Lecture # 05: Velocimetry Techniques and Instrumentation

Dr. Hui Hu

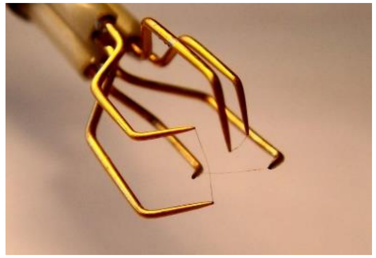
Department of Aerospace Engineering
Iowa State University
Ames, Iowa 50011, U.S.A

Feedback from In-class Quiz #01

- ***Concerns about the final exam since no previous experience on lab class before.***
- ***Discuss information related to the lab the week before.***
- ***Some lab instructions are confusing and hard to determine what equations to use.***
- ***More streamlined communication between students, TA and professor.***
- ***More in the lab work.***
- ***Leadership rotation activity is interesting.***
- ***Like the website with everything in one place.***
- ***Wait to list groups until after the first week or before the first lab.***
- ***Having some more help resources to complete the pre-labs.***
- ***Is there a schedule for quizzes?***

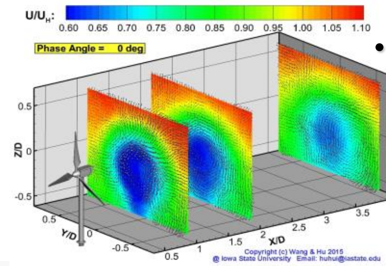
❑ Various measurement Techniques for Thermo-Flow Studies

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

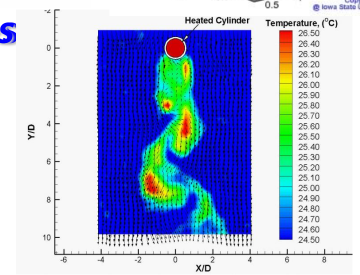


• **Hotwire probe**

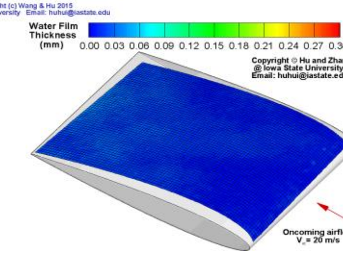
• **Thermocouples**



• *Stereoscopic PIV*



• *MTV & MTT*



• *DIP measurements*

Thermal-Fluids measurement techniques →

- **Intrusive techniques** →
  - Pitot probe
  - hotwire, hot film
  - thermocouples
  - etc...
- **Non-intrusive techniques** →
  - **particle-based techniques** →
    - *Laser Doppler Velocimetry (LDV)*
    - *Planar Doppler Velocimetry (PDV)*
    - *Particle Image Velocimetry (PIV)*
    - *etc...*
  - **molecule-based techniques** →
    - *Laser Induced Fluorescence (LIF)*
    - *Molecular Tagging Velocimetry (MTV)*
    - *Molecular Tagging Therometry (MTT)*
    - *Digital Image Projection (DIP)*
    - *Pressure Sensitive Paint (PSP)*
    - *Temperature Sensitive Paint (TSP)*
    - *Quantum Dot Imaging*
    - *etc ...*

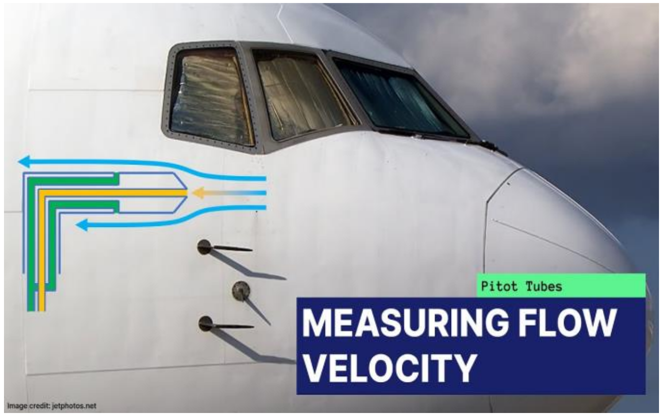
Flow velocity V_f = Velocity of particles or molecule Tracers, V_{tracer}

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

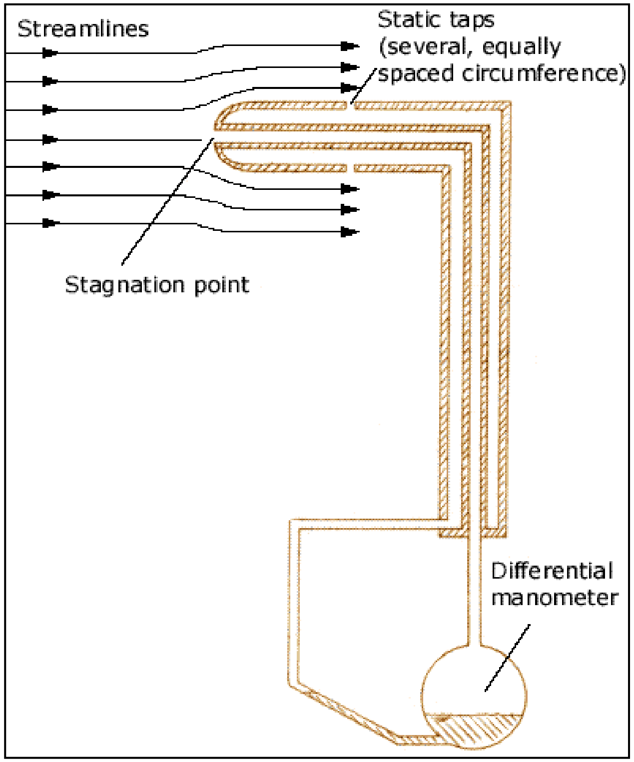
Methods to Measure Local Flow Velocity -2

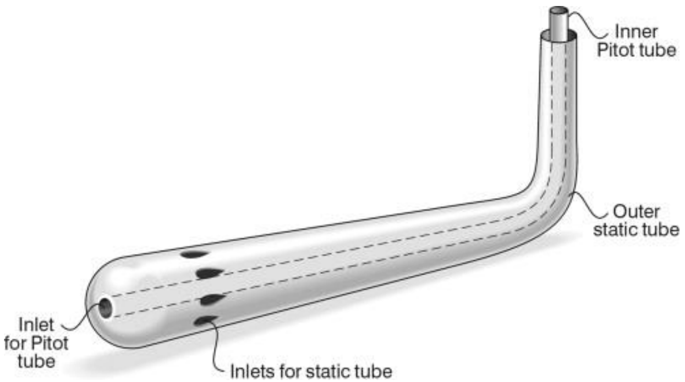
- *Pressure difference methods:*
  - Utilize analytical relationship between the local velocity and the static and total pressures
  - The tubes sensing static and stagnation pressures are usually combined into one instrument known as *Pitot- static tube*.

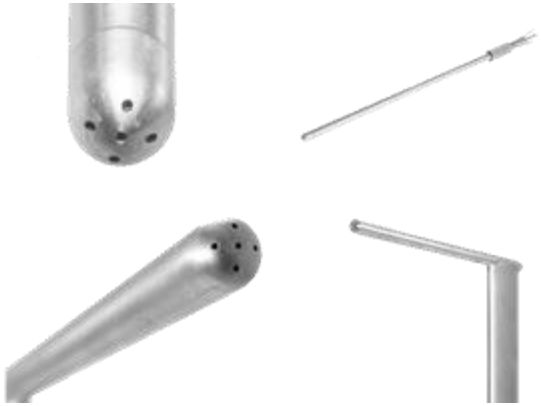


Wing mounted Pitot Tube on a Cessna 172

https://commons.wikimedia.org/wiki/File:Cessna_172_Skyhawk_II_-_Pitot_tube.jpg







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

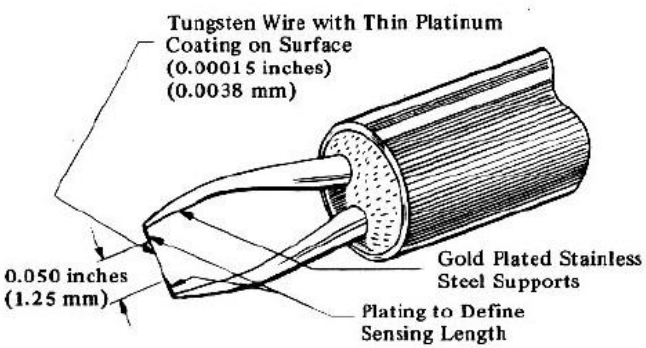
$$V = \sqrt{2(p_0 - p_{stat})/\rho}$$

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

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

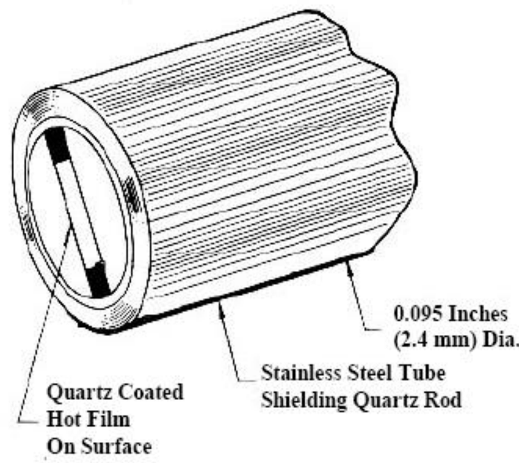


Figure 6: Hot Film Flush Mounted Probe

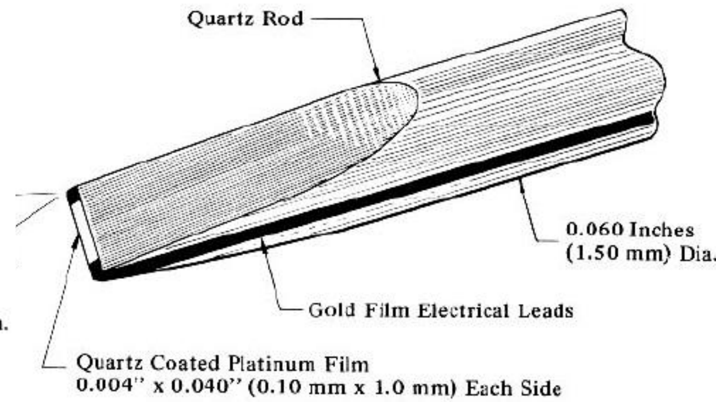
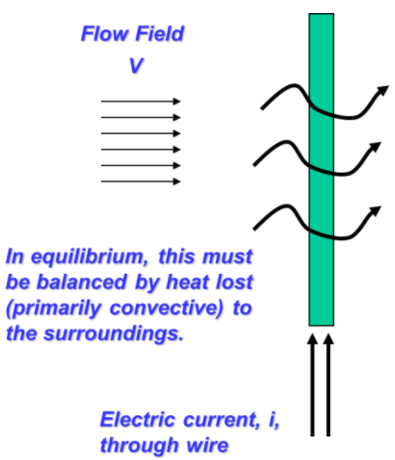
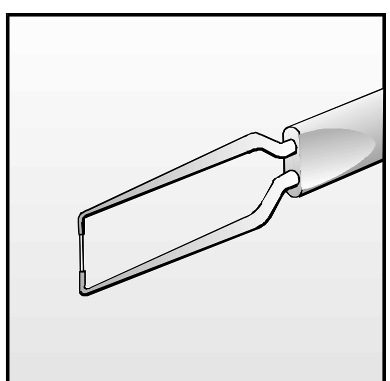
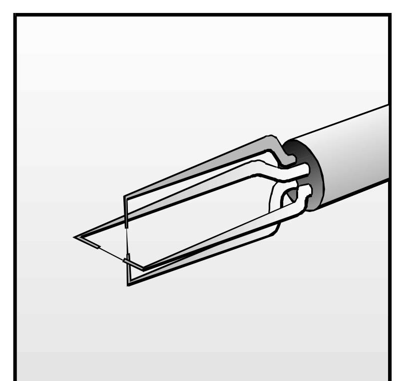
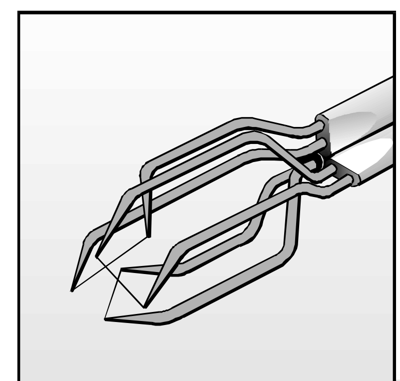


Figure 7: Hot Film Wedge Probe









Particle-based Flow Diagnostic Techniques

- *Seeded the flow with small particles (~ μm in size)*

- ***Assumption**: the particle tracers move with the same velocity as local flow velocity!*

Flow velocity V_f = **Particle velocity V_p**

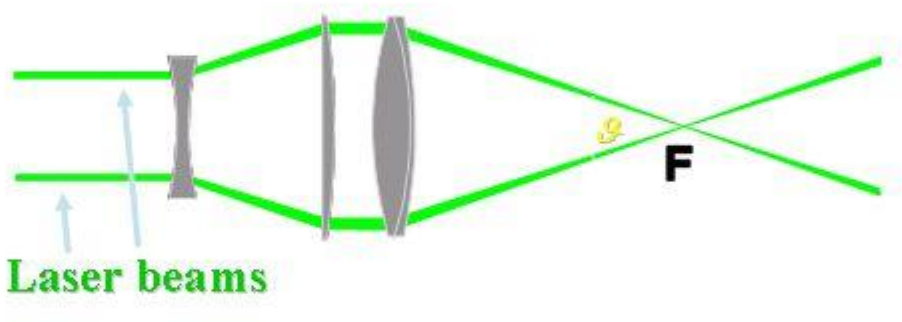
↑

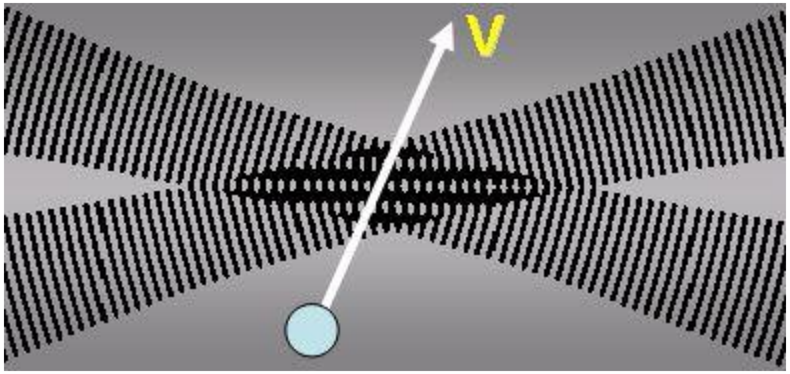
Measurement of particle velocity

Methods to Measure Local Flow Velocity - 4

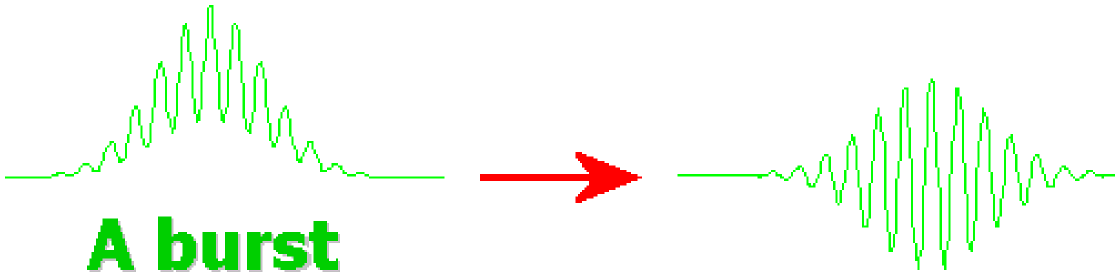
❑ *Frequency-shift methods:*

- *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)*





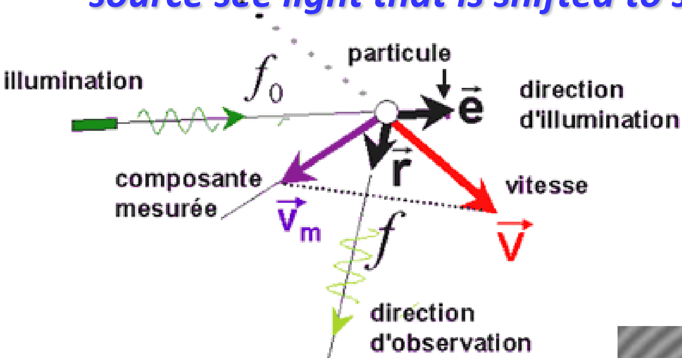
Interference fringes

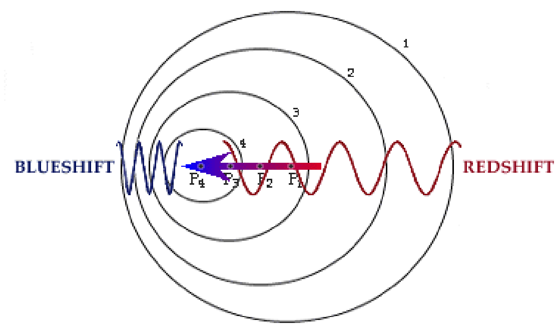


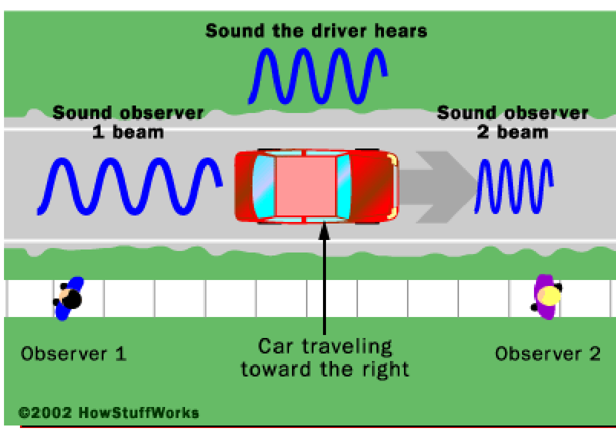
$$v_{\perp} = \frac{\lambda}{2\sin\frac{\vartheta}{2}} f$$

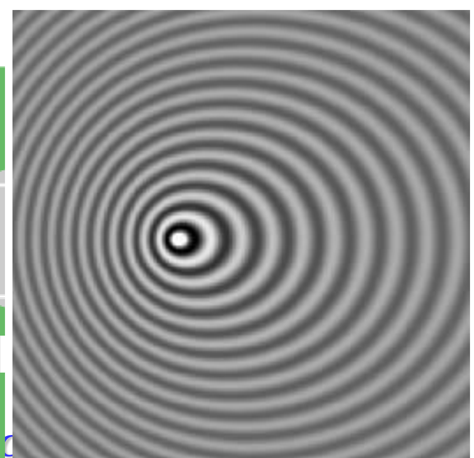
Doppler Shift

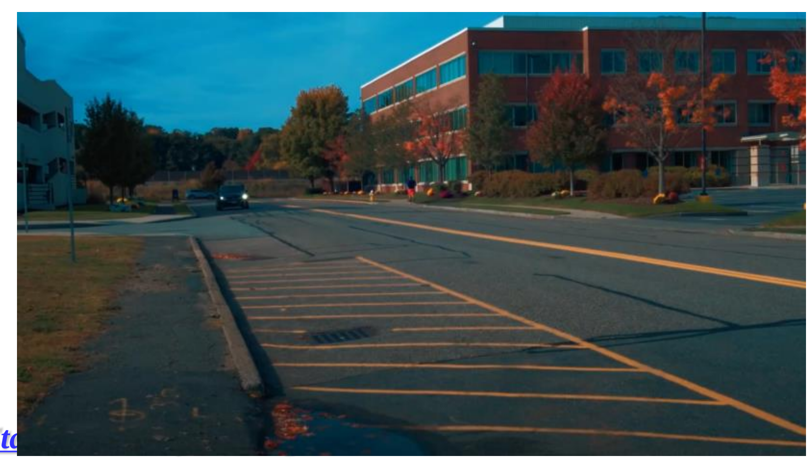
- *The Doppler effect, named after* Christian Doppler (an Austrian mathematician and physicist), *is the change in frequency and wavelength of a wave that is perceived by an observer moving relative to the source of the waves.*
- *Light from moving objects will appear to have different wavelengths depending 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).*









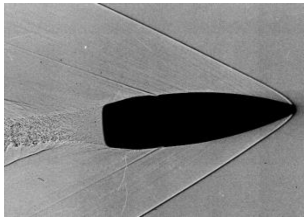


Doppler Shift

a. Stationary Sound Source

b. Source moving with Vsource < Vsound

c. Source moving with Vsource = Vsound
(Mach 1 - breaking the sound barrier)



d. Source moving with Vsource > Vsound
(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 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.*

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

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

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

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

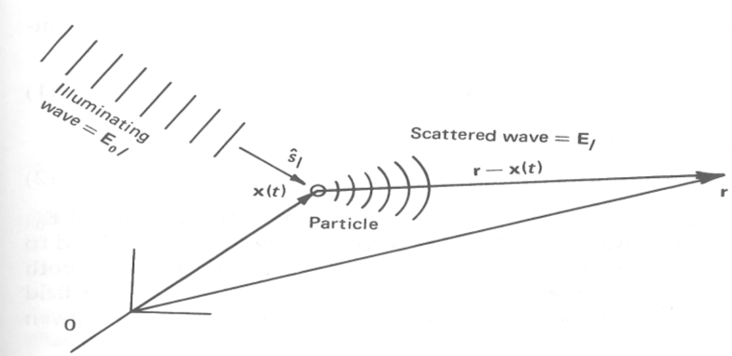


Figure 4.1 Light scattered by a moving particle

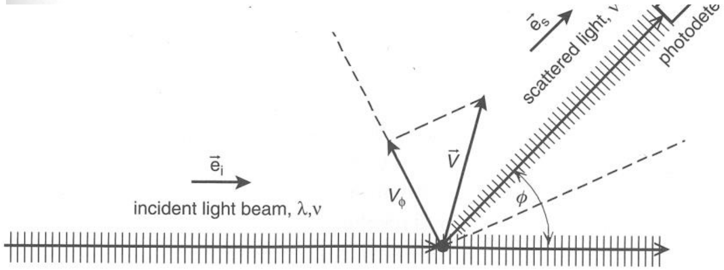


Figure 11.9. Sketch of a laser beam light scattered by a moving particle.

https://www.youtube.com/watch?v=JxfWi85l0hg

Fundamentals of LDV

- *By using a laser bean of wavelength λ=488nm (Argon-Ion laser), the maximum Doppler shift from a particle moving with a velocity of V would be:*
  - *V=1.0m/s $\Delta f \approx$ 4.1 MHz*
  - *V=10.0m/s $\Delta f \approx$ 41 MHz*
  - *V=100.0m/s $\Delta f \approx$ 410 MHz*
  - *V=1000m/s $\Delta f \approx$ 4100 MHz*

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

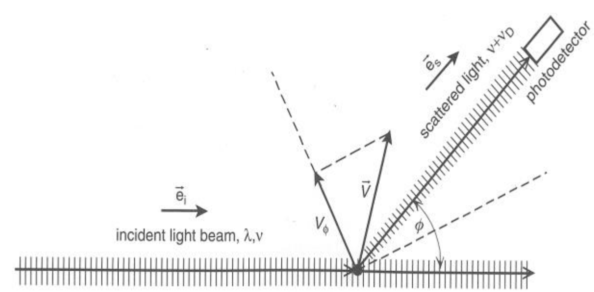
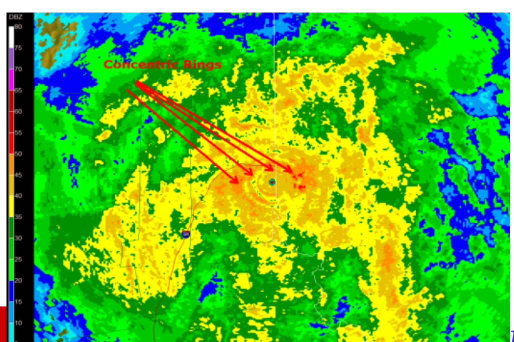


Figure 11.9. Sketch of a laser beam light scattered by a moving particle.

- *However, since C = 2.998×10^8 m/s, λ=488nm, then, f=c/ λ= 1.4 ×10^9 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.*



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 photoditec tor (heterodyn ing process) produces an output vol tage E that is proportion al to the squire of the combined light intensity.

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

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

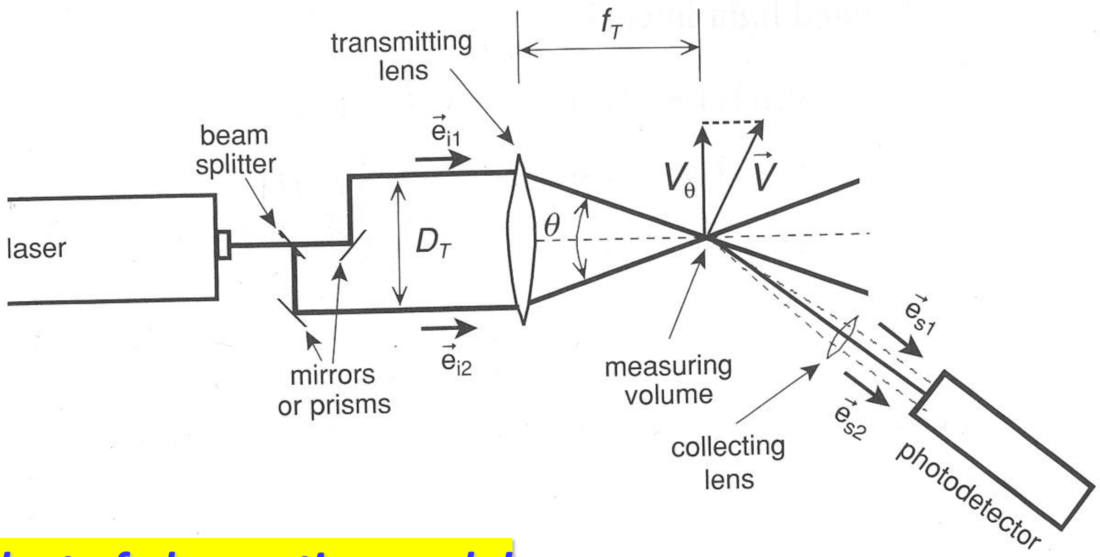
$$then: E \sim a + b\sin 2\pi f' t$$

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

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

$$f' = \frac{\vec{V}\cdot(\vec{e}_{i2}-\vec{e}_{i1})}{\lambda} = \frac{2\sin(\frac{\theta}{2})}{\lambda} V_\theta$$

$$\Rightarrow V_\theta = \frac{\lambda}{2\sin(\frac{\theta}{2})} f'$$



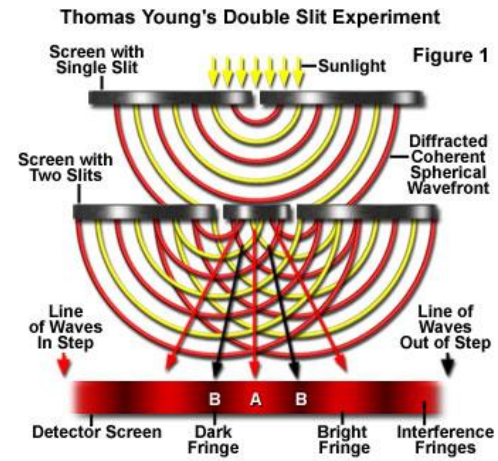
- ***The above equation is independent of observation angle!***

Generated Fringes for the Dual-Beam LDV

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

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

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

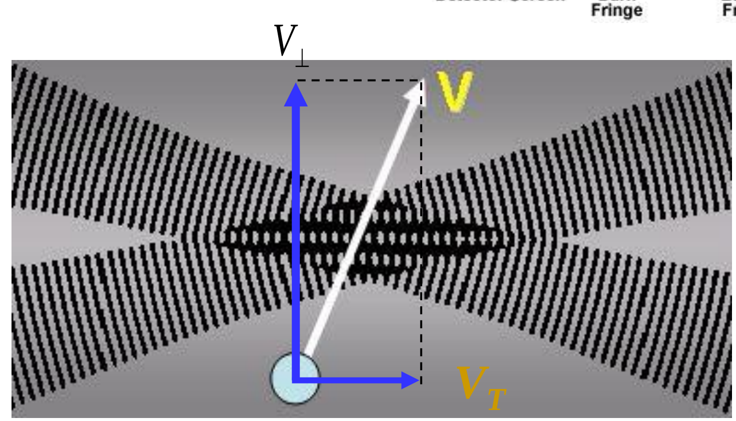


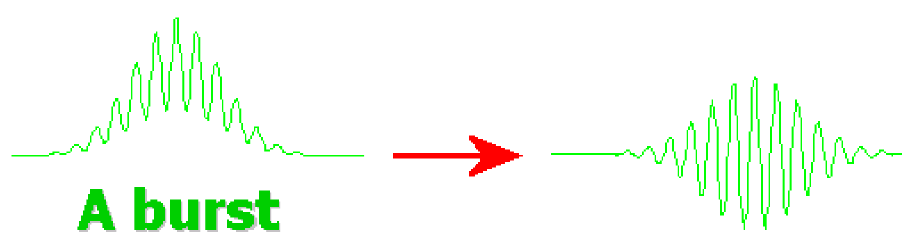
Frequency of the scattering light :

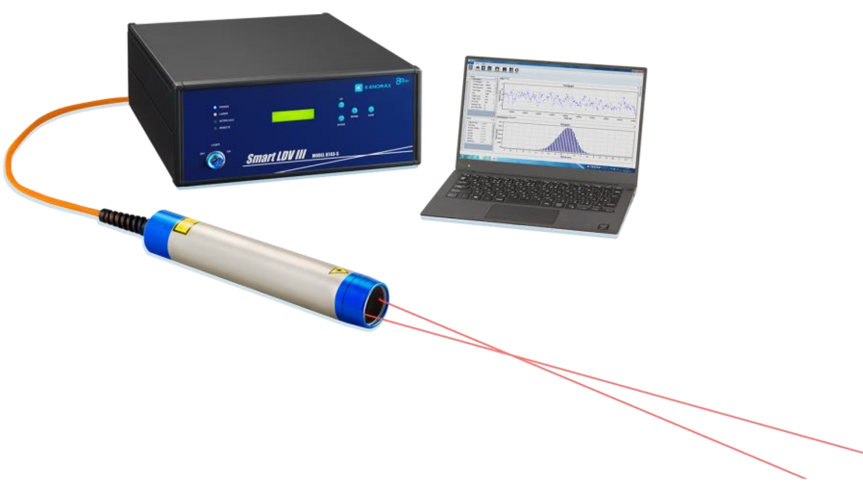
$$f = \frac{V_\perp}{\delta} = \frac{2\sin(\theta/2)}{\lambda} V_\perp$$

Frequency shift according to Doppler shift theo ry :

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



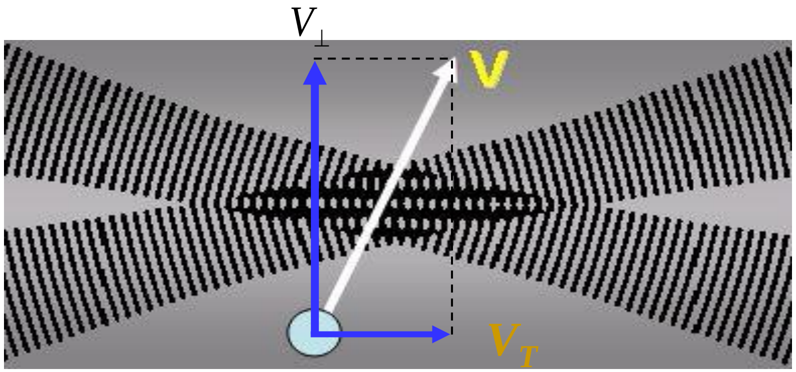


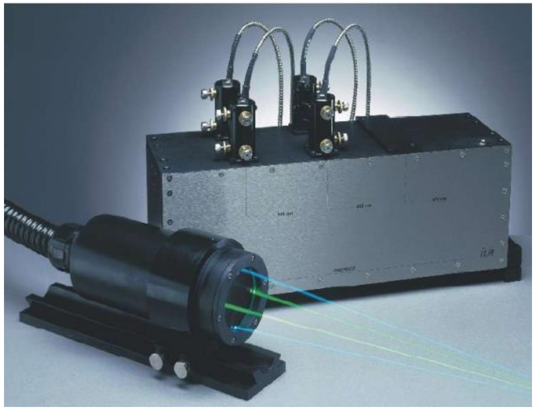


2-component LDV systems

- 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)

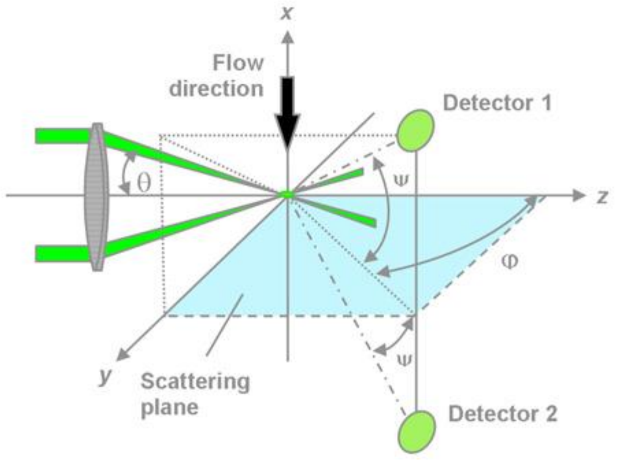


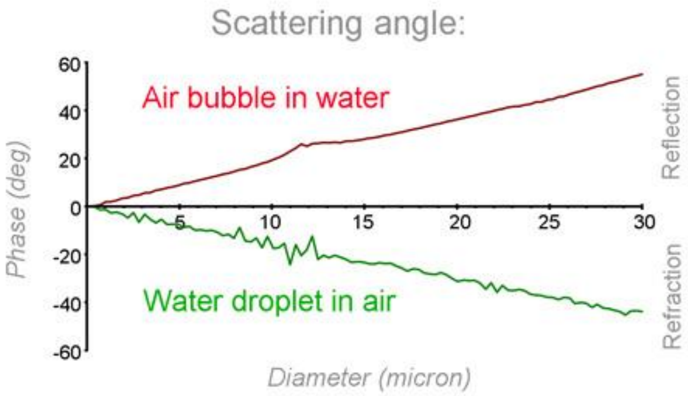


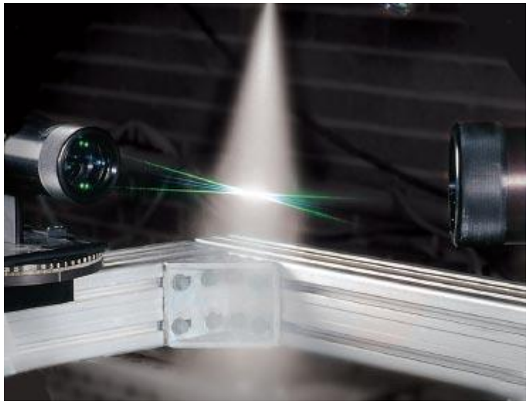
2-component LDV

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.*

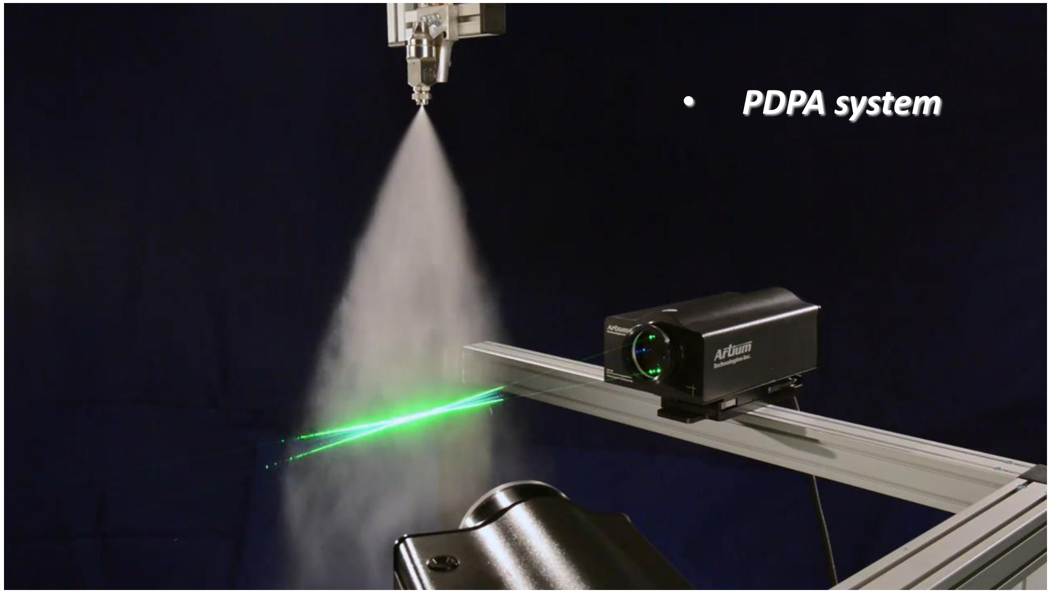


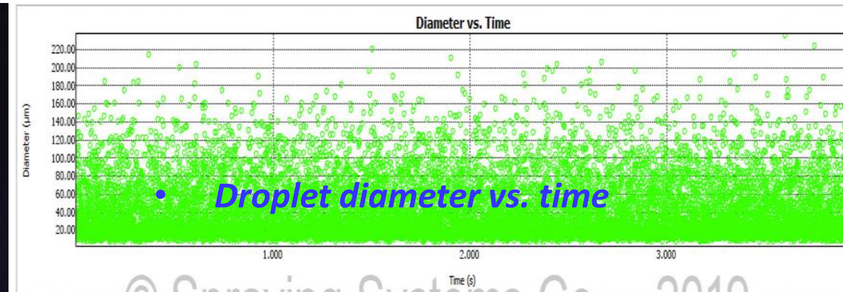


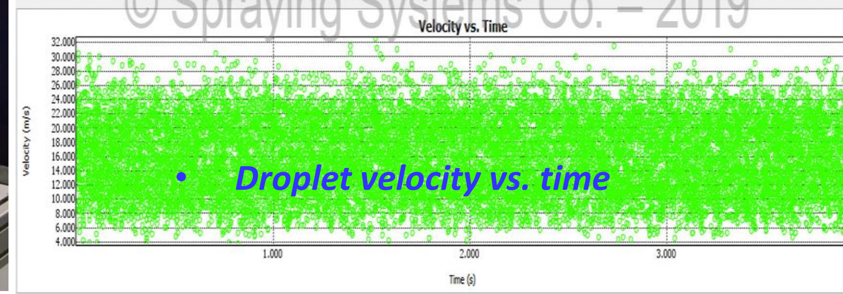


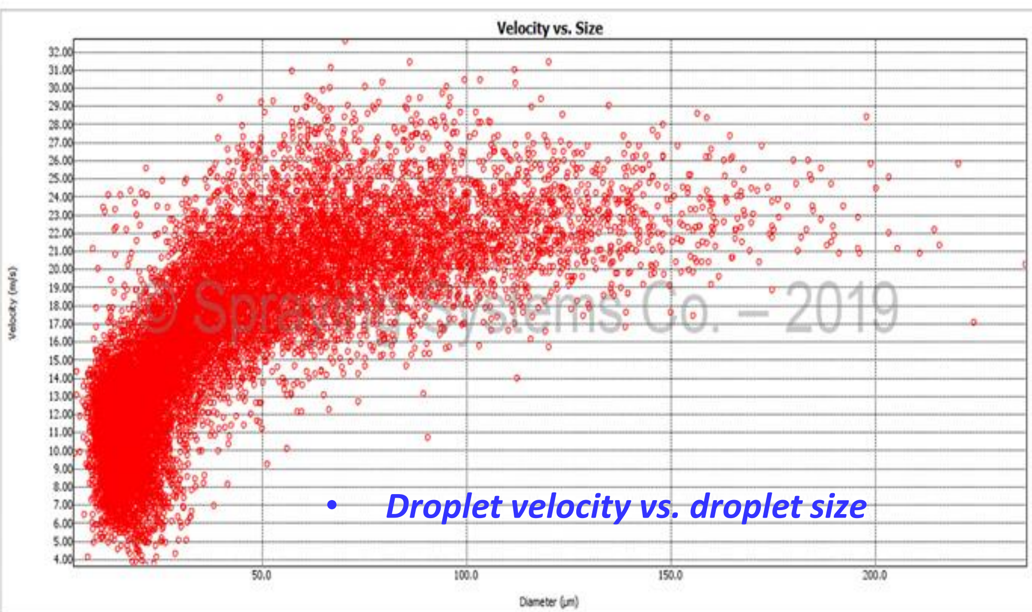
PDPA system

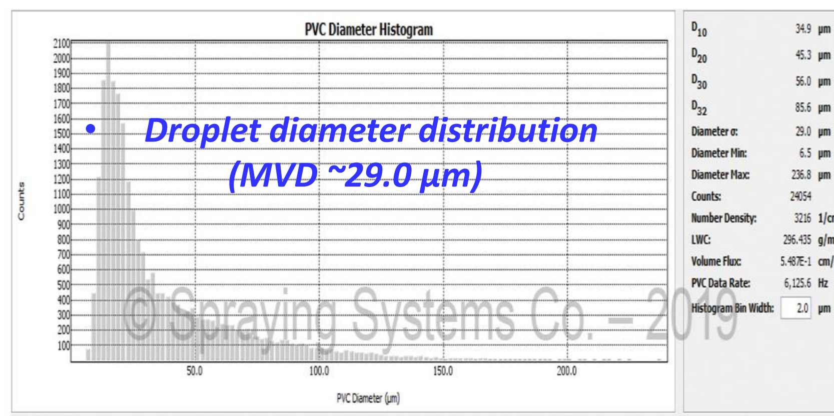
Phase Doppler Particle Analyzers/PDPA Systems

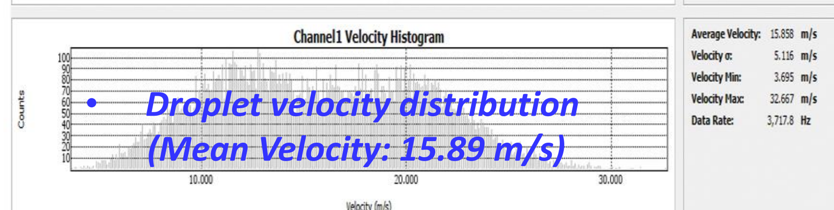












Particle-based Flow Diagnostic Techniques

❑ Time-of-Flight method:

- *Seeded the flow with small particles (~ µm in size)*

- *Assumption: the particle tracers move with the same velocity as local flow velocity!*

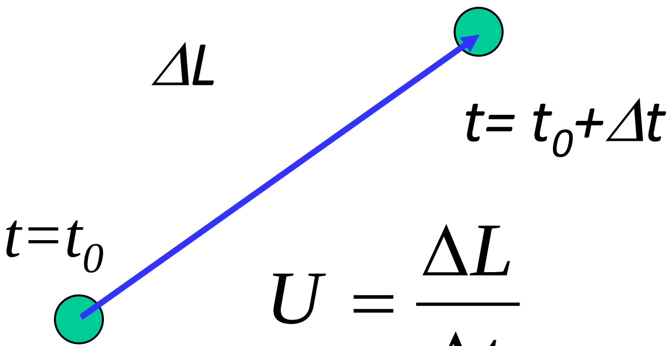
Flow velocity V_f = **Particle velocity V_p**

Measurement of particle velocity

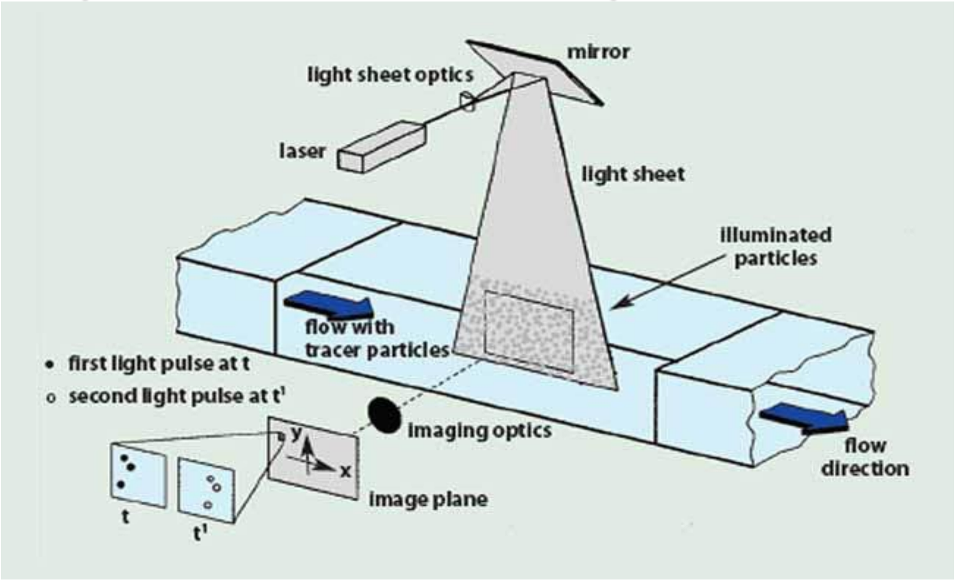
- *Smoke visualization*

Particle Image Velocimetry (PIV) technique

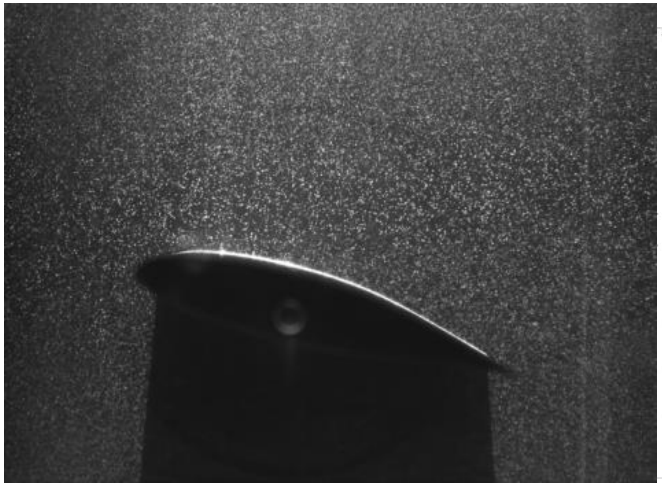
- ***Time-of-flight method:*** *to measure the displacements of the tracer particles seeded in the flow in a fixed time interval.*



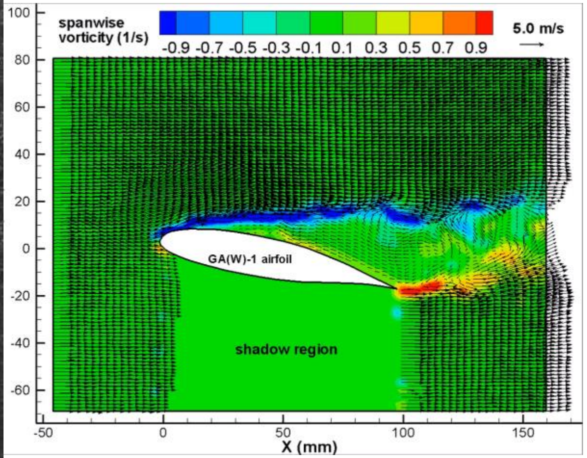
$$U = \frac{\Delta L}{\Delta t}$$



a. T=t0



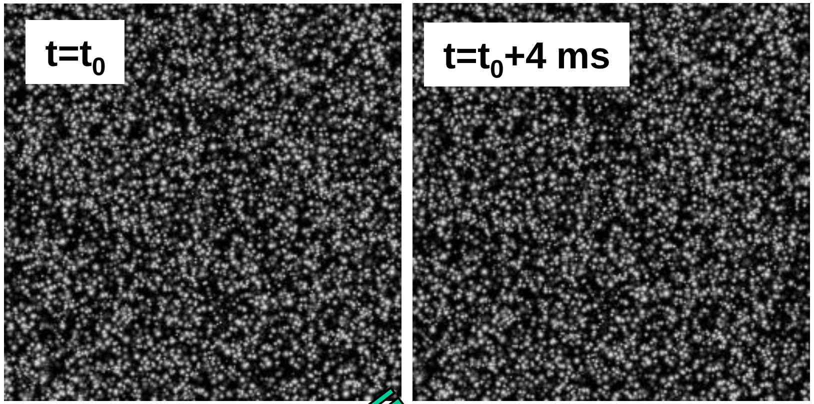
b. T=t0+10μs



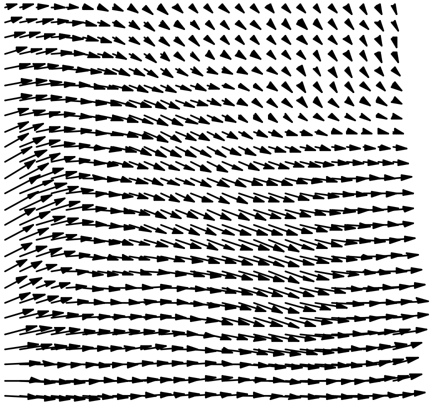
Corresponding Velocity field

Methods to Measure Local Flow Velocity - 5

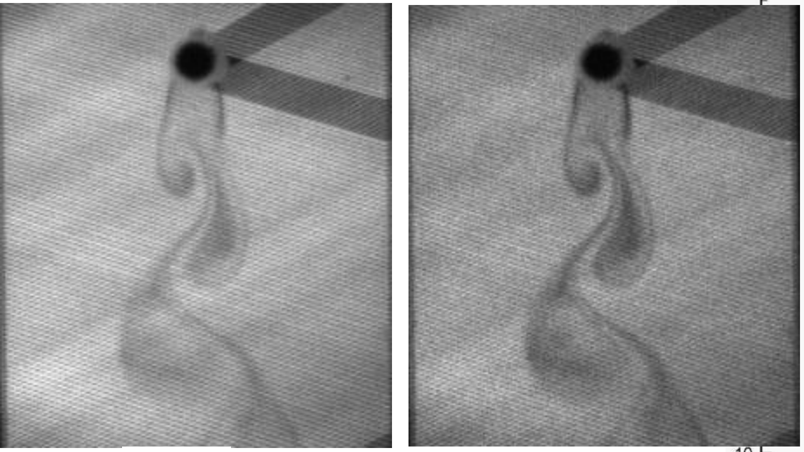
- ***Marker tracing methods:***
  - *Trace the motion of suitable flow makers, optically or by other means to derive local flow velocity.*
  - *Particle Imaging Velocimetry (PIV)*
  - *Particle Tracking Velocimetry (PTV)*
  - *Molecular Tagging Velocimetry (MTV)*



PIV image pair

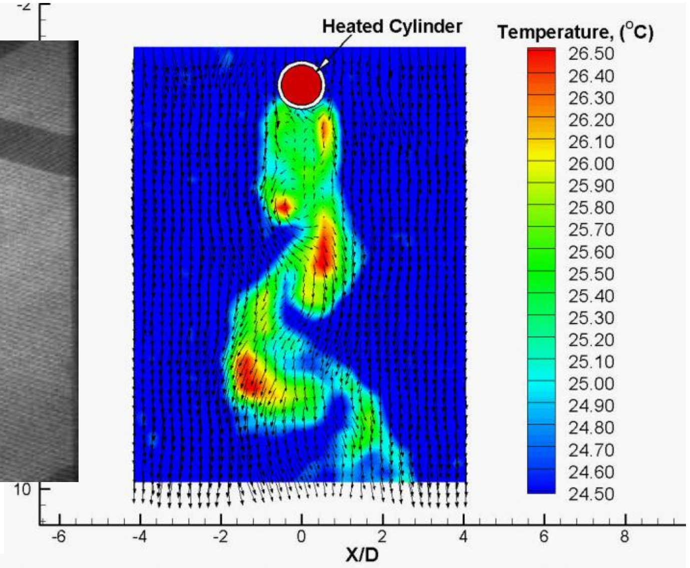


Corresponding flow velocity field

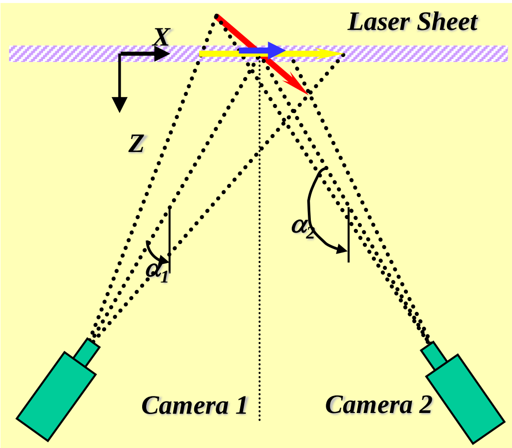


$t=t_0$ *$t=t_0+5ms$*

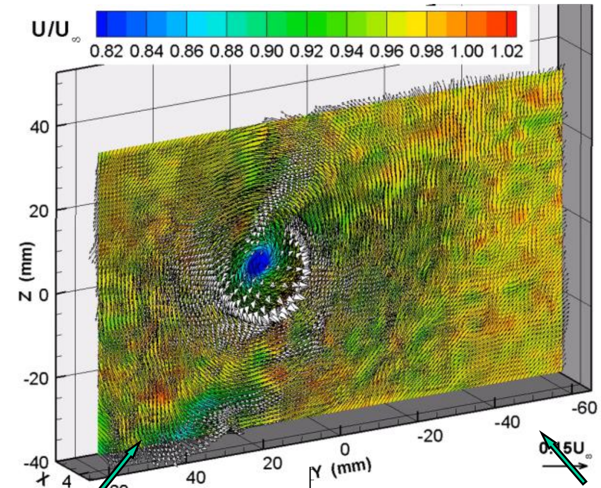
MTV&T image pair

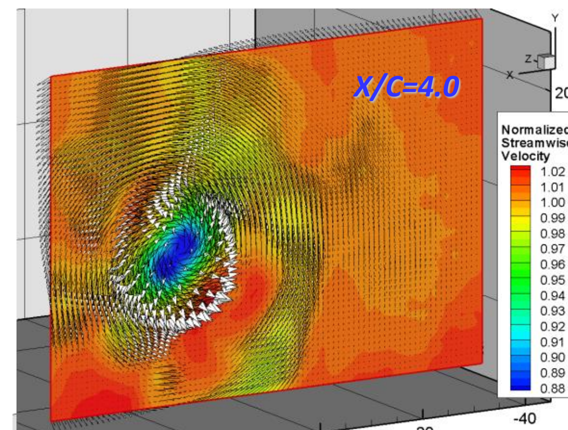


Stereoscopic PIV Measurements of a Wing-Tip Vortex (Funded by AFOSR)



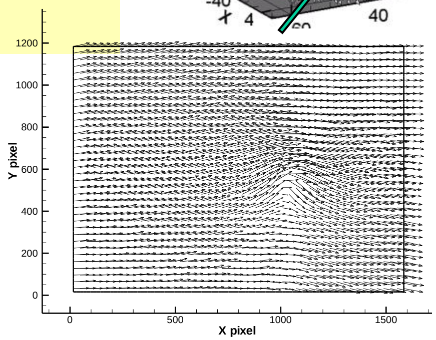
Stereo PIV technique



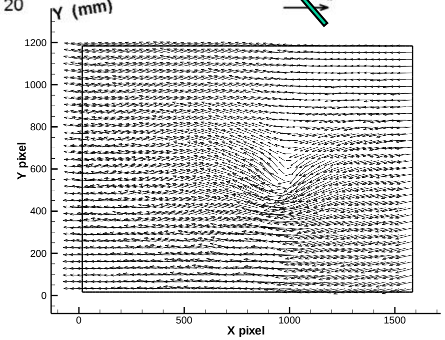


$\mathrm{Re}_C = 52{,}000; \alpha = 5.0\ \mathrm{deg.}$

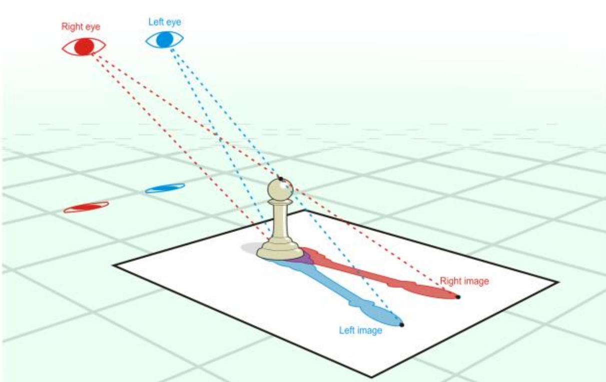
X/C =4.0

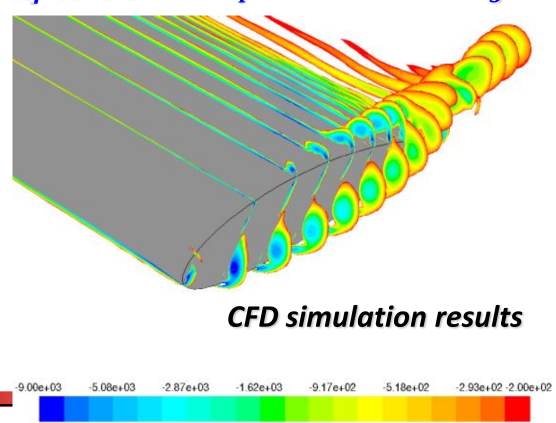


Displacement vectors in left camera

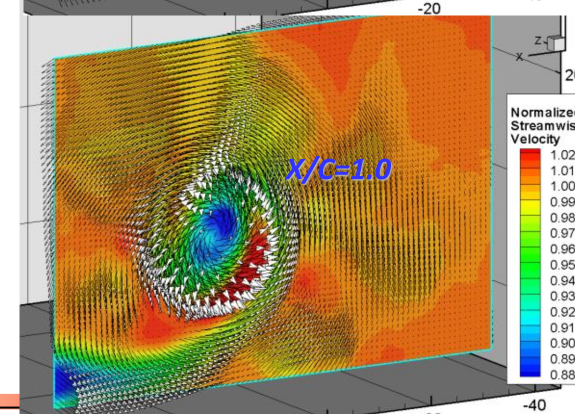


Displacement vectors in right camera





CFD simulation results



Lab#04 Measurements of Pressure Distributions around a Circular Cylinder

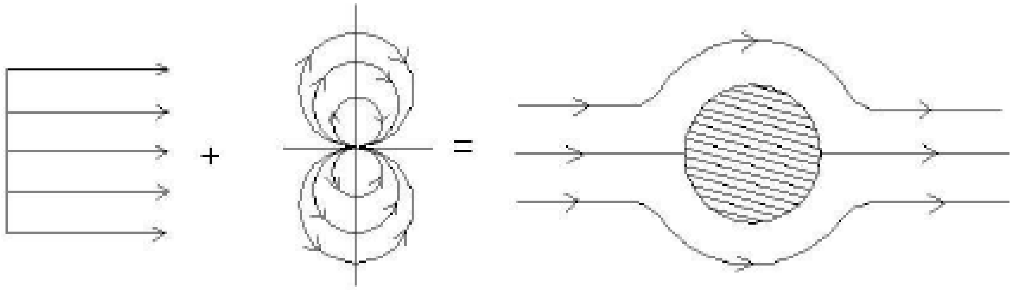
- *Flow Around a Circular Cylinder*
  - ***uniform flow + a 2-D doublet = flow around a circular cylinder***
  - ***Stagnation points***
  - ***Pressure coefficient on the surface of cylinder***

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

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

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

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



Lab#04 Measurements of Pressure Distributions around a Circular Cylinder

- *At the surface of the cylinder,*

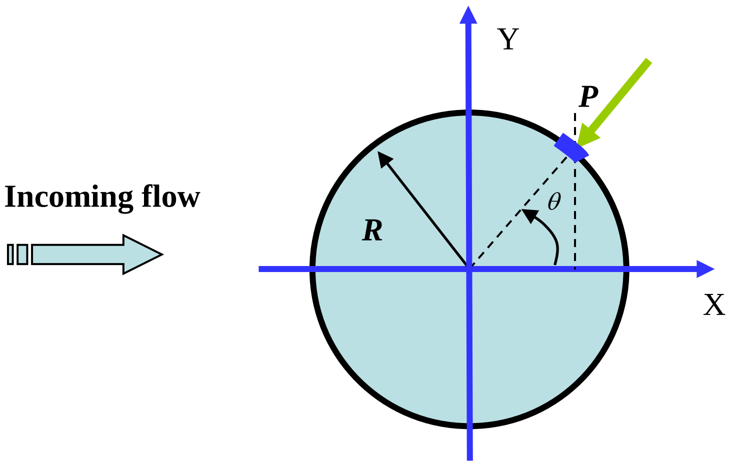
$$r = a \Rightarrow \begin{cases} V_r = 0 \\ V_\theta = -2V_\infty \sin\theta \end{cases}$$

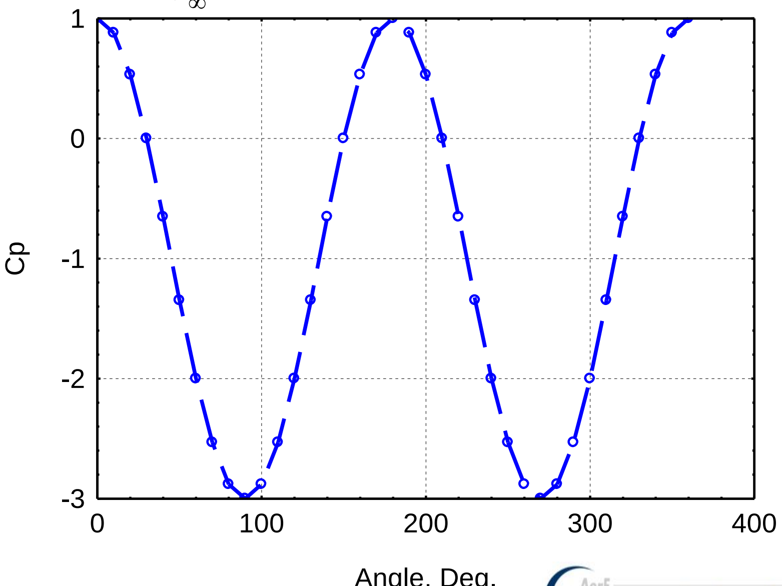
- *According to Bernoulli's equation*

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

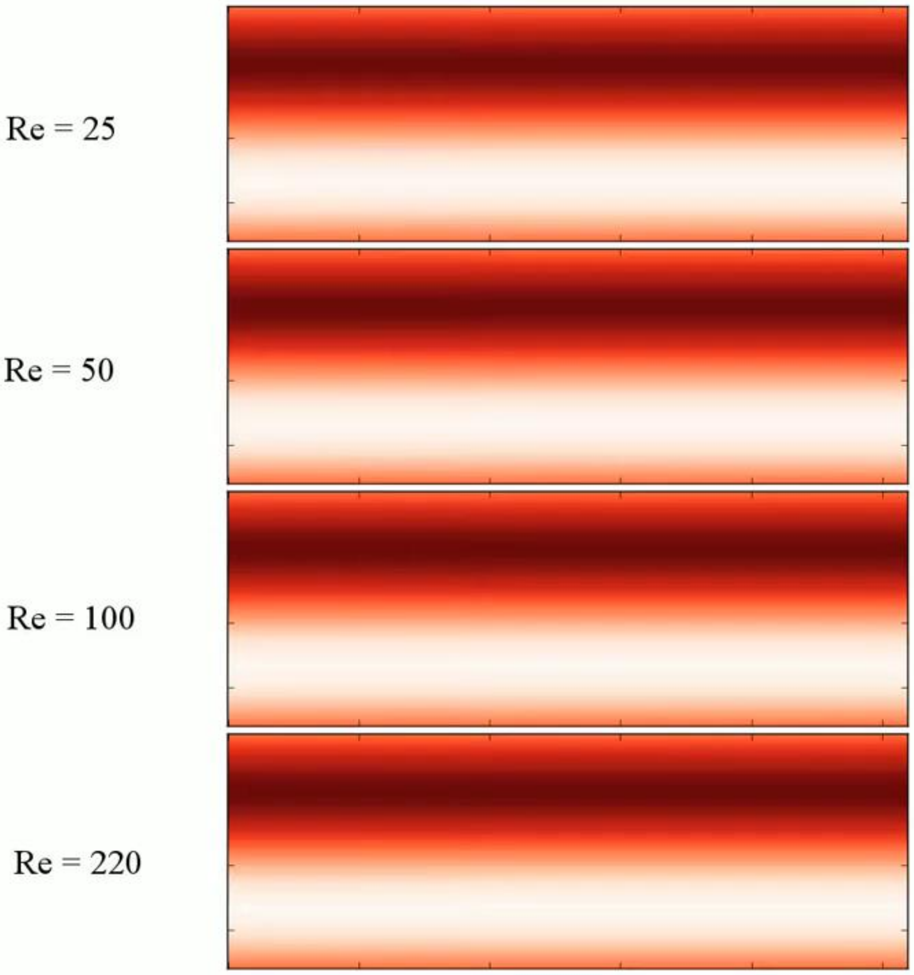
- *Pressure coefficient distribution on the surface of the circular cylinder will be:*

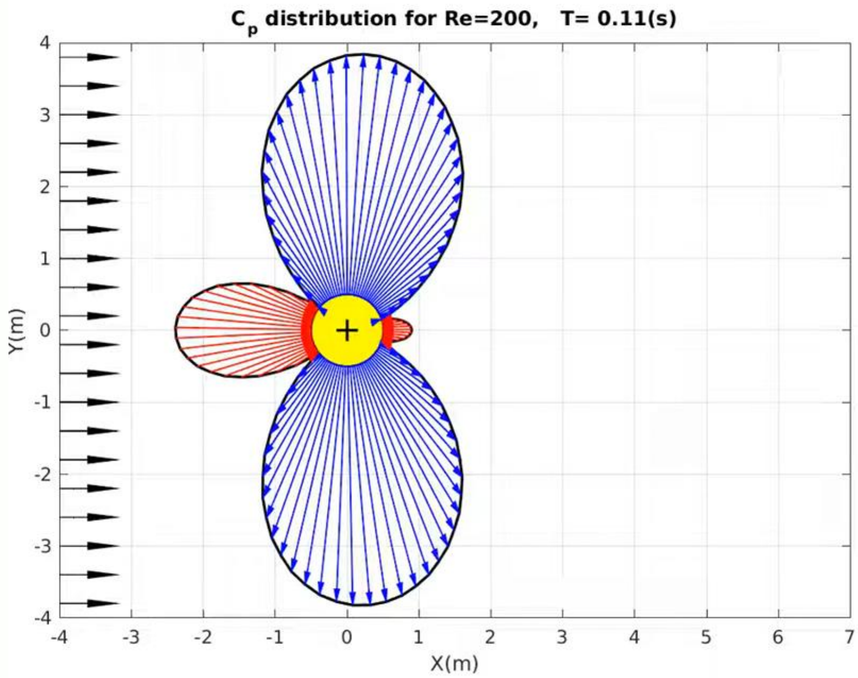
$$C_p = \frac{P - P_\infty}{\frac{1}{2}\rho V_\infty^2} = 1 - \frac{V^2}{V_\infty^2} = 1 - \frac{(-2V_\infty \sin\theta)^2}{V_\infty^2} = 1 - 4\sin^2\theta$$





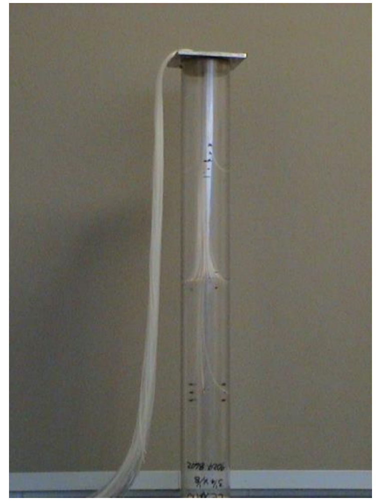
Pressure Distribution around a Circular Cylinder

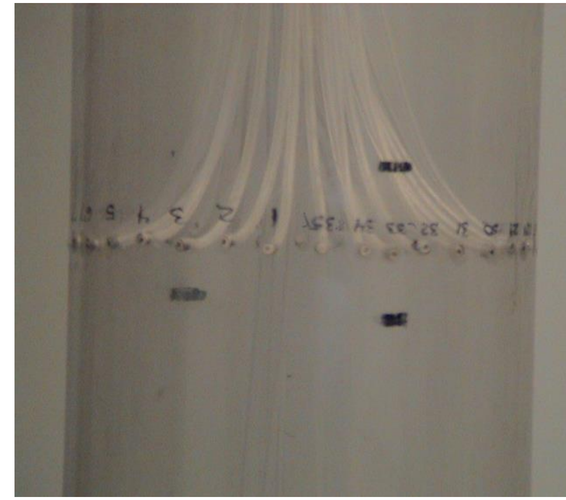


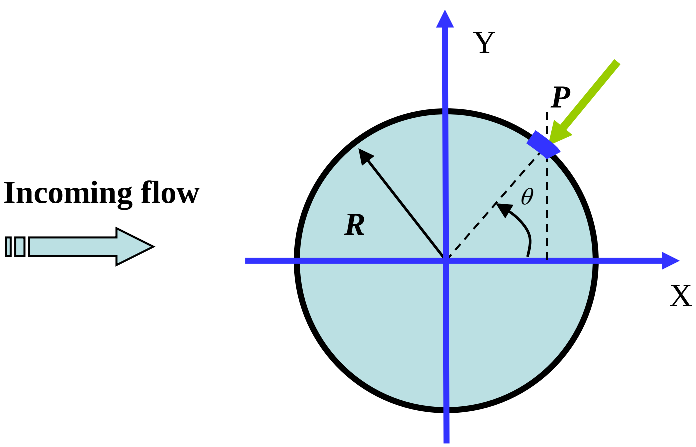


- *Numerical results for the velocity magnitude and pressure distributions over a circular cylinder using FlowLab*

Lab#04 Measurements of Pressure Distributions around a Circular Cylinder

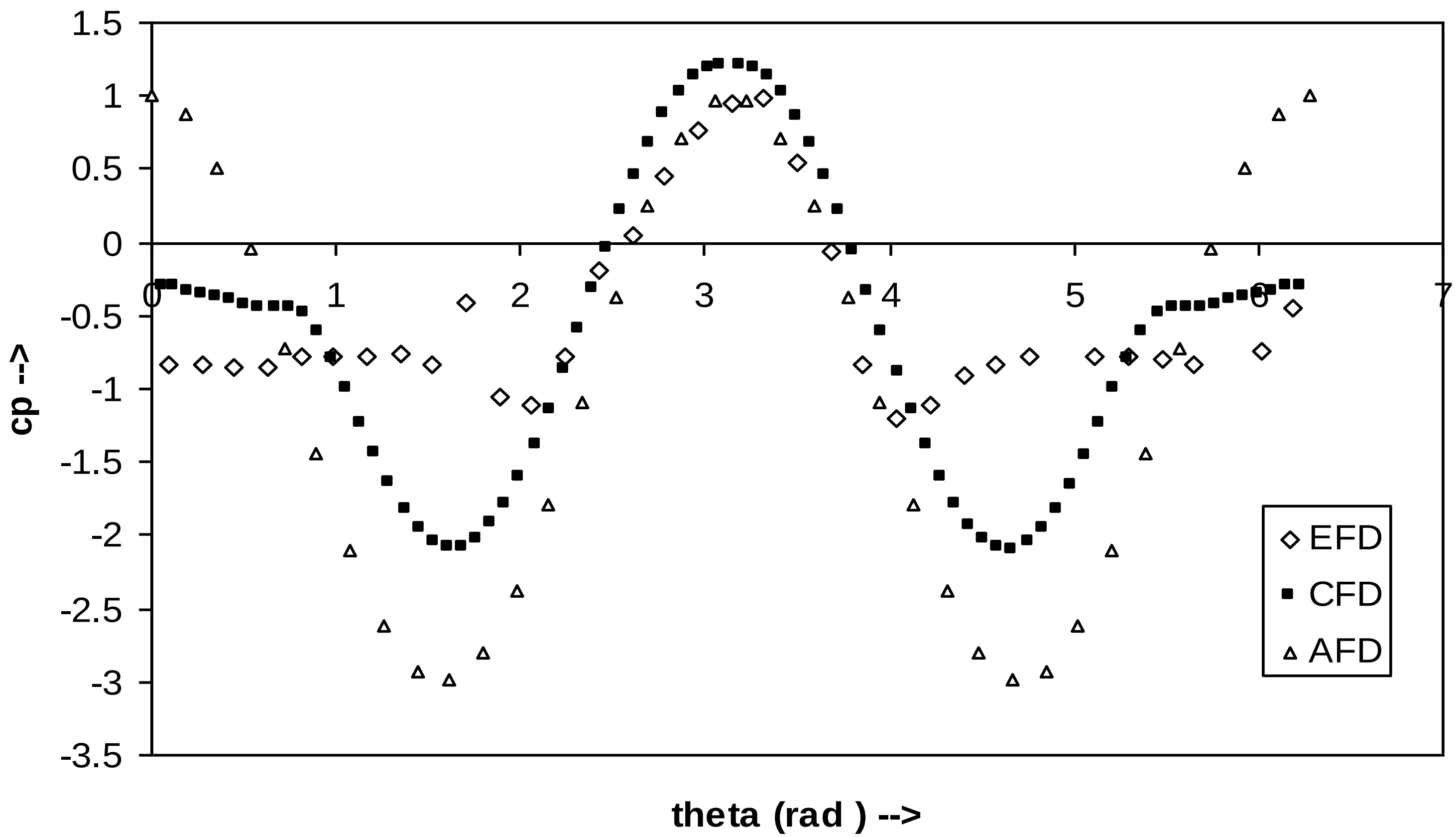






DSA3217 (Shown)

Lab#04 Measurements of Pressure Distributions around a Circular Cylinder



Cp 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.*