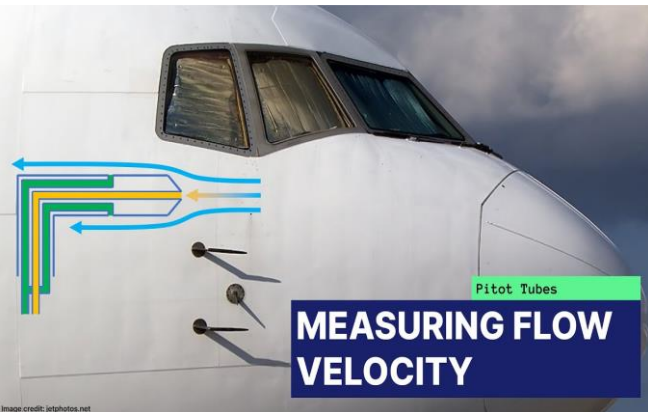
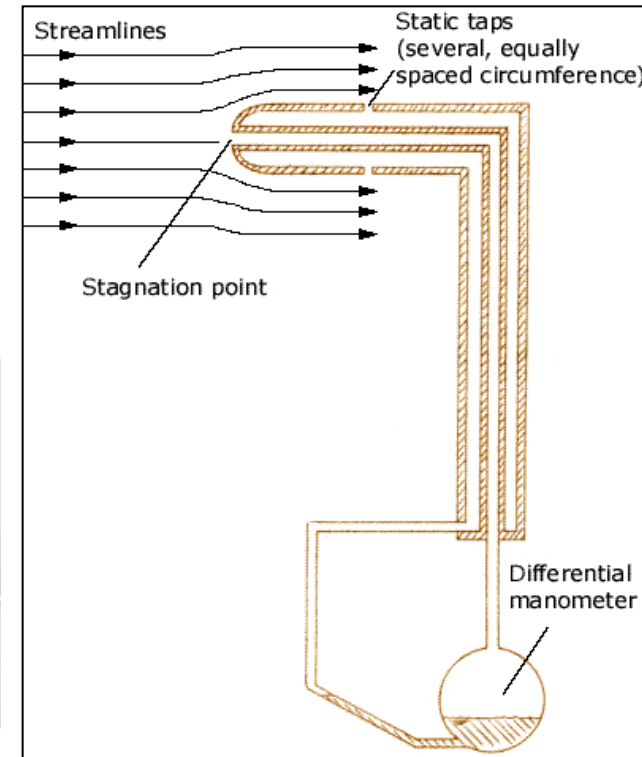
- Taking advantage of force and moments that a moving stream applies on immersed objects.
- Vane anemometers
- Propeller anemometers



Methods to Measure Local Flow Velocity -2

• Pressure difference methods:

- Utilize analytical relationship between the local velocity and the static and total pressures
- The tubes sensing static and stagnation pressures are usually combined into one instrument known as *Pitot-static tube*.



$$p_0 = p_{stat} + \frac{1}{2} \rho V^2, (Bernoulli)$$

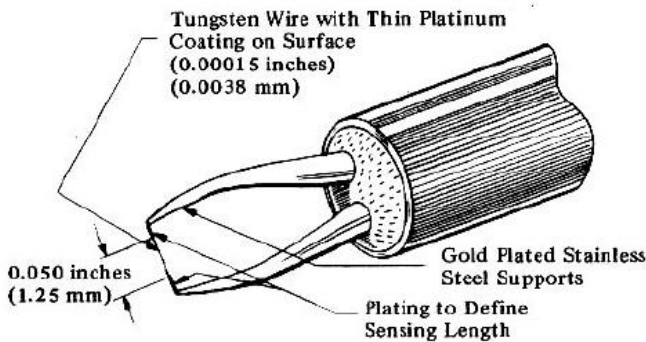
$$V = \sqrt{2(p_0 - p_{stat}) / \rho}$$

$$V = C \sqrt{2(p_0 - p_{stat}) / \rho}$$

Methods to Measure Local Flow Velocity -3

• Thermal methods:

- Compute flow velocity from its relationship between local flow velocity and the convective heat transfer from heated elements.



Hot wire anemometers

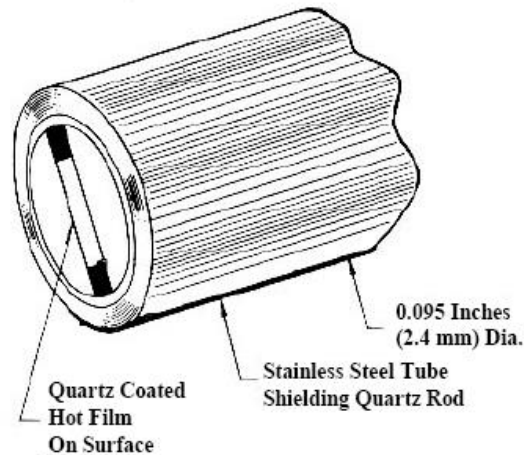


Figure 6: Hot Film Flush Mounted Probe

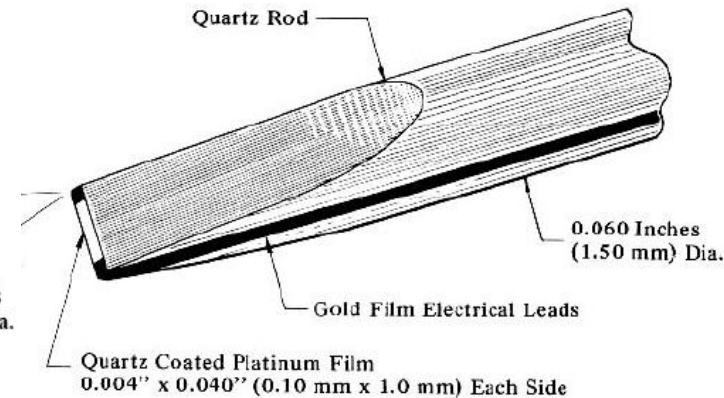
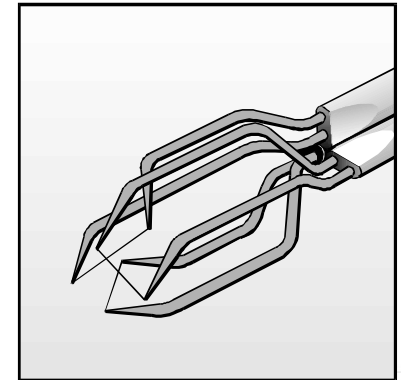
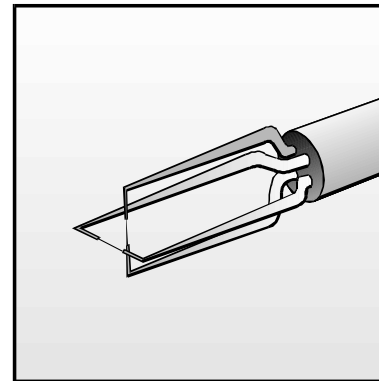
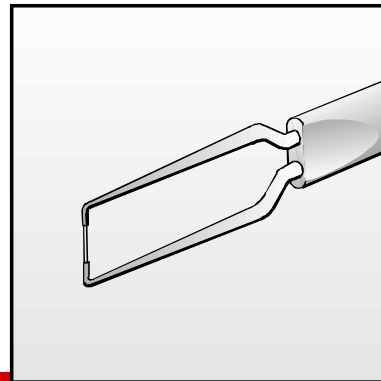
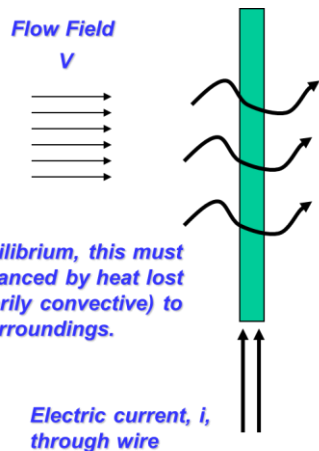


Figure 7: Hot Film Wedge Probe



Particle-based Flow Diagnostic Techniques

- *Seeded the flow with small particles ($\sim \mu\text{m}$ in size)*
- **Assumption**: *the particle tracers move with the same velocity as local flow velocity!*

$$\boxed{\begin{array}{c} \text{Flow velocity} \\ V_f \end{array}} = \boxed{\begin{array}{c} \text{Particle velocity} \\ V_p \end{array}}$$



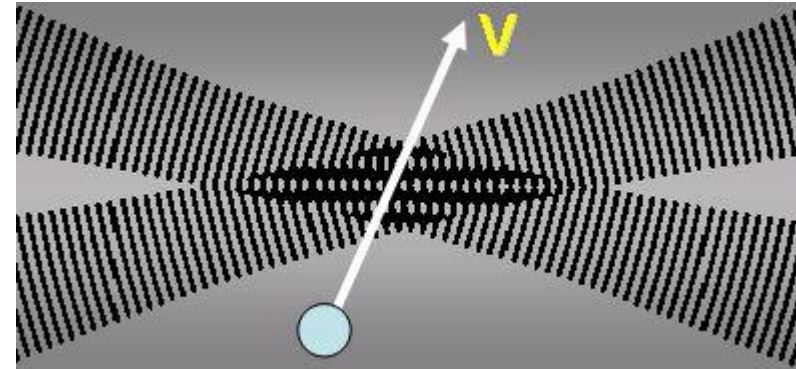
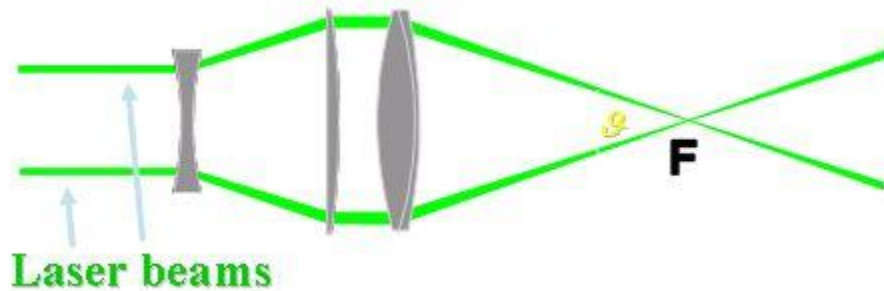
Measurement of
particle velocity



Methods to Measure Local Flow Velocity - 4

□ Frequency-shift methods:

- Based on the Doppler phenomenon, namely the shift of the frequency of waves scattered by moving particles.
- Laser Doppler Velocimetry(LDV) or Laser Doppler Anemometry (LDV)
- Planar Doppler Velocimetry (PDV) or Planar Doppler Anemometry (PDA)



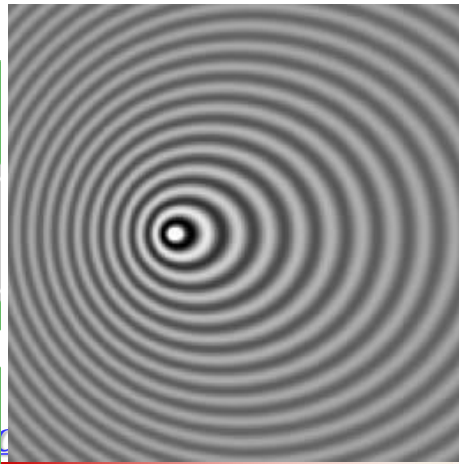
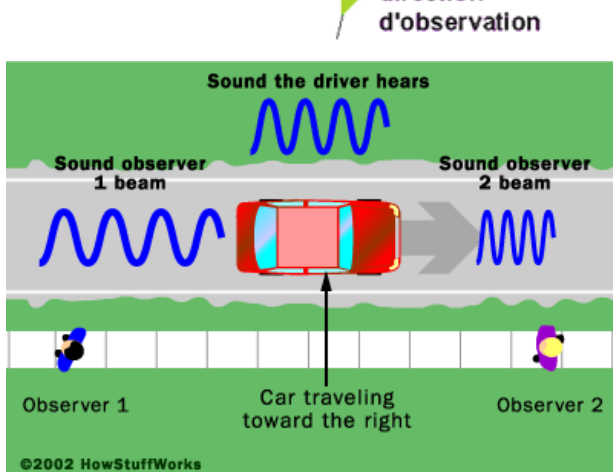
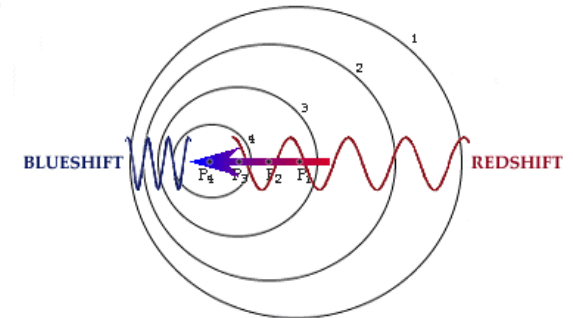
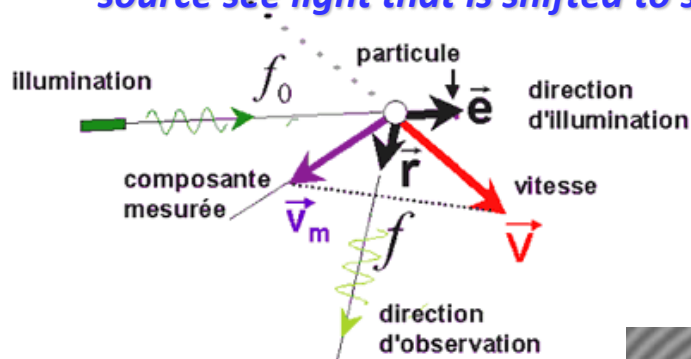
Interference fringes



$$v_{\perp} = \frac{\lambda}{2 \sin \frac{\theta}{2}} f$$

Doppler Shift

- The Doppler effect, named after Christian Doppler (an Austrian mathematician and physicist), is the change in frequency and wavelength of a wave that is perceived by an observer moving relative to the source of the waves.
- Light from moving objects will appear to have different wavelengths depending on the relative motion of the source and the observer.
- Observers looking at an object that is moving away from them see light that has a longer wavelength than it had when it was emitted (a red shift), while observers looking at an approaching source see light that is shifted to shorter wavelength (a blue shift).



Doppler Shift

•

a. Stationary Sound Source

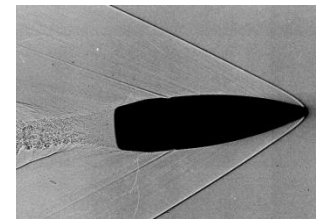
•

b. Source moving with $V_{\text{source}} < V_{\text{sound}}$

•



•



*c. Source moving with $V_{\text{source}} = V_{\text{sound}}$
(Mach 1 - breaking the sound barrier)*

*d. Source moving with $V_{\text{source}} > V_{\text{sound}}$
(Mach 1.4 - supersonic)*

Fundamentals of LDV

- Take the coordinate system to be at rest with respect to the medium, whose speed of light wave is c . There is a source s moving with velocity V_s and emitting light waves with a frequency f_s .
- There is a detector r moving with velocity V_r , and the unit vector from s to r is \mathbf{n} i.e. $\mathbf{r}_r - \mathbf{r}_s = \mathbf{n}|\mathbf{r}_r - \mathbf{r}_s|$

- Then the frequency f_r at the detector is found from

$$\frac{f_r}{f_s} = \frac{1 - \mathbf{n} \cdot \mathbf{v}_r / c}{1 - \mathbf{n} \cdot \mathbf{v}_s / c}$$

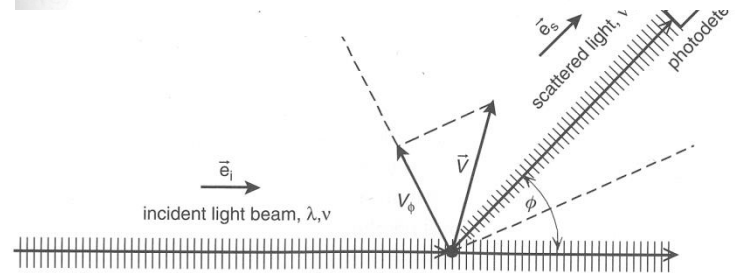
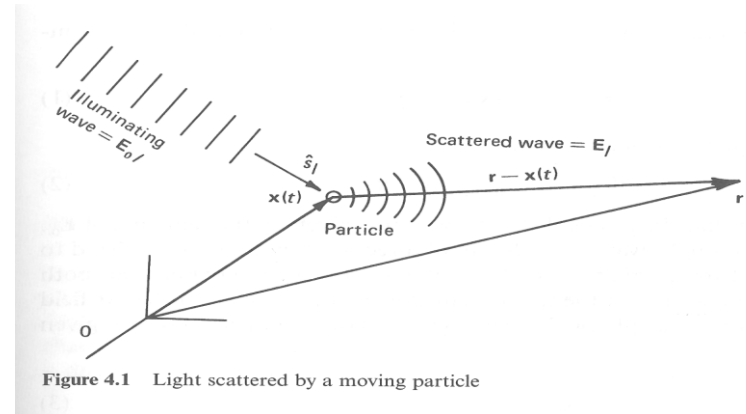
- If $c \gg V_s$, then the change in frequency depends mostly on the relative velocity of the source and detector.

$$\frac{f_r}{f_s} \approx 1 - \mathbf{n} \cdot (\mathbf{v}_r - \mathbf{v}_s) / c$$

$$\frac{\Delta f}{f_s} = \frac{f_r - f_s}{f_s} = -\hat{n} \cdot \frac{\vec{V}_r - \vec{V}_s}{c}$$

$$\left. \begin{array}{l} \hat{n} = \hat{e}_r - \hat{e}_i \\ V_r = 0 \end{array} \right\} \Rightarrow \frac{\Delta f}{f_s} = \frac{\vec{V}_s \cdot (\hat{e}_r - \hat{e}_i)}{c} = \frac{V_\phi \cdot 2 \sin(\frac{\phi}{2})}{c}$$

$$\Rightarrow \Delta f = \frac{V_\phi \cdot 2 \sin(\frac{\phi}{2}) f}{f \lambda} = \frac{V_\phi \cdot 2 \sin(\frac{\phi}{2})}{\lambda}$$



Fundamentals of LDV

- By using a laser beam of wavelength $\lambda=488\text{nm}$ (Argon-Ion laser), the maximum Doppler shift from a particle moving with a velocity of V would be:
 - $V=1.0\text{m/s}$ $\Delta f \approx 4.1\text{ MHz}$
 - $V=10.0\text{m/s}$ $\Delta f \approx 41\text{ MHz}$
 - $V=100.0\text{m/s}$ $\Delta f \approx 410\text{ MHz}$
 - $V=1000\text{m/s}$ $\Delta f \approx 4100\text{ MHz}$
- However, since $C = 2.998 \times 10^8\text{ m/s}$, $\lambda=488\text{nm}$, then, $f=c/\lambda = 1.4 \times 10^9\text{ MHz}$. the Doppler shift in frequency is very small compared with the frequency of the source laser light.
- In practice, it is always quit difficult to measure the Doppler shift of frequency accurately for low-speed flows by measuring the received total frequency directly.
- Dual-beam LDV technique was developed to measure the relative frequency change due to the Doppler shift other than the total frequency.

$$\Delta f = \frac{V_\phi \cdot 2 \sin(\frac{\phi}{2}) f}{f \lambda} = \frac{V_\phi \cdot 2 \sin(\frac{\phi}{2})}{\lambda}$$

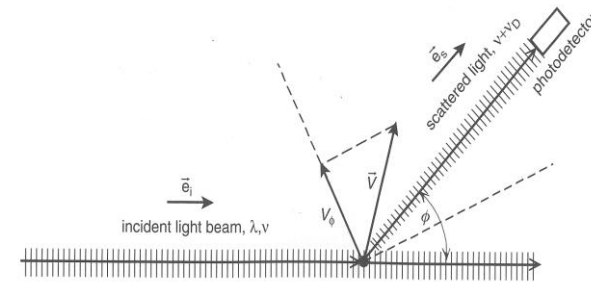
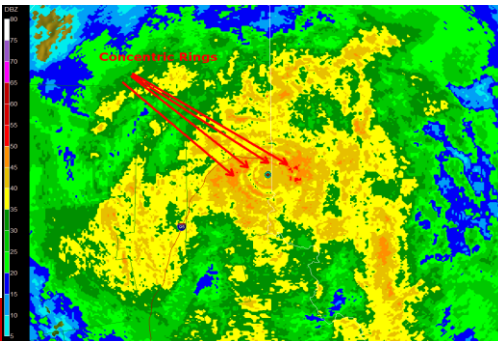


Figure 11.9. Sketch of a laser beam light scattered by a moving particle.



Fundamentals of Dual-Beam LDV

If the intensity of each scattered beam collected by the photo detector varies sinusoidal ,

$$A_i \sin 2\pi(f + \Delta f_i)t, \quad i = 1, 2.$$

Then, the optical mixing of these beams on the photodetector (heterodyning process) produces an output voltage E that is proportional to the square of the combined light intensity.

$$\begin{aligned} E &\sim \{A_1 \sin 2\pi(f + \Delta f_1)t + A_2 \sin 2\pi(f + \Delta f_2)t\} \\ &= A_1^2 \sin^2 2\pi(f + \Delta f_1)t + A_2^2 \sin^2 2\pi(f + \Delta f_2)t + 2A_1A_2[\sin 2\pi(f + \Delta f_1)t][\sin 2\pi(f + \Delta f_2)t] \\ &= A_1^2 \sin^2 2\pi(f + \Delta f_1)t + A_2^2 \sin^2 2\pi(f + \Delta f_2)t + A_1A_2[\cos 2\pi(\Delta f_1 - \Delta f_2)t - \cos 2\pi(2f + \Delta f_1 + \Delta f_2)t] \\ &= \underbrace{A_1^2 \sin^2 2\pi(f + \Delta f_1)t + A_2^2 \sin^2 2\pi(f + \Delta f_2)t - \cos 2\pi(2f + \Delta f_1 + \Delta f_2)t}_{\text{high-frequency}} + \underbrace{A_1A_2[\cos 2\pi(\Delta f_1 - \Delta f_2)t]}_{\text{low-frequency}} \end{aligned}$$

If we define, $\Delta f_1 - \Delta f_2 = f'$

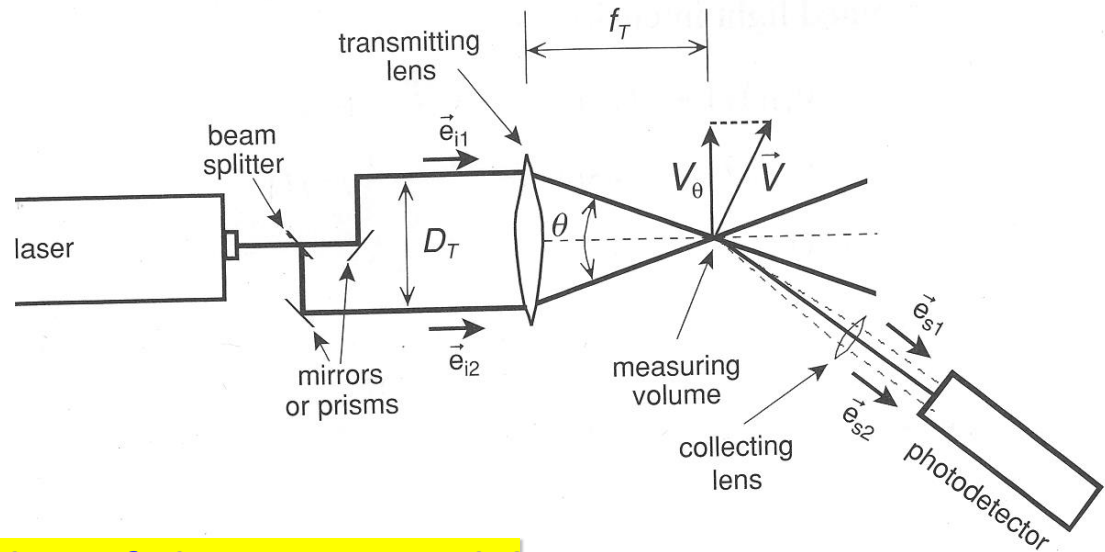
then: $E \sim a + b \sin 2\pi f' t$

$$f' = \Delta f_1 - \Delta f_2 = \frac{\vec{V} \cdot (\vec{e}_{s1} - \vec{e}_{i1})}{\lambda} - \frac{\vec{V} \cdot (\vec{e}_{s2} - \vec{e}_{i2})}{\lambda}$$

Since $\vec{e}_{i1} = \vec{e}_{i2}$,
then

$$\begin{aligned} f' &= \frac{\vec{V} \cdot (\vec{e}_{s1} - \vec{e}_{s2})}{\lambda} = \frac{2 \sin(\frac{\theta}{2})}{\lambda} V_\theta \\ \Rightarrow V_\theta &= \frac{\lambda}{2 \sin(\frac{\theta}{2})} f' \end{aligned}$$

- The above equation is independent of observation angle!**



Generated Fringes for the Dual-Beam LDV

Fring spacing :
$$\delta = \frac{\lambda}{2 \sin(\theta/2)}$$

Fring number :
$$N = \frac{4 D_T}{\pi d_e};$$

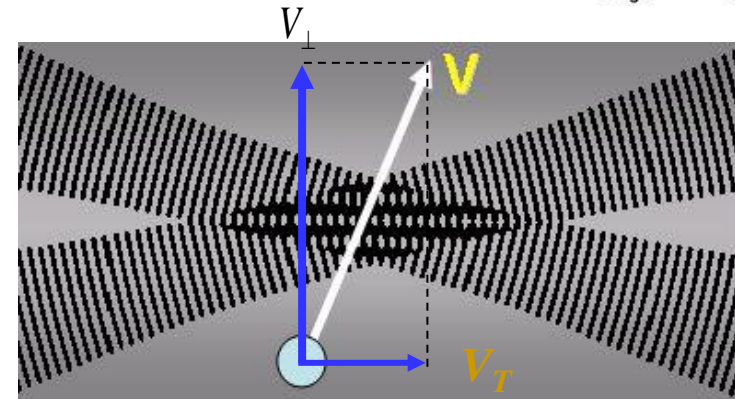
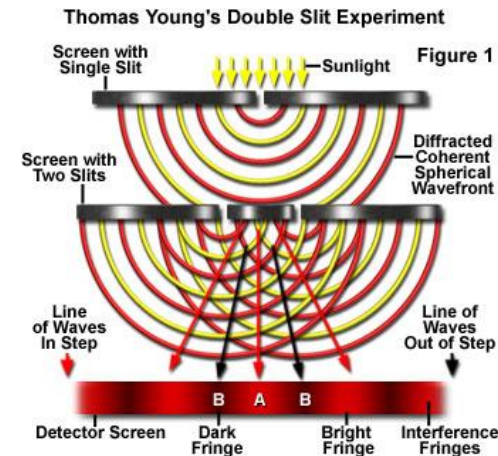
$$D_T = 2 f_T \sin(\theta/2)$$

Frequency of the scattering light :

$$f = \frac{V_{\perp}}{\delta} = \frac{2 \sin(\theta/2)}{\lambda} V_{\perp}$$

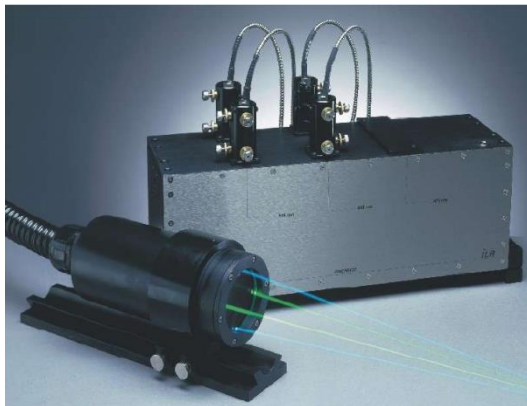
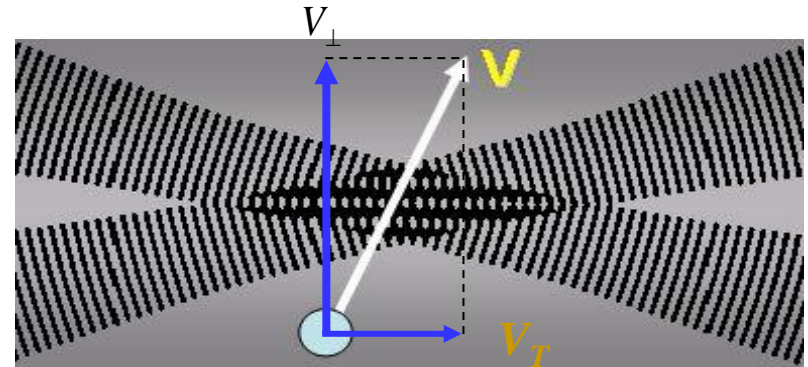
Frequency shift according to Doppler shift theory :

$$f = \frac{2 \sin(\theta/2)}{\lambda} V_{\perp}$$



2-component LDV systems

- *Dual-beam laser setup only can measure one component of the velocity with its direction normal to the fringe planes.*
- *Two-color LDV system can be used for 2-components of flow velocity measurements.*
 - *Ar-ion Laser beams*
 - *Blue (488nm)*
 - *Yellow (514.5 nm)*

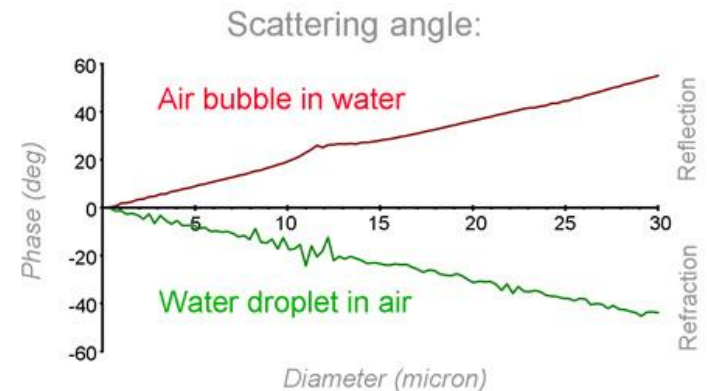
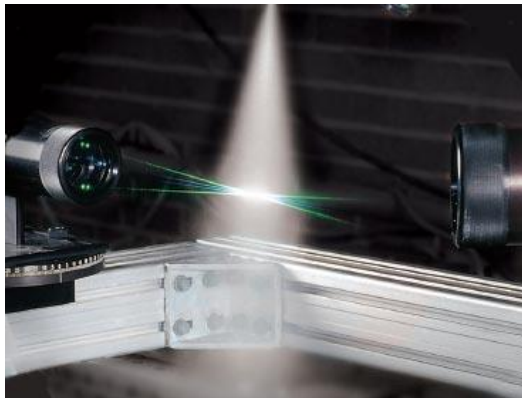
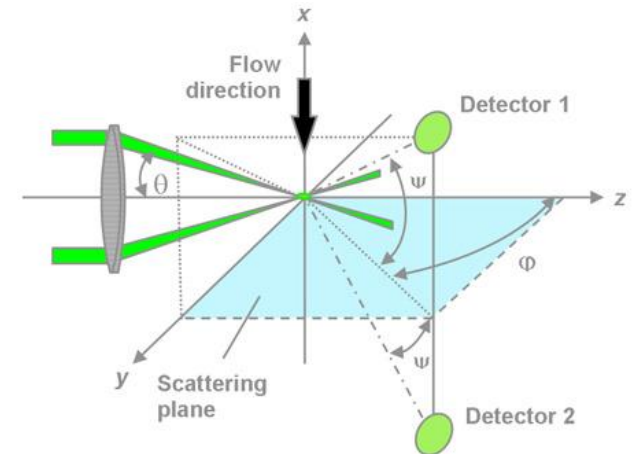


2-component LDV

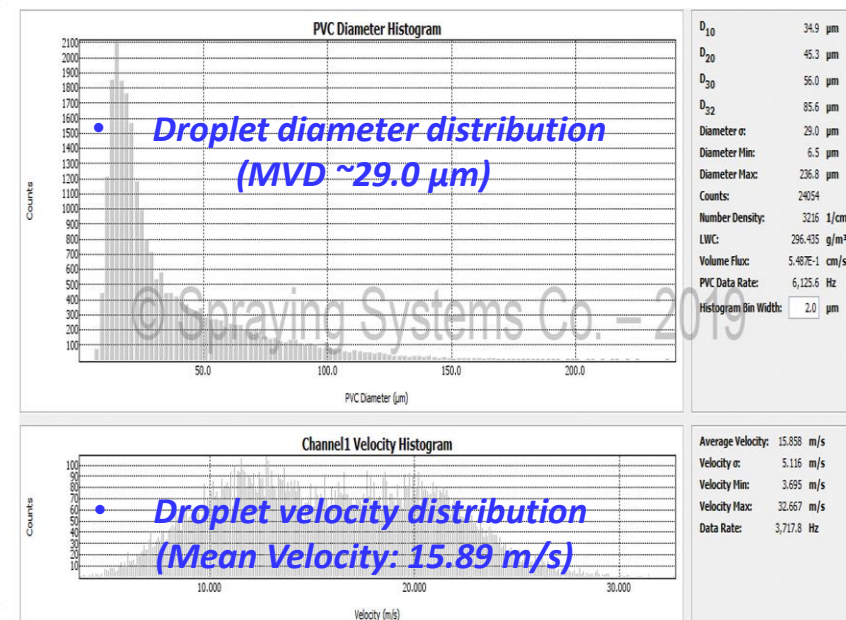
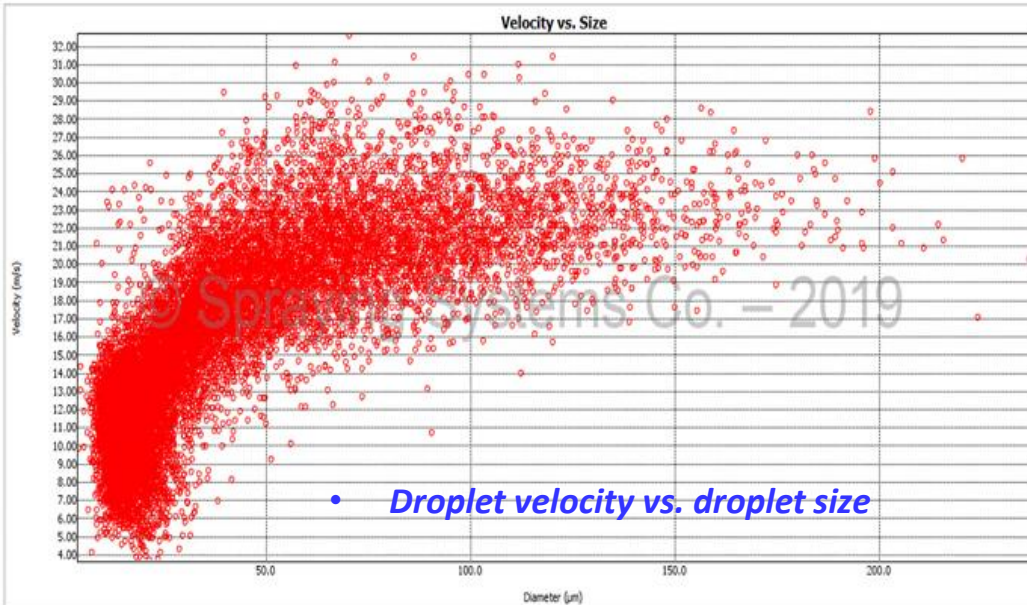
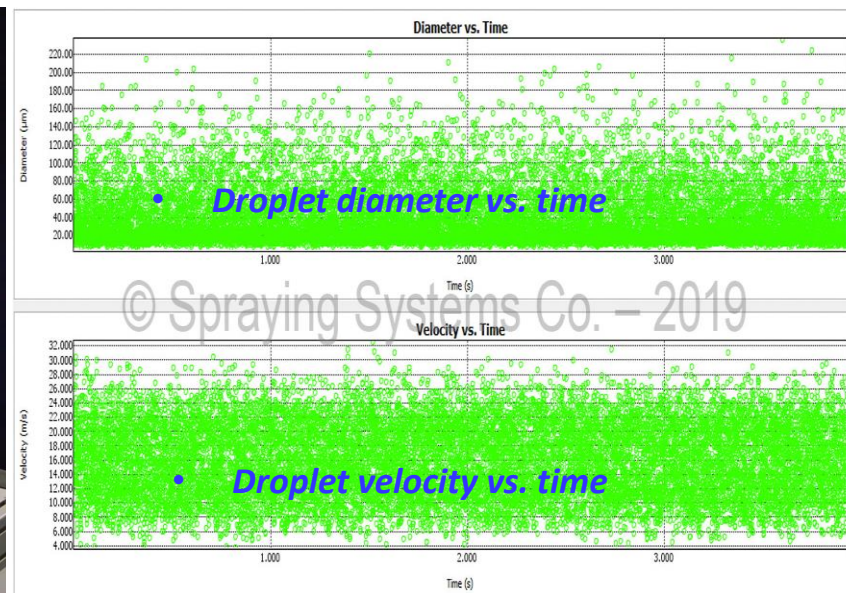
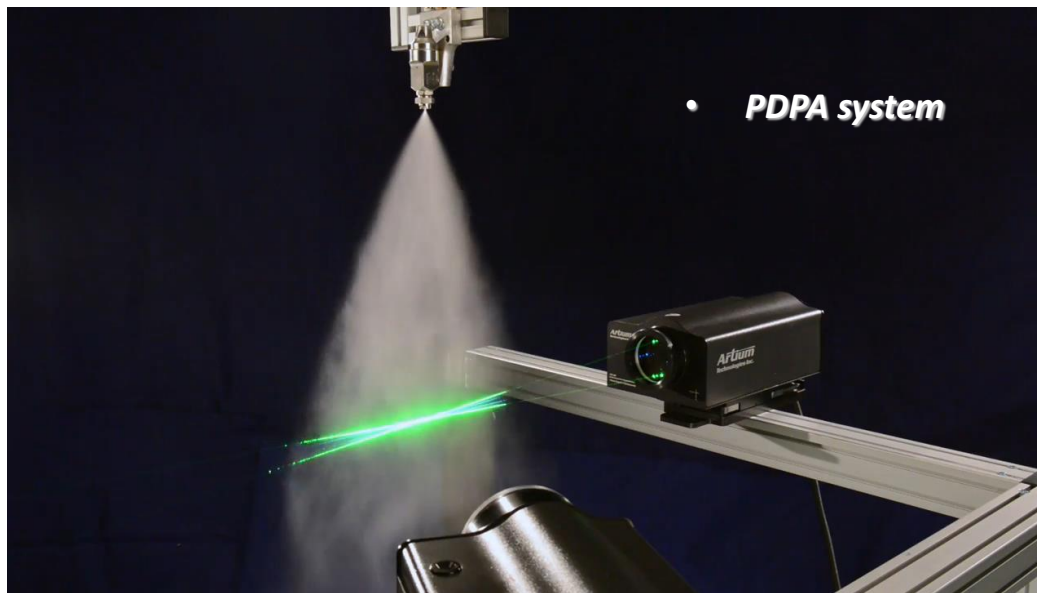


Phase Doppler Particle Analyzers/PDPA Systems

- As particles pass through the probe volume, they scatter light from the beams and create an interference fringe pattern.
- A receiving lens at an off-axis collection angle projects part of this fringe pattern onto detectors, which produce a Doppler burst signal with a frequency proportional to the particle velocity.
- The phase shift between the Doppler burst signals from the different detectors is proportional to the size of the spherical particles.



Phase Doppler Particle Analyzers/PDPA Systems



Particle-based Flow Diagnostic Techniques

□ Time-of-Flight method:

- Seeded the flow with small particles ($\sim \mu\text{m}$ in size)
- **Assumption**: the particle tracers move with the same velocity as local flow velocity!

$$\boxed{\begin{array}{c} \text{Flow velocity} \\ V_f \end{array}} = \boxed{\begin{array}{c} \text{Particle velocity} \\ V_p \end{array}}$$



• Smoke visualization



Measurement of
particle velocity

Particle Image Velocimetry (PIV) technique

- Time-of-flight method:** to measure the displacements of the tracer particles seeded in the flow in a fixed time interval.

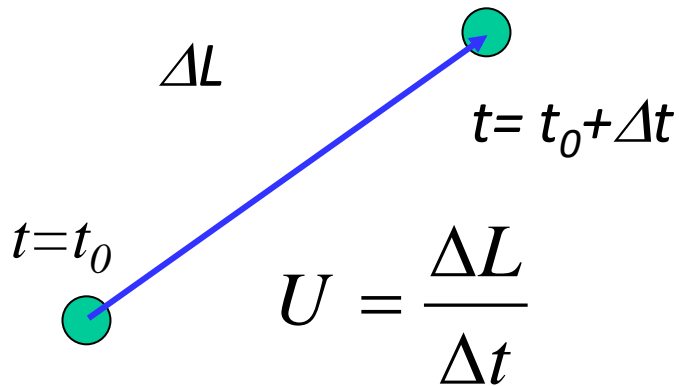
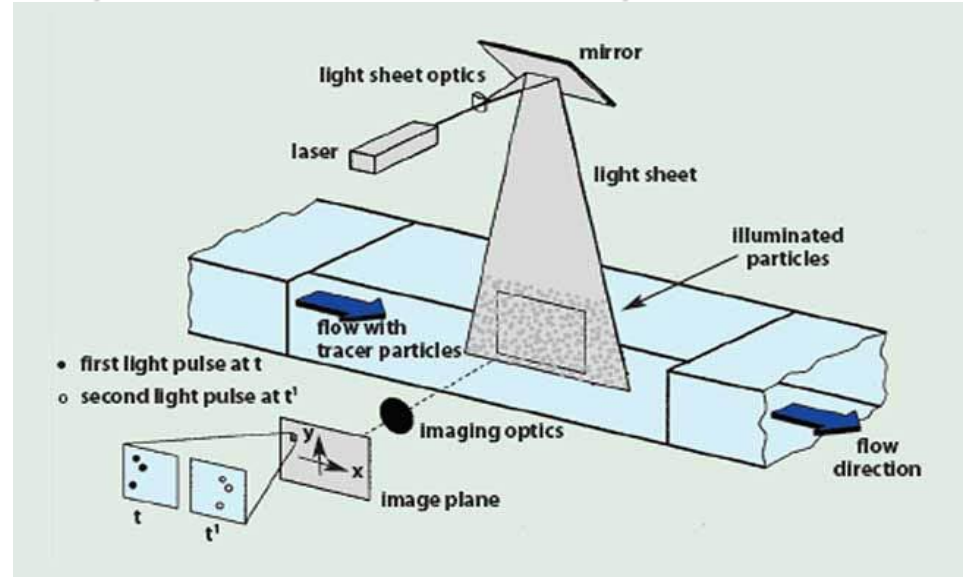


Diagram illustrating the time-of-flight method. A particle (green circle) moves from position $t=t_0$ to position $t=t_0+\Delta t$ over a distance ΔL . The velocity U is calculated as:

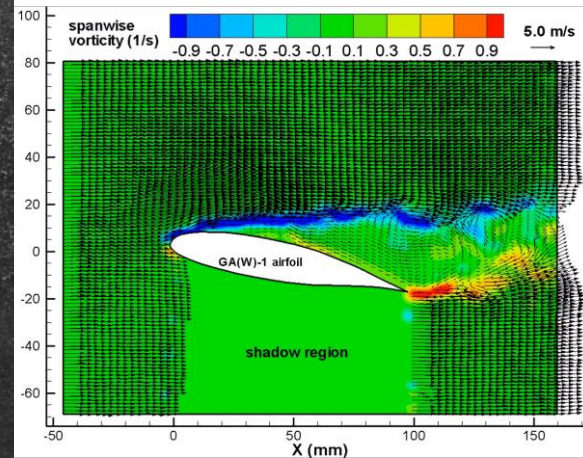
$$U = \frac{\Delta L}{\Delta t}$$



a. $T=t_0$



b. $T=t_0+10\mu s$

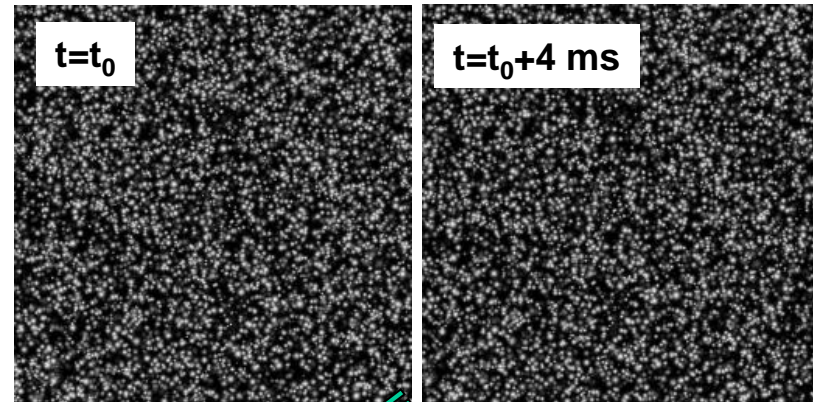


Corresponding Velocity field

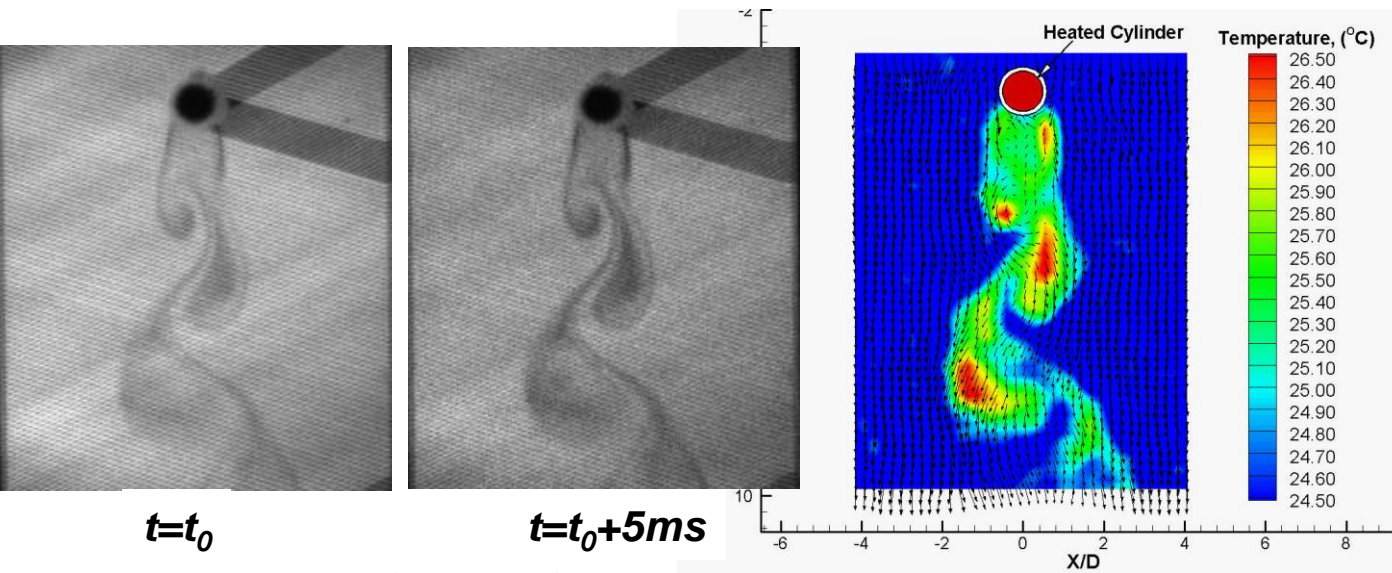
Methods to Measure Local Flow Velocity - 5

• Marker tracing methods:

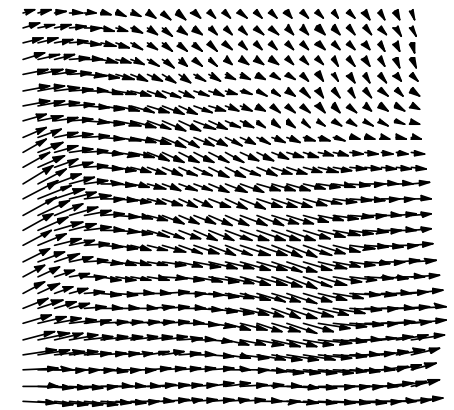
- Trace the motion of suitable flow makers, optically or by other means to derive local flow velocity.
- Particle Imaging Velocimetry (PIV)
- Particle Tracking Velocimetry (PTV)
- Molecular Tagging Velocimetry (MTV)



PIV image pair

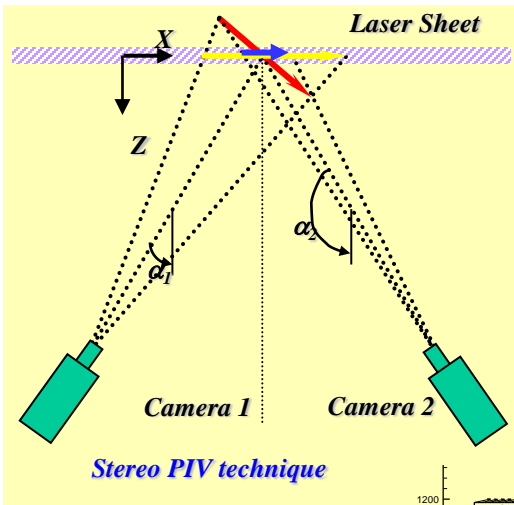


MTV&T image pair



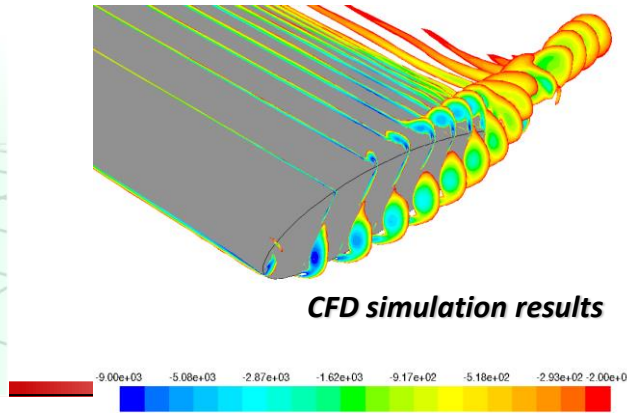
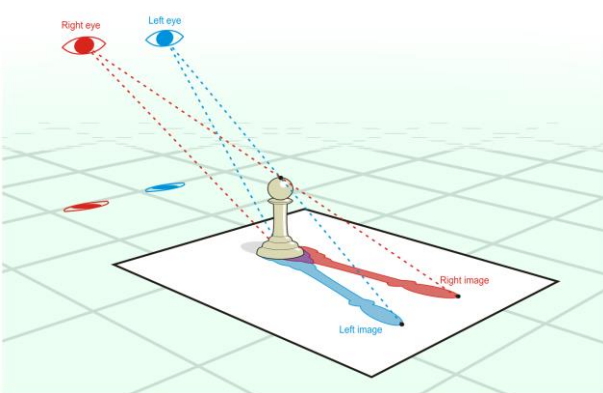
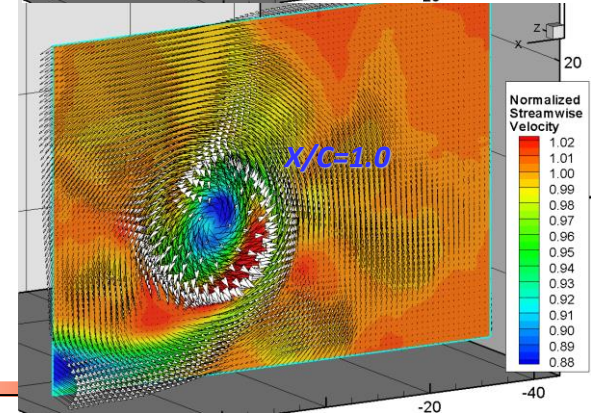
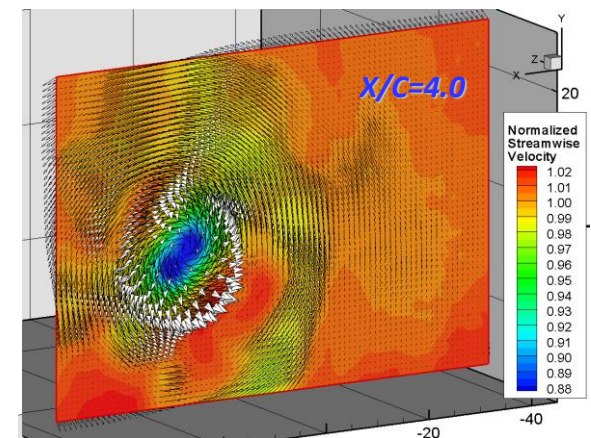
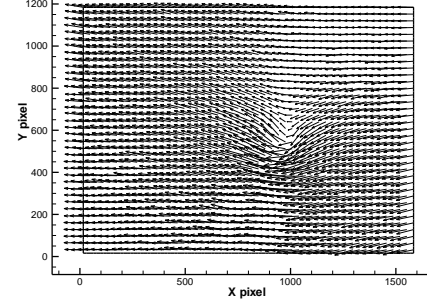
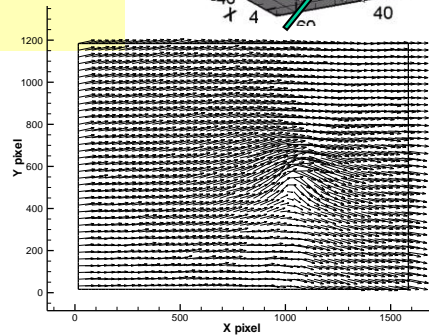
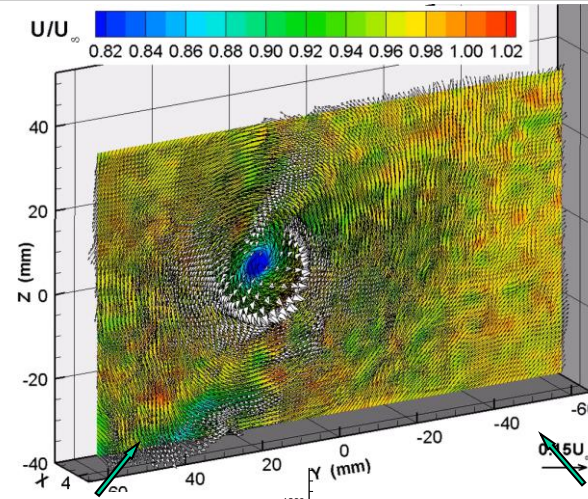
Corresponding flow velocity field

Stereoscopic PIV Measurements of a Wing-Tip Vortex (Funded by AFOSR)



$Re_C = 52,000; \alpha = 5.0 \text{ deg.}$

$X/C = 4.0$



Lab#04 Measurements of Pressure Distributions around a Circular Cylinder

▪ Flow Around a Circular Cylinder

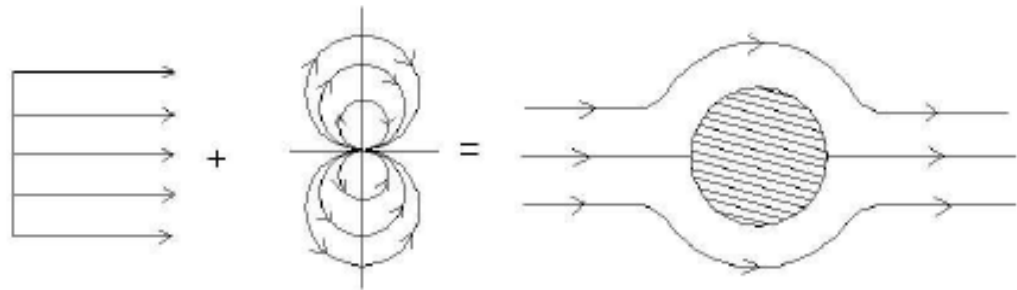
- ***uniform flow + a 2-D doublet = flow around a circular cylinder***
- ***Stagnation points***
- ***Pressure coefficient on the surface of cylinder***

$$\psi = V_{\infty} r \sin \theta \left(1 - \frac{R^2}{r^2}\right)$$

$$\phi = V_{\infty} r \cos \theta \left(1 + \frac{R^2}{r^2}\right)$$

$$V_r = V_{\infty} \cos \theta \left(1 - \frac{R^2}{r^2}\right)$$

$$V_{\theta} = -V_{\infty} \sin \theta \left(1 + \frac{R^2}{r^2}\right)$$



Lab#04 Measurements of Pressure Distributions around a Circular Cylinder

- At the surface of the cylinder,

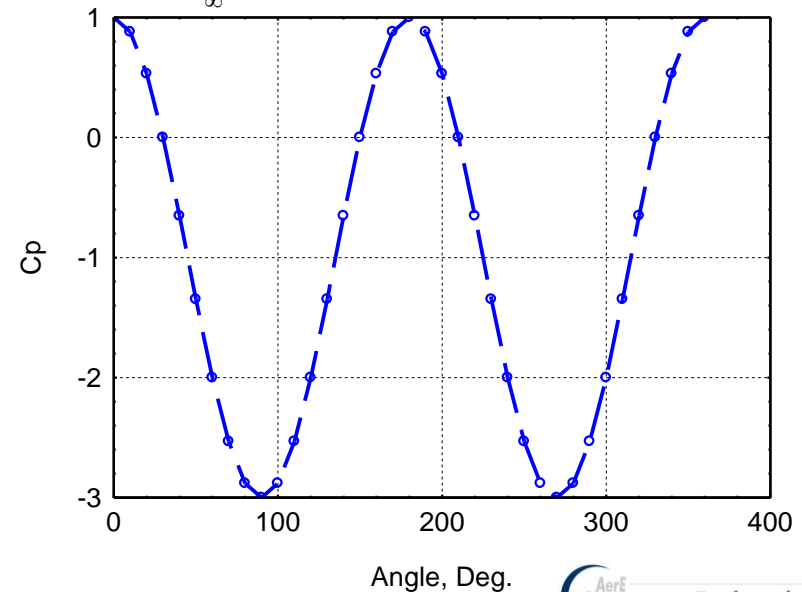
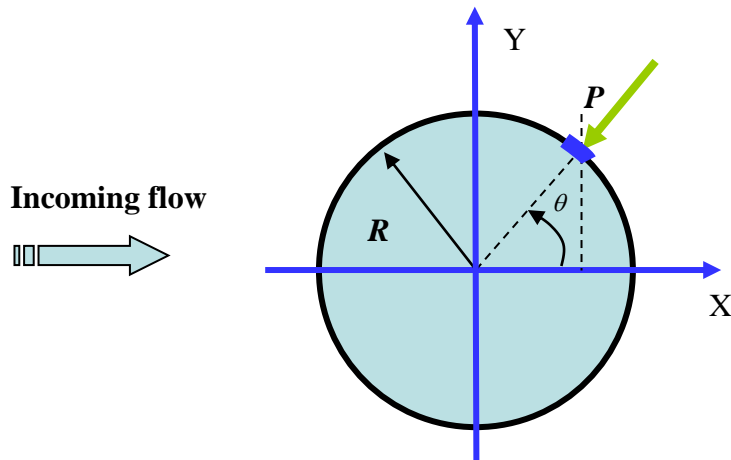
$$r = a \Rightarrow \begin{cases} V_r = 0 \\ V_\theta = -2V_\infty \sin \theta \end{cases}$$

- According to Bernoulli's equation

$$P + \frac{1}{2}\rho V^2 = P_\infty + \frac{1}{2}\rho V_\infty^2 \Rightarrow \frac{P - P_\infty}{\frac{1}{2}\rho V_\infty^2} = 1 - \frac{V^2}{V_\infty^2}$$

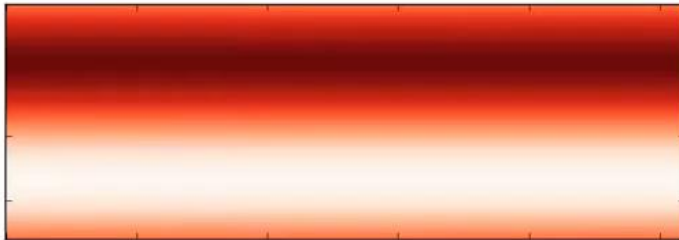
- Pressure coefficient distribution on the surface of the circular cylinder will be:

$$C_p = \frac{P - P_\infty}{\frac{1}{2}\rho V_\infty^2} = 1 - \frac{V^2}{V_\infty^2} = 1 - \frac{(-2V_\infty \sin \theta)^2}{V_\infty^2} = 1 - 4\sin^2 \theta$$

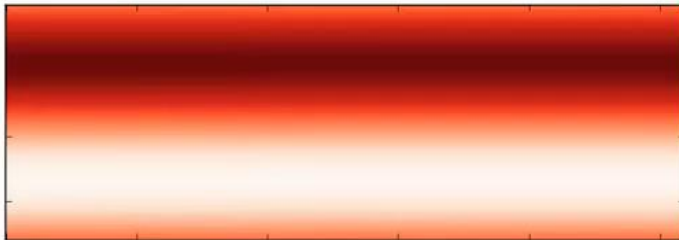


Pressure Distribution around a Circular Cylinder

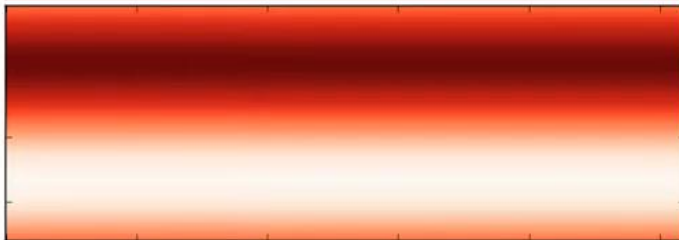
Re = 25



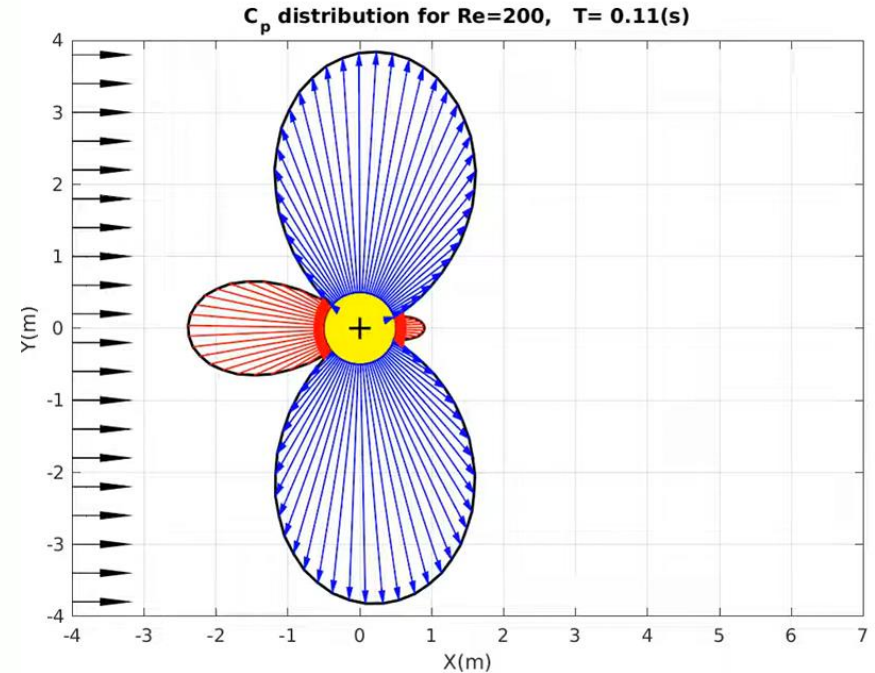
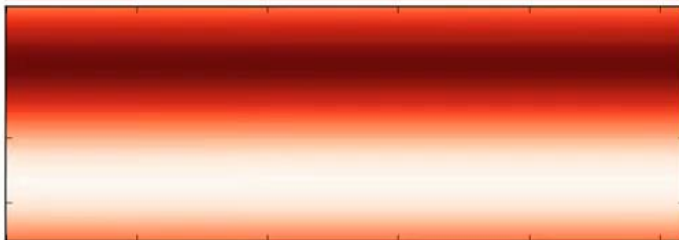
Re = 50



Re = 100

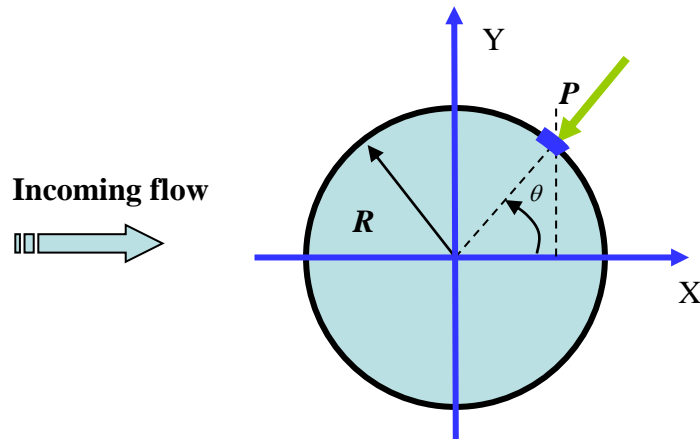
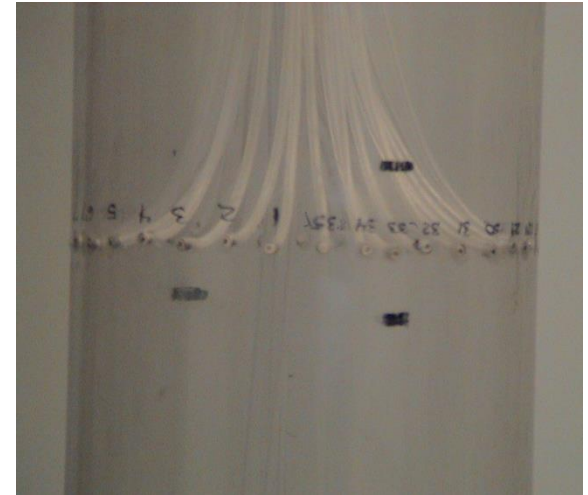


Re = 220



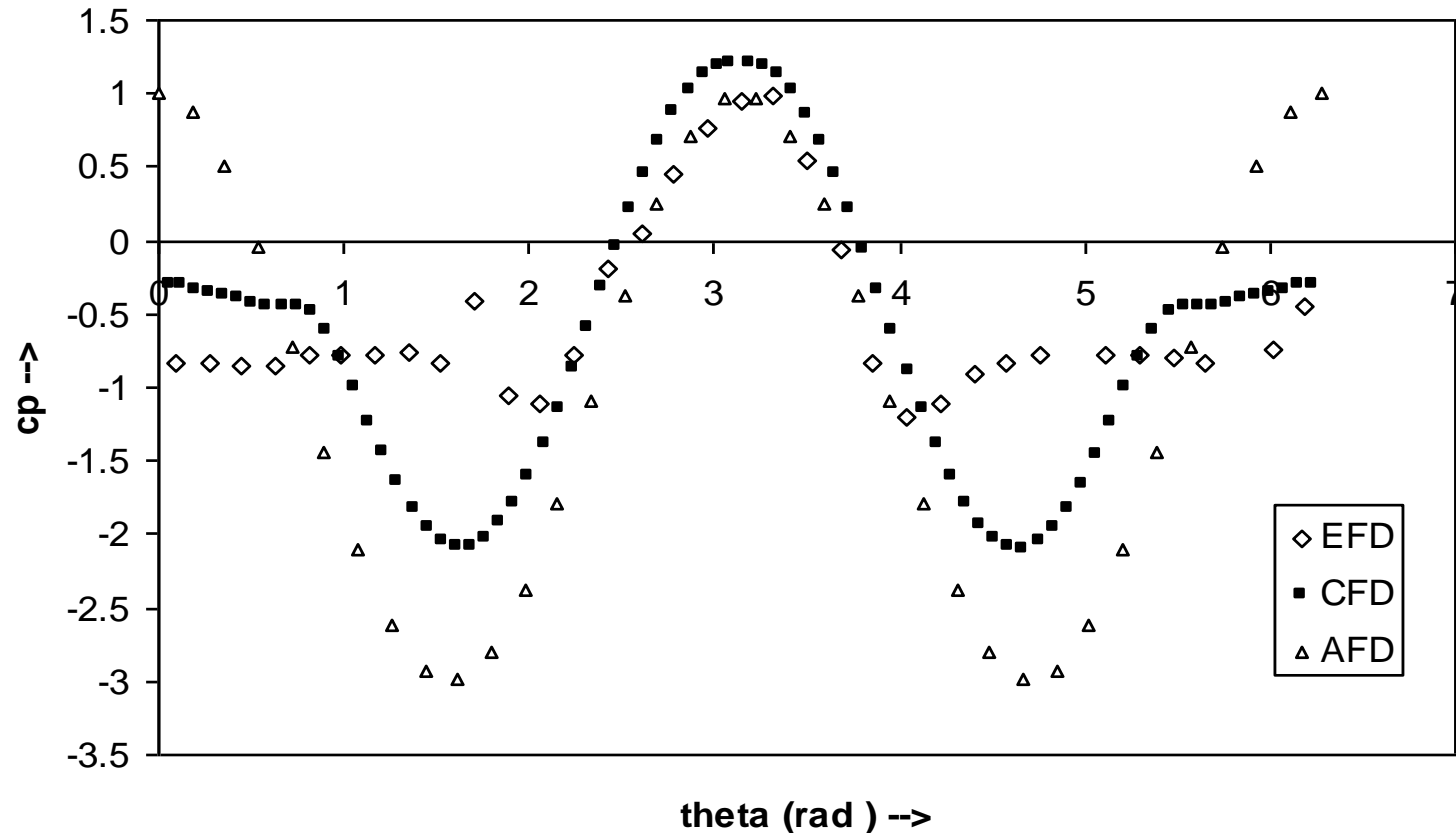
- Numerical results for the velocity magnitude and pressure distributions over a circular cylinder using FlowLab*

Lab#04 Measurements of Pressure Distributions around a Circular Cylinder



DSA3217 (Shown)

Lab#04 Measurements of Pressure Distributions around a Circular Cylinder



C_p distributions over a circular cylinder

REQUIRED RESULTS FOR THE LAB REPORT

- *To make a table showing all the time-averaged data you obtained for all the cases you tested.*
- *To show all the calculation steps leading up to the final answer.*
- *To plot pressure coefficient (C_p) distributions on the cylinder from for all the cases you tested.*
- *To make comments on the characteristics of the pressure distribution compared with the theoretic predictions.*
- *To calculate the drag coefficients (C_d) of the circular cylinder for all the cases you tested.*
- *To plot the drag coefficients (C_d) of the circular cylinder as a function of at the Reynolds numbers.*