LECTURE 24: Molecular Tagging Techniques

Part - 01

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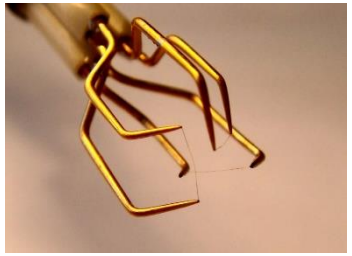
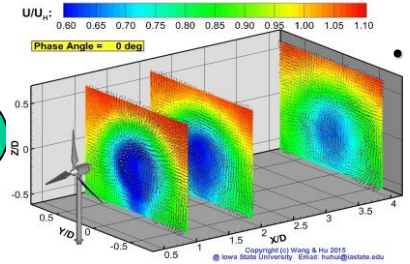
❑ Various measurement Techniques for Thermo-Flow Studies



• Hotwire probe

• Thermocouple probe

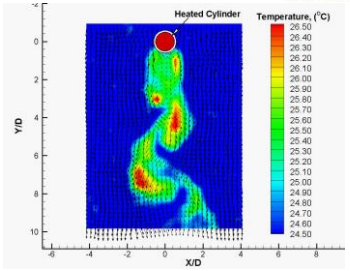
Velocity, temperature, pressure, density (concentration), etc..



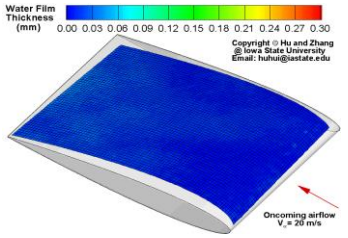
• Stereoscopic PIV

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 …



• MTV & MTT

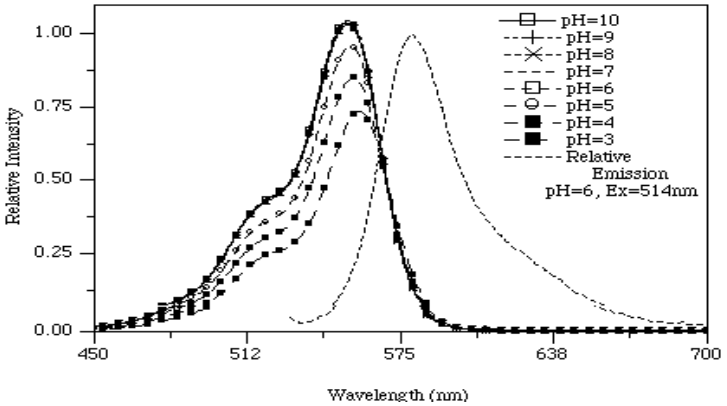


• DIP measurements

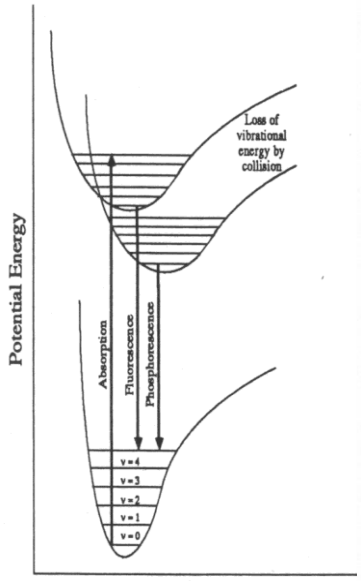
Flow velocity V_f = Velocity of particles or molecule Tracers, V_{tracer}

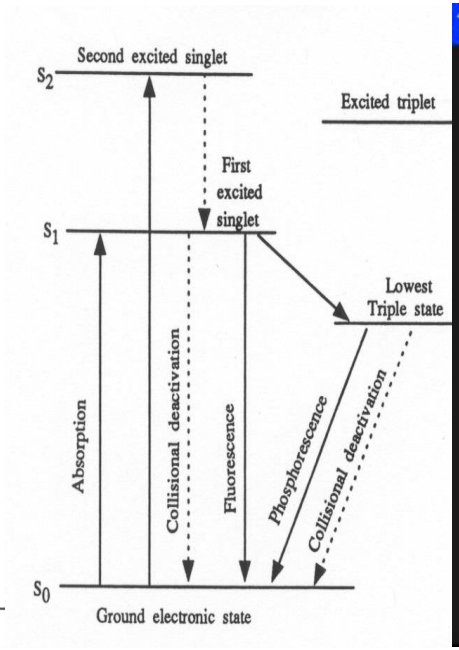
❑ Fluorescence and phosphorescence

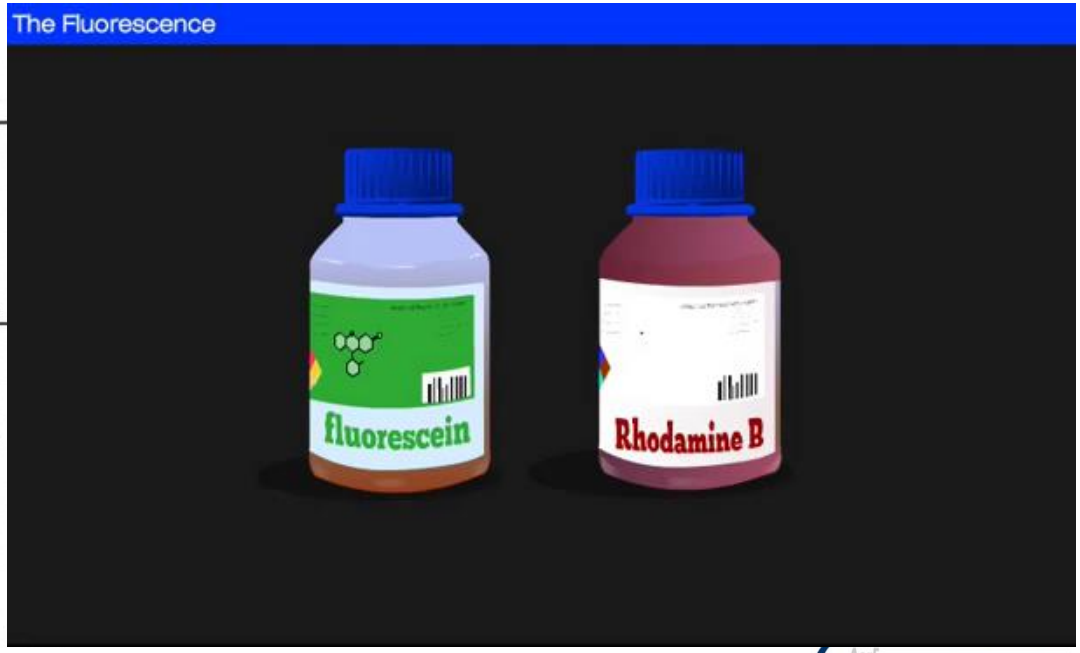
- ***Rayleigh and Raman scattering occurs essentially instantaneously. Not allowing other energy conversion phenomena to occur.***
- ***Fluorescence and phosphorescence: Photoluminescence with time delay***
- ***Fluorescence***
- ***Emission when the excited from singlet state to ground,***
  - ***lifetime is about 10^{-10} ~ 10^{-5} s.***



Rhodamine B





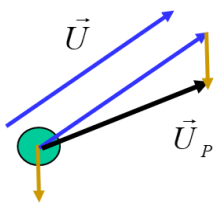


❑ Molecule-based Flow Diagnostic Techniques !? Why!!?

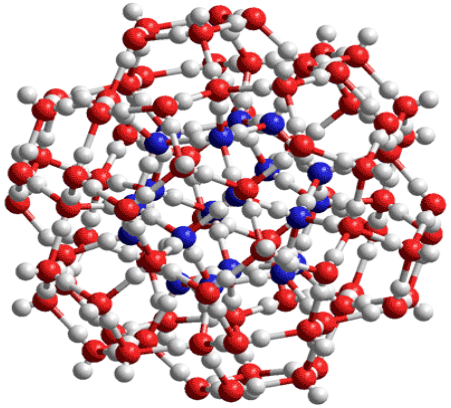
Flow velocity V_f	=	Velocity of particles or molecule Tracers, V_{tracer}

- ***Gravity induced velocity to the particle tracers:***

$$U_g = d_p^{\,2} \frac{(\rho_p - \rho)}{18\mu} g$$



- ***Particles as tracers***



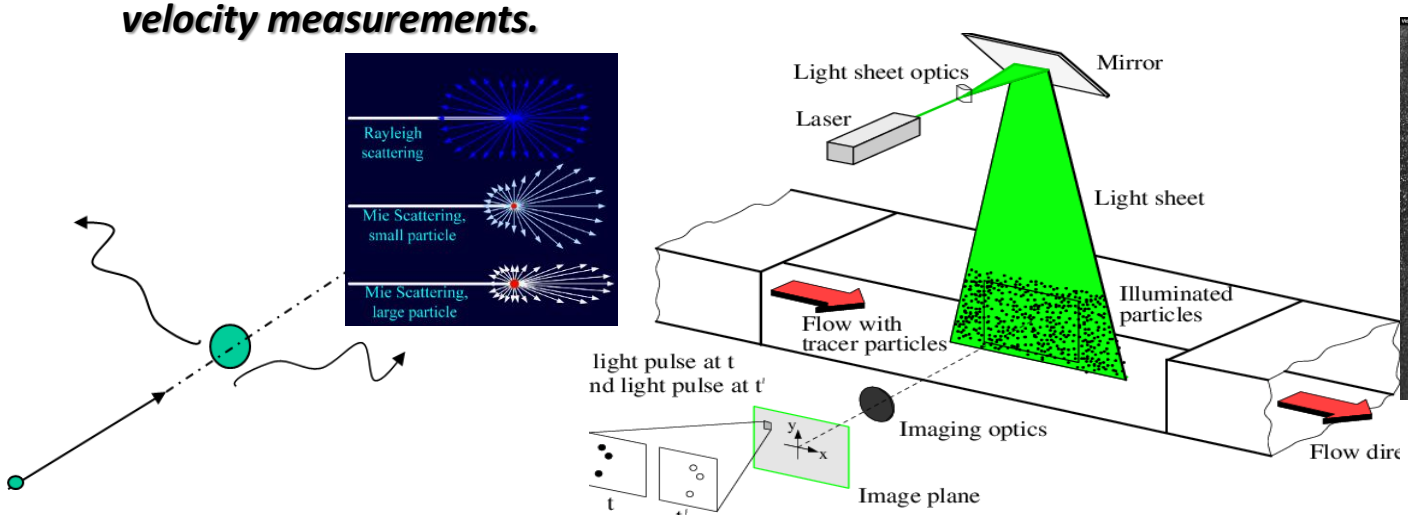
- ***Molecules as tracers***

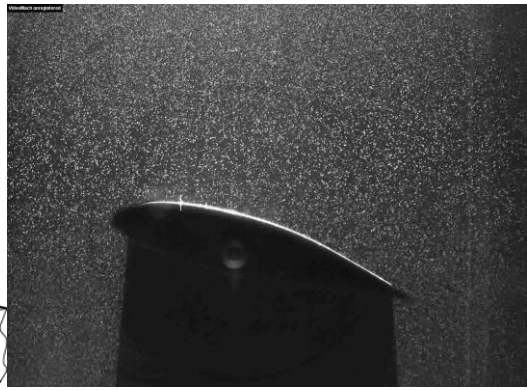
- ***Particle-based*** **techniques (LDV, PIV, Particle Image Thermometry, etc…):**
  - **The *particle-based* techniques measure the velocity or temperature of *tracer particles*, other than the velocity of *working fluid* directly.**
    - ***Flow tracking issues (particle size, density mismatch, …)***
    - ***Seeding issues (particles don't always go where you need them)***
    - ***Existence of particles may change the physics of the phenomena (such as solidification or icing process).***

- ***Molecule-based*** **techniques (*PLIF, MTV, MTT, PSP, DIP…*):**
  - ***Flow tracking issues can be solved.***
    - ***Molecular tracers can usually be dissolved in the working fluids, which move exactly with the velocity as the local fluid molecules.***
    - ***Thermal response for fluid temperature measurement can be significantly mitigated, and perhaps even eliminated.***
      - ***Molecular tracers are usually much smaller than particle tracers.***
    - ***Simultaneous measurements of multiple flow variables.***
      - ***In addition to velocity field measurement, simultaneous mapping of scalar parameters such as temperature and/or concentration of fluid spices can also be achieved easily.***

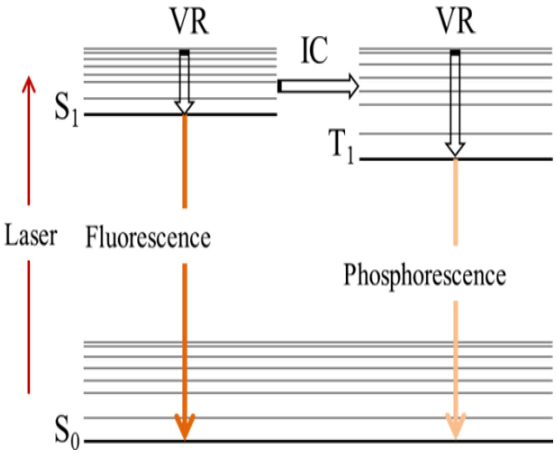
❑ Particle-based Techniques vs. Molecule-based Techniques. How?

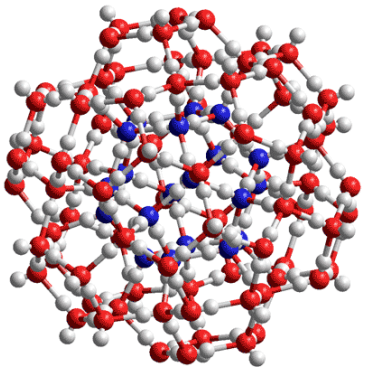
- ***Particle-based techniques** usually depend on **light scattering** of the **tracer particles** to achieve flow velocity measurements.*

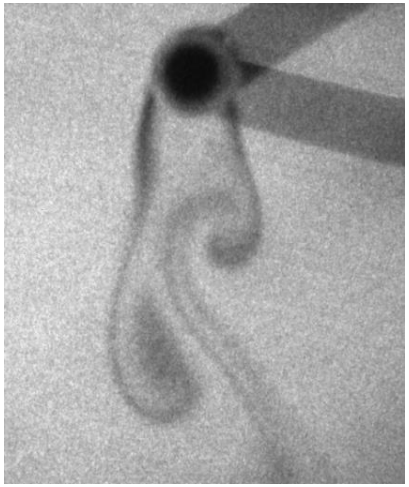


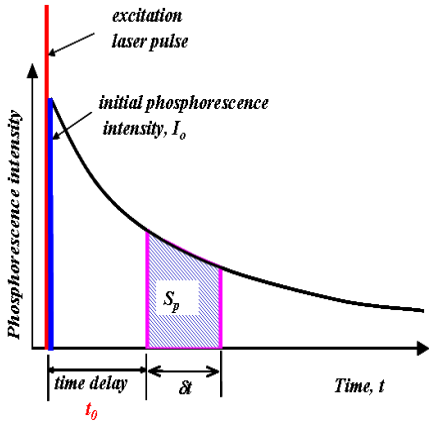


- ***Molecular-based techniques** usually leverage **lased-induced photoluminescence** of the **tracer molecules** to measure **multiple flow properties** (velocity, temperature, pressure, concentration…).*









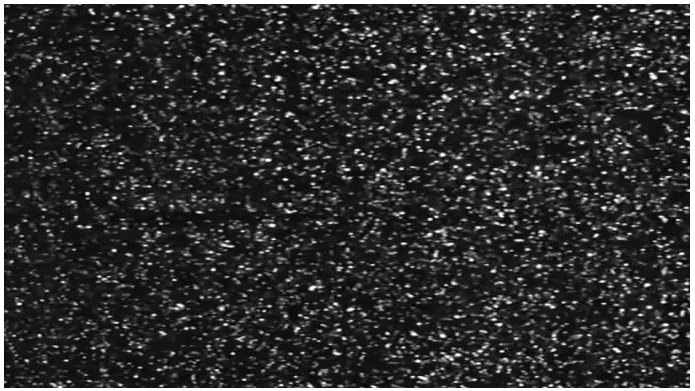
❑ Particle-based vs. Molecule-based Measurements in Supersonic Flows

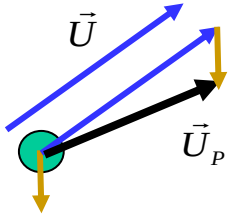
- ***The velocity lag of a particle in a continuously accelerating fluid flow will be:***

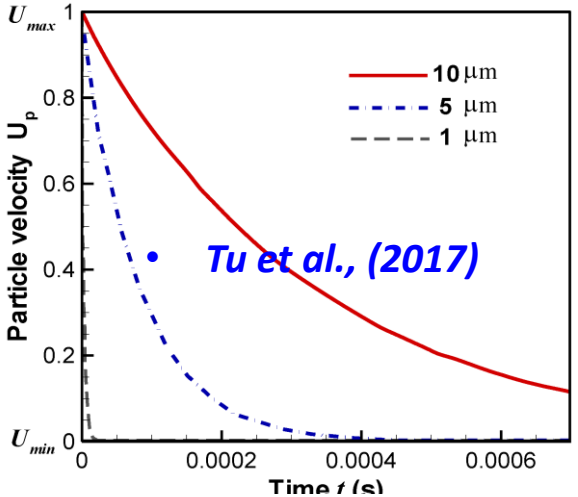
$$\vec{U}_s = \vec{U}_P - \vec{U} = d_p{}^2 \frac{(\rho_p - \rho)}{18\mu} g$$

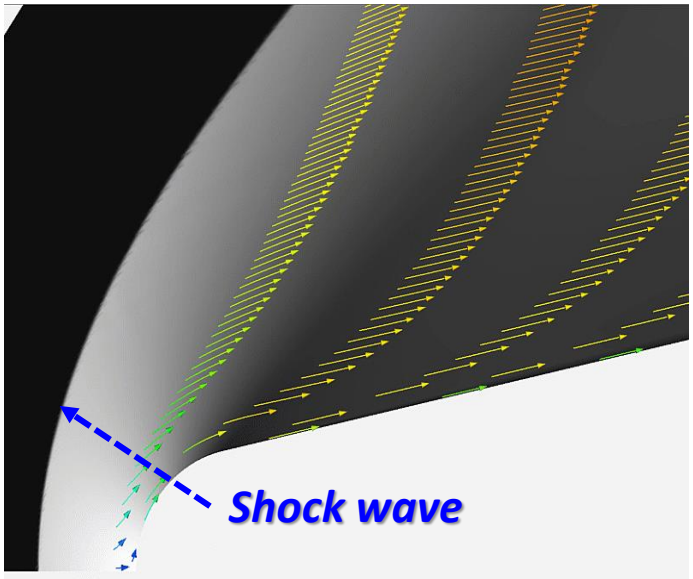
$$\vec{U}_p(t) = \vec{U}(1 - \exp(-\frac{t}{\tau_s});$$

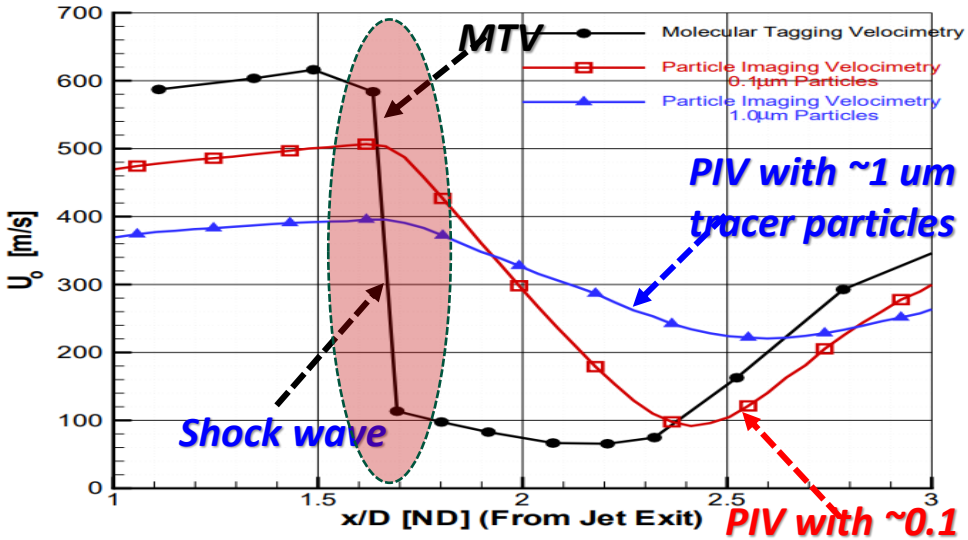
$$\tau_s = d_p{}^2 \frac{\rho_p}{18\mu}$$







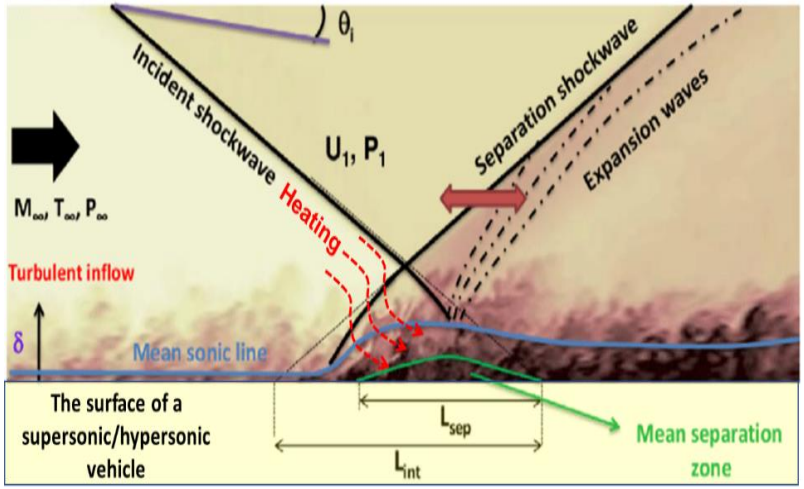


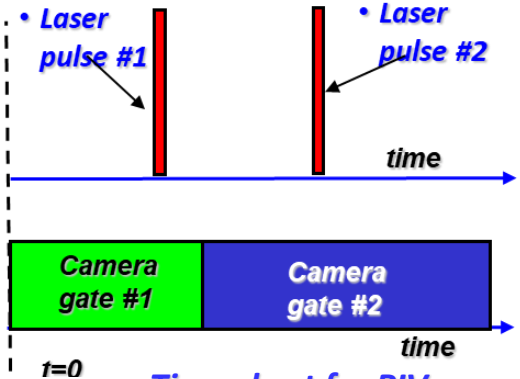


• ***Huffman & Elliott (2009)***

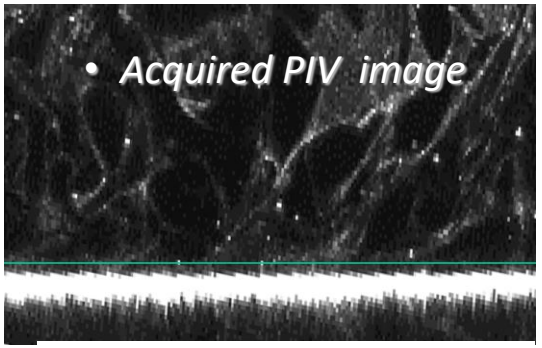
- *Tu et al., A Review of Experimental Techniques for Measuring Micro- to Nano-Particle-Laden Gas Flows". Applied Sciences, Appl. Sci. 7(2), 120, 2017.*
- *Huffman & Elliott, An experimental investigation of accurate particle tracking in supersonic, rarefied axisymmetric jets, 47th AIAA Aerospace Sciences Meeting, Paper No. AIAA-2009-1265, Orlando, Florida, USA, 2009*

❑ Comparison of PIV vs. MTV Measurements in the Near Wall Regions



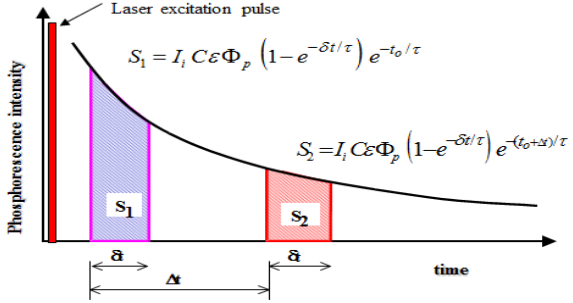


• Time chart for PIV

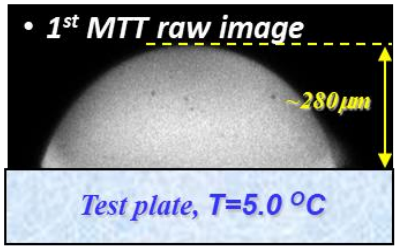


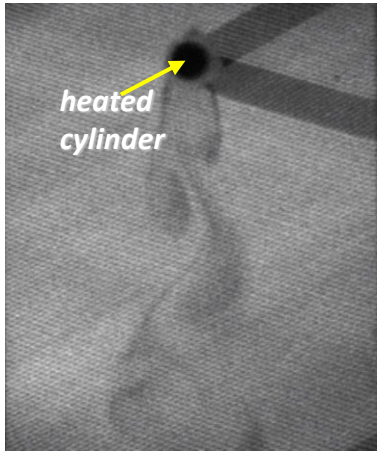
• Strong reflection from the wall surface

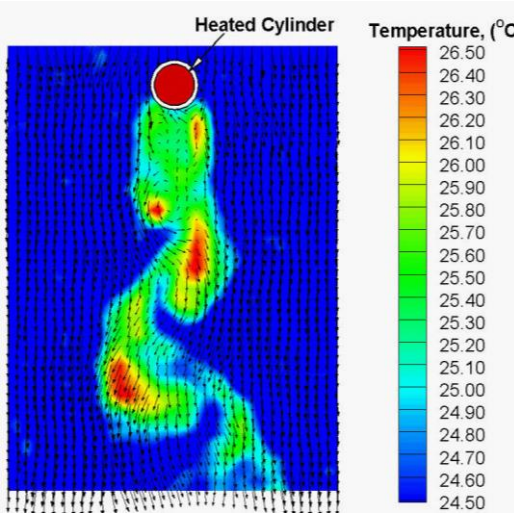
• **Particle-based technique – PIV measurements**



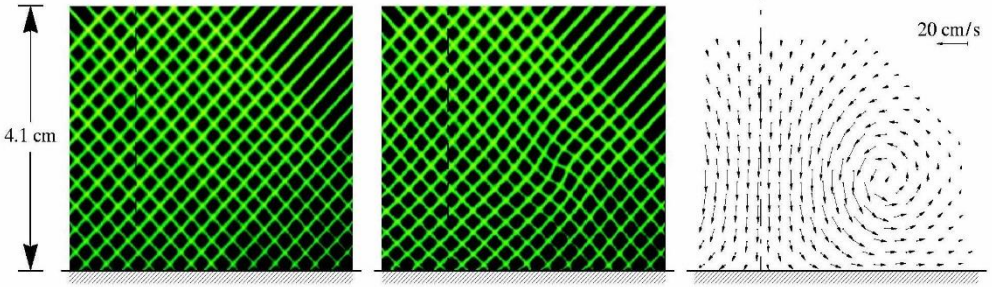
• Time chart for MTV measurements







• MTV&T results

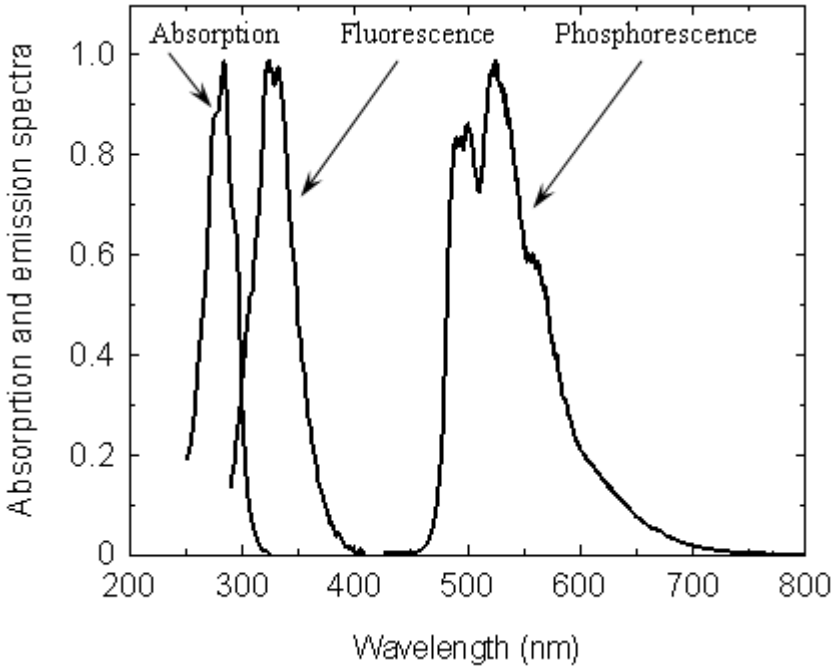


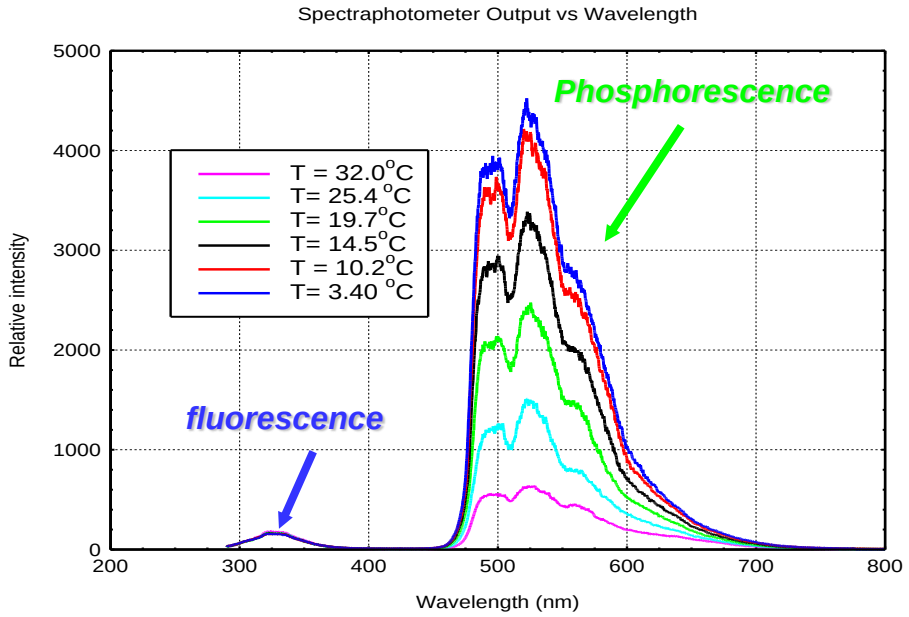
Phosphorescence images at 0.5ms after

• **Molecule-based techniques, - Molecular Tagging measurements**

Fluorescence and Phosphorescence

- *Laser induced phosphorescence*
  - *Emission when the excited atom or molecule from triplet state to ground,*
  - *lifetime is about 10^{-4} ~ 10^{-5} s.*





MTV chemical: 1-BrNp•Mβ-CD•ROH complex

Long Lifetime Phosphorescent Molecular Tracers for Liquids

- Lifetime decreases in the presence of a quencher

$$\tau = \frac{\tau_o}{1 + K_q [Q] \tau_o}$$

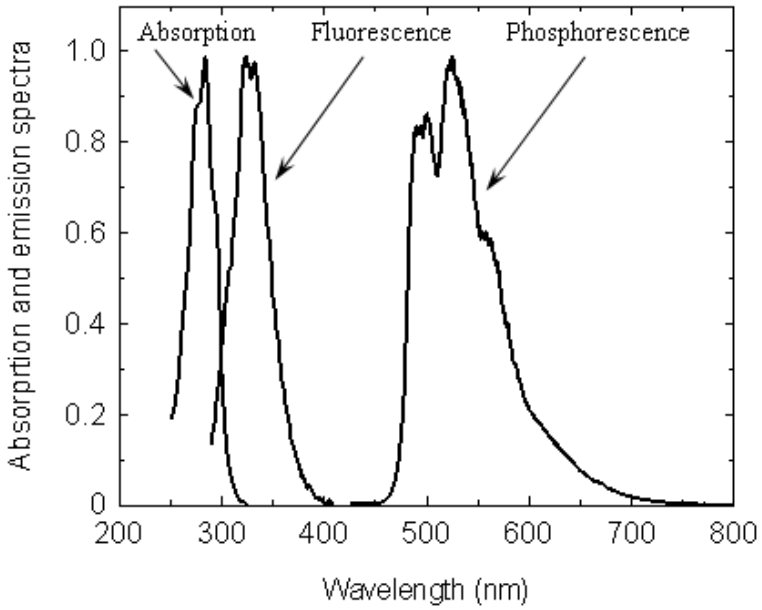
Lifetime without quencher

Lifetime with quencher

Quenching rate

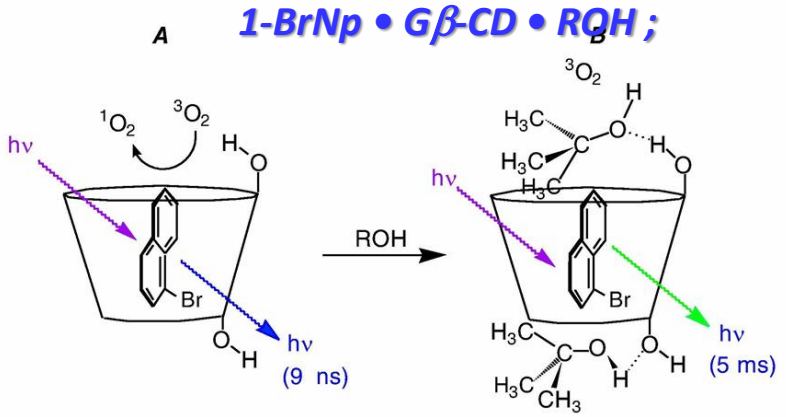
Quencher concentration

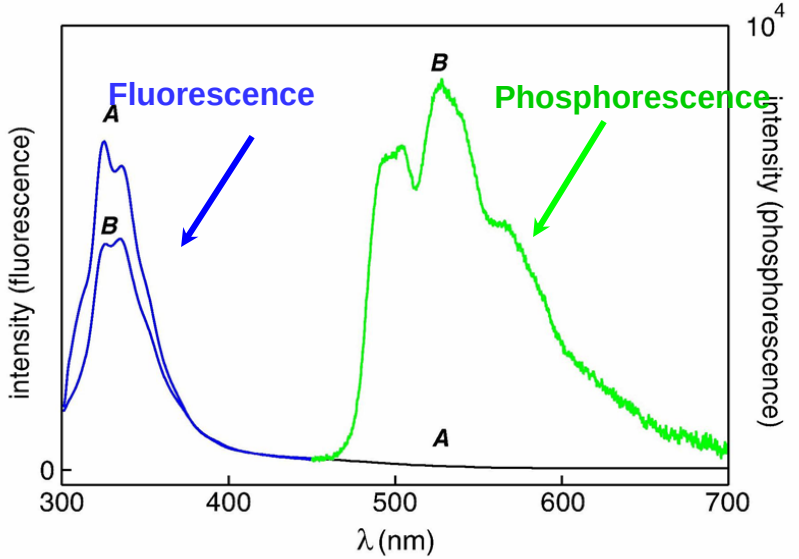
- *Design molecular complexes with small quenching rate K_q*
- *Minimize quencher concentration [Q]*



- ***Phosphorescent triplex:***

1-BrNp • Gβ-CD • ROH ;

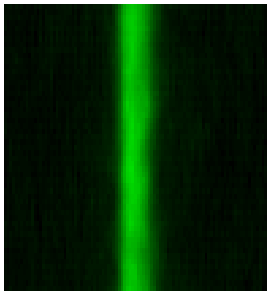




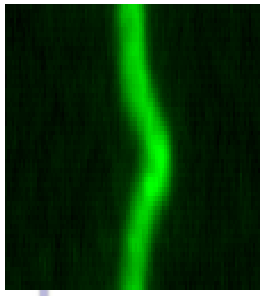
(A) without alcohol, (B) with alcohol.

❑ Molecular Tagging Velocimetry (MTV) technique (line-typed tagging for 1 - component velocity measurements)

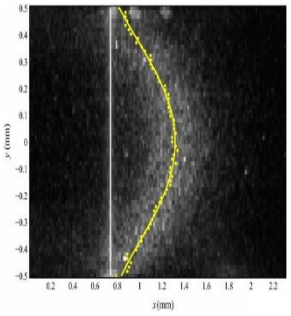
- *Premix the tracer molecules in the fluid flow.*
- *Tagged lines are imaged twice with a known time dela*
- *Intensity profile for each row -> line center locations*
- *Difference between the line centers gives the displacement*
- *Velocity = displacement/delay time*



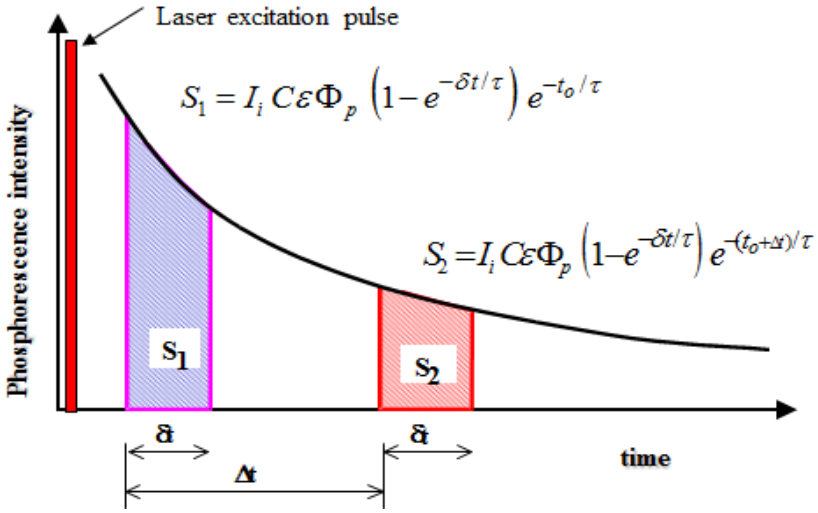
• *first image (right after the laser firing)*



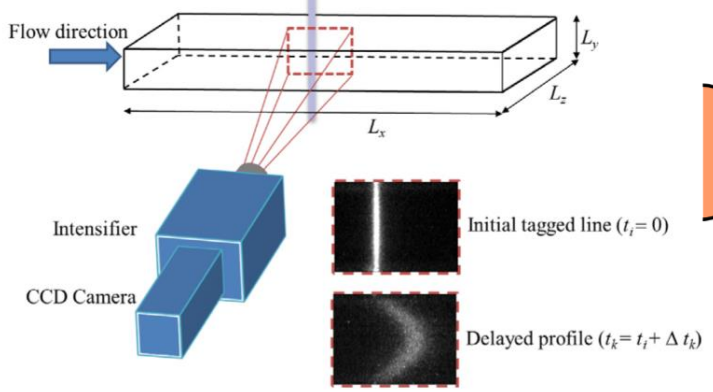
• *second image (a few μsec later)*

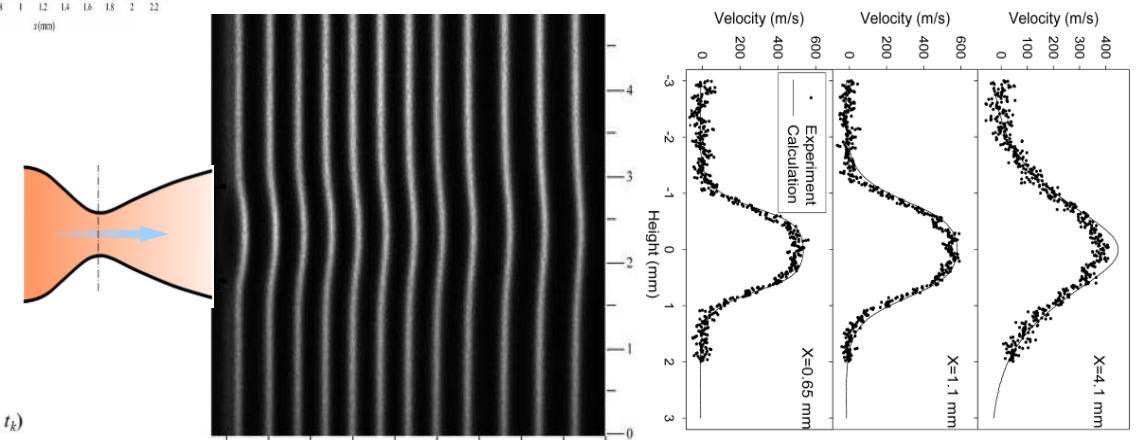


• *Derived velocity profile*



• *Time chart for MTV measurements (Hu et al. 2010)*



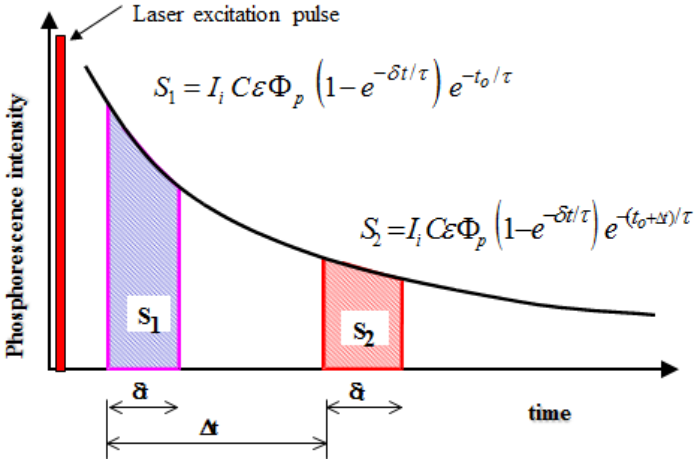


• *MTV Measurements in a supersonic jet flow.*

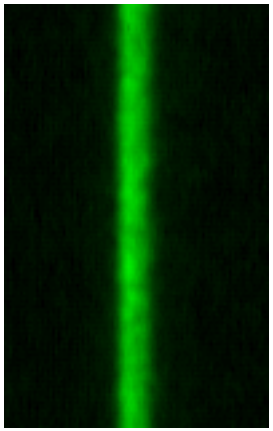
- ***H Hu ZY Jin, D Nocera, C Lum, and MM Koochesfahani****, Experimental Investigation of Micro-Scale Flow and Heat Transfer Phenomena by Using Molecular Tagging Techniques", Measurement Science and Technology,* ***21****, 085401, 2010.*
- ***WR Lempert, NB Jiang, S Sethuram and M Samimy,*** *"Molecular Tagging Velocimetry Measurements in Supersonic Microjets" AIAA Journal, Vol.40 (6), pp1065-1070, 2012.*

❑ Molecular Tagging Velocimetry (MTV) technique (line-typed tagging for one-component velocity measurements)

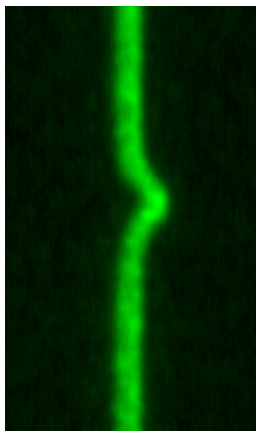
- *Premix the tracer molecules in the fluid flow.*
- *Tagged lines are imaged twice with known time delay*
- *Intensity profile for each row -> line center locations*
- *Difference between the line centers gives displacement*
- *Velocity = displacement / delay time*

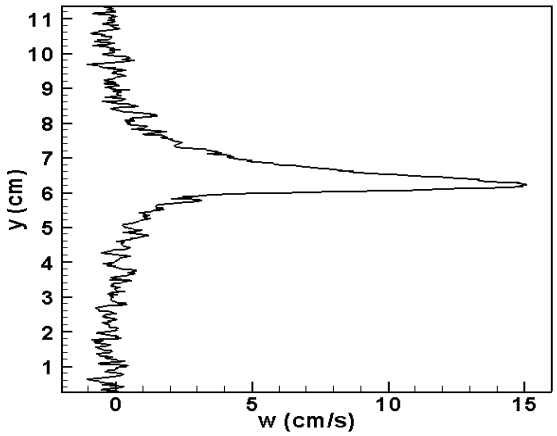


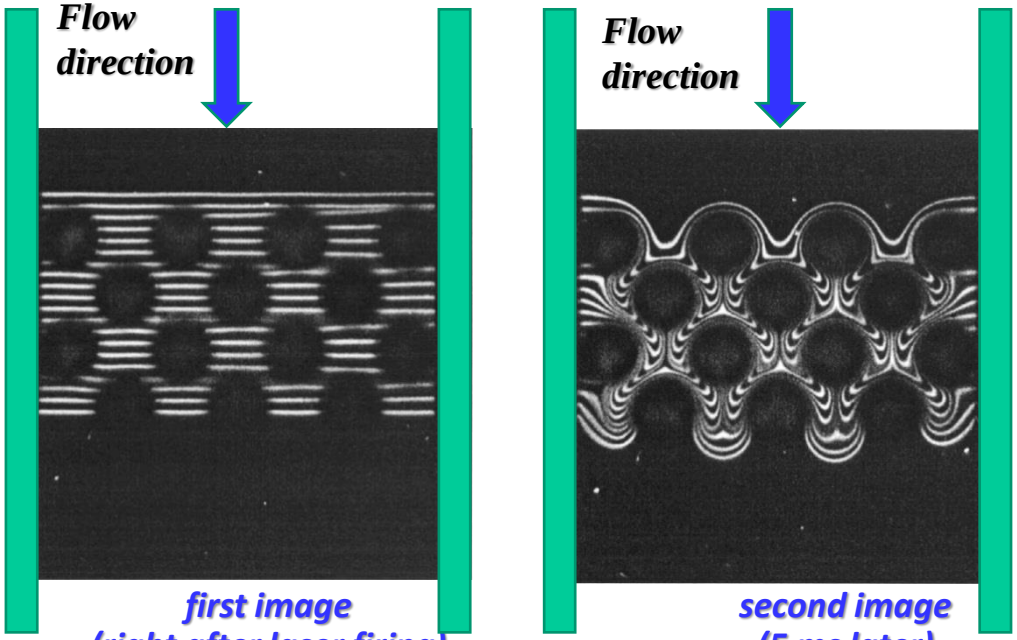
first image (right after laser firing)



second image (5 ms later)







first image (right after laser firing)

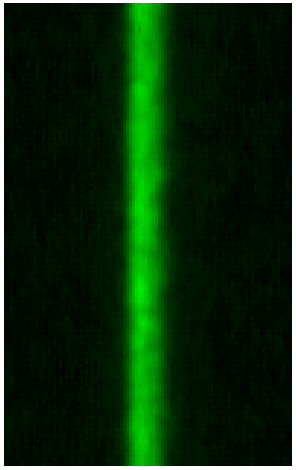
second image (5 ms later)

(Koochesfahani et al., 2002)

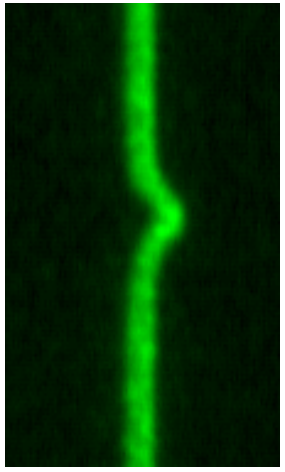
❑ Molecular Tagging Velocimetry (MTV) technique (line-typed tagging for one-component velocity measurement)

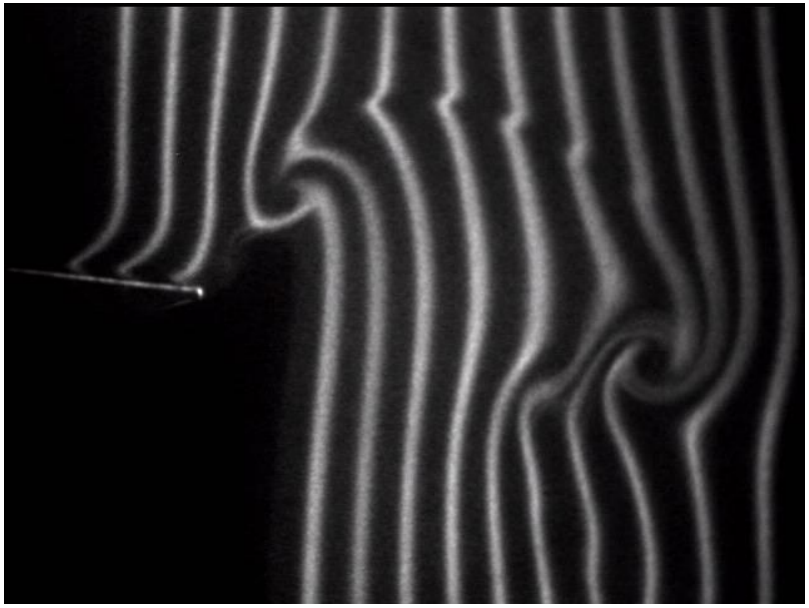
- Tagged lines are imaged twice with known time delay
- Intensity profile for each row -> line center locations
- Difference between the line centers gives displacement
- Velocity = displacement / delay time

first image (right after laser firing)

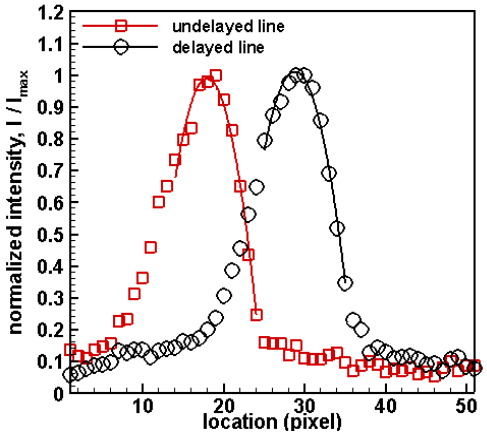


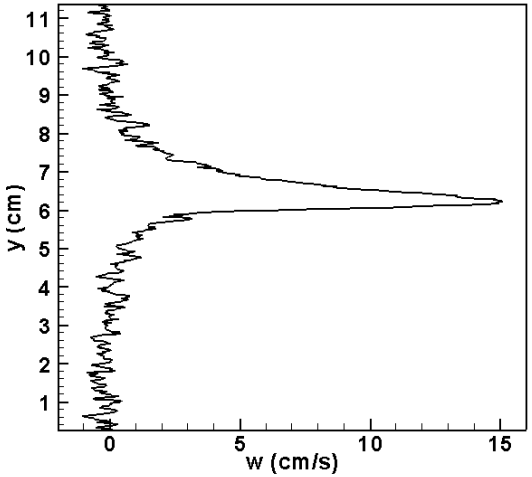
second image (14 ms later)





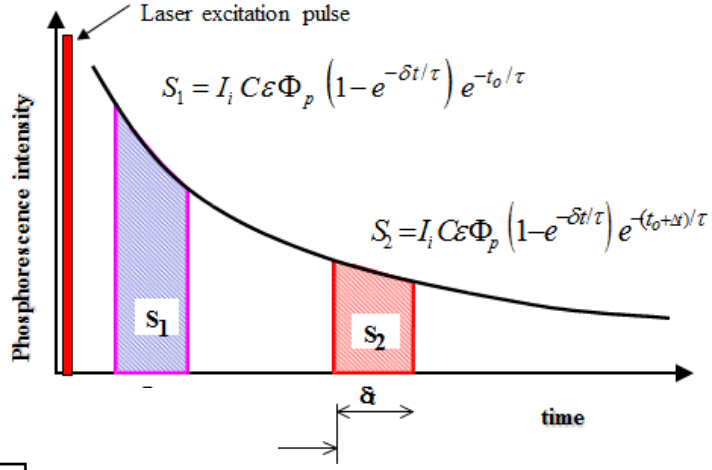
Flow visualization of the vortex shedding from the trailing edge of an oscillating airfoil (Bohl et al. 2002)





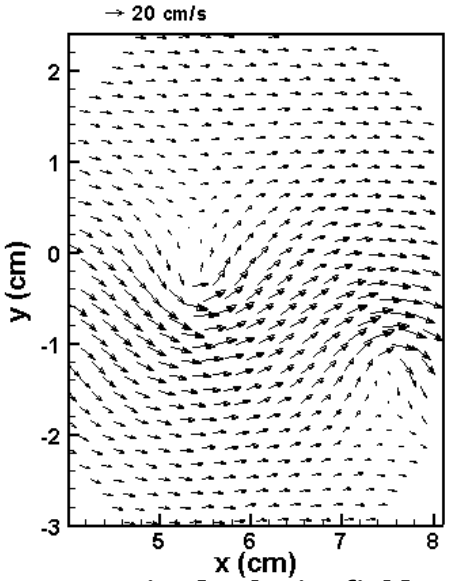
Molecular Tagging Velocimetry (MTV)
(Grid-typed tagging for two-component velocity measurements)

- *Premixed the molecular tracers in the fluid flow*
- *Create a 2-D grids with multiple laser beams.*
- *Take two images after the same laser pulse with known time delay.*
- *Find the displacement vectors of the grids through a image processing procedure.*
- *Local velocity = displacement/time delay.*

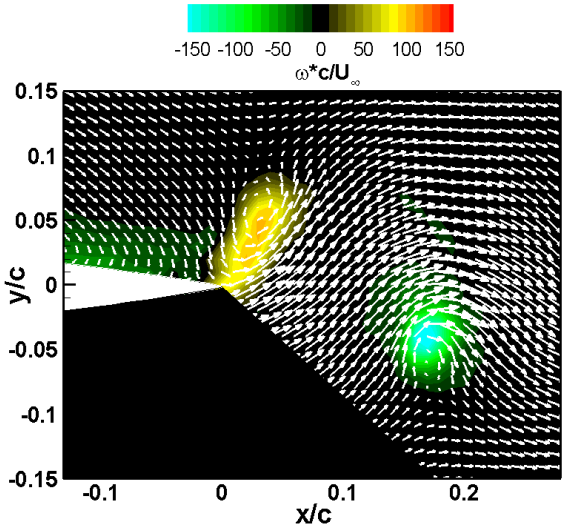


First image (right after the laser pulse)

Second image (imaged 3.5 ms later)



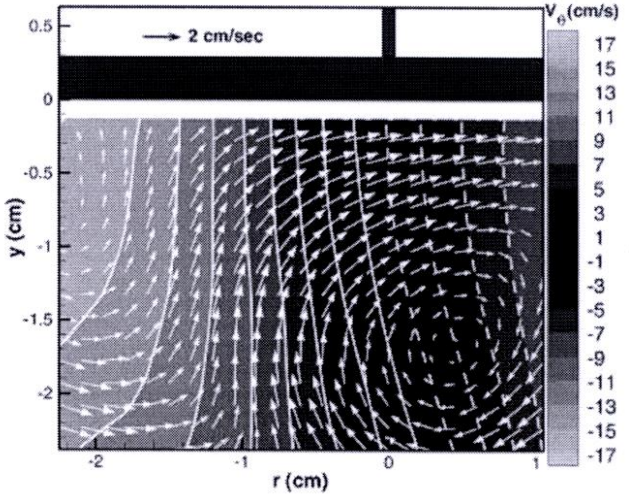
Derived velocity field (Bohl et al. 2002)

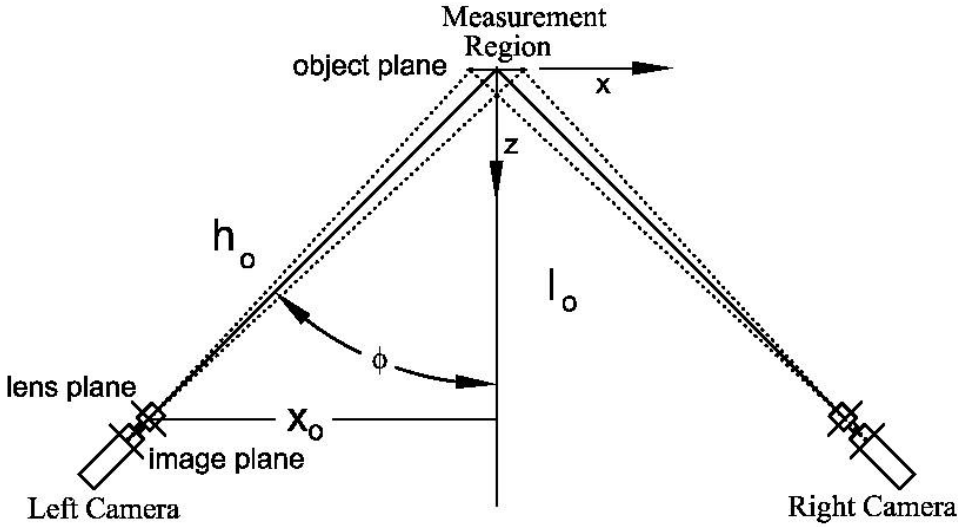


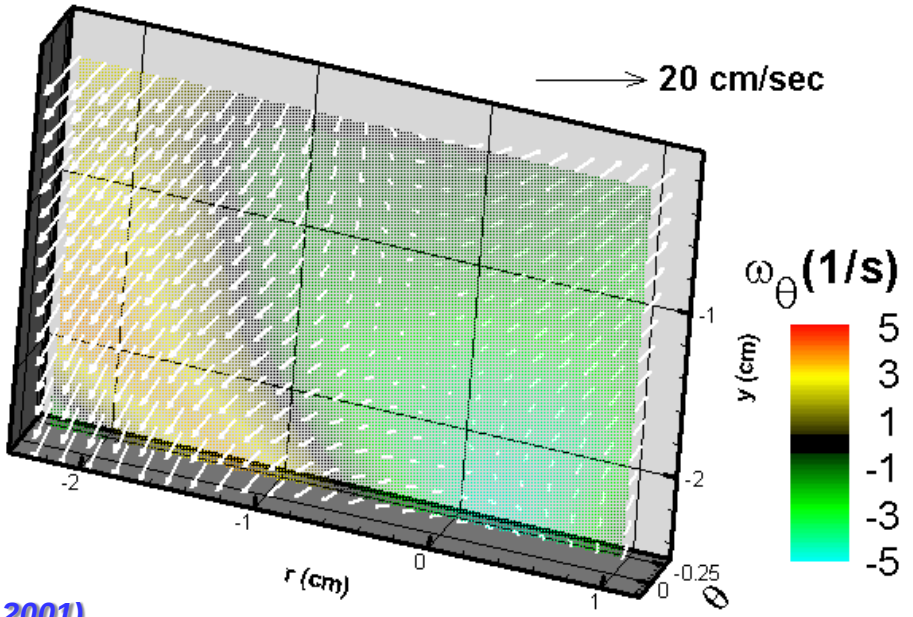
(Bohl et al., Physics of Fluids, 2002)

Stereoscopic Molecular Tagging Velocimetry (three-component velocity measurements)

- *Use 2 cameras viewing from different perspectives.*
- *Each camera is processed using a planar MTV technique.*
- *Information from the two cameras is combined to reconstruction three components of velocity vectors.*

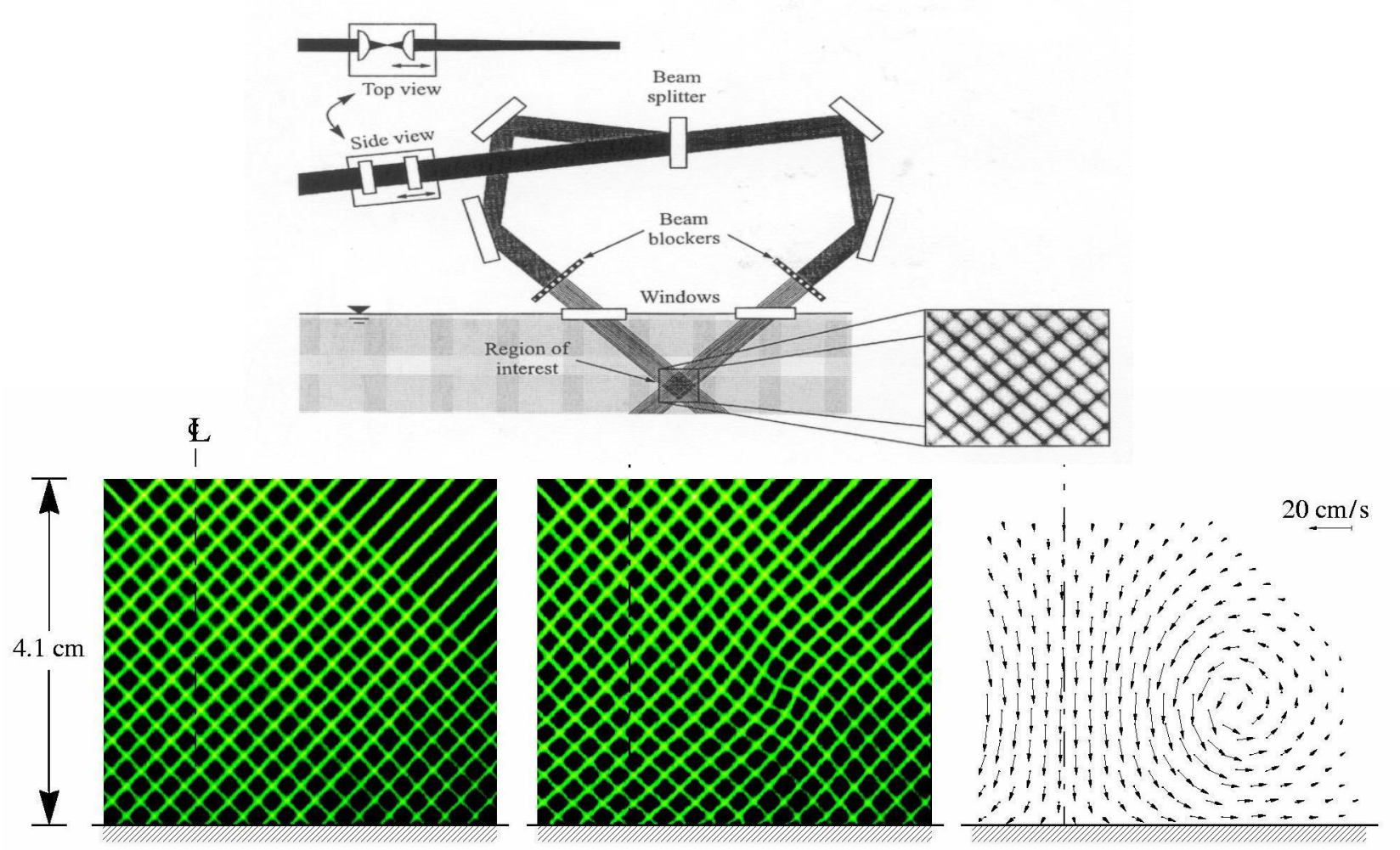






(Bohl et al. Experiments in Fluids, 2001)

❑ Planar MTV (two- component measurements)



Tagged regions imaged right after the laser pulse

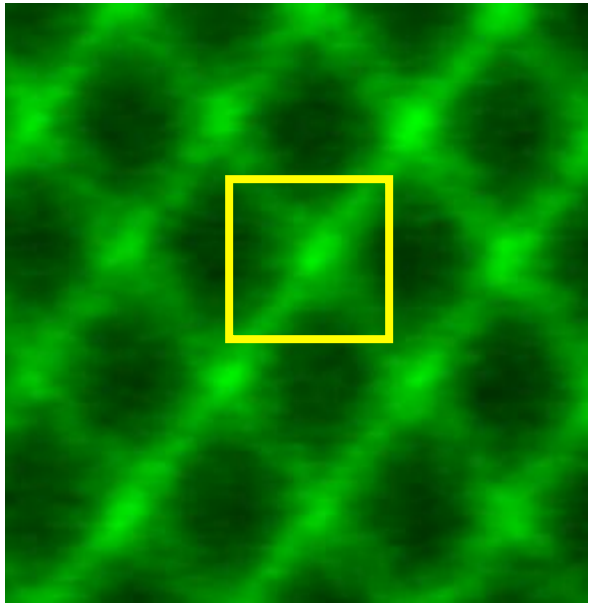
Tagged regions imaged 8 ms later

The velocity field derived using a spatial correlation procedure

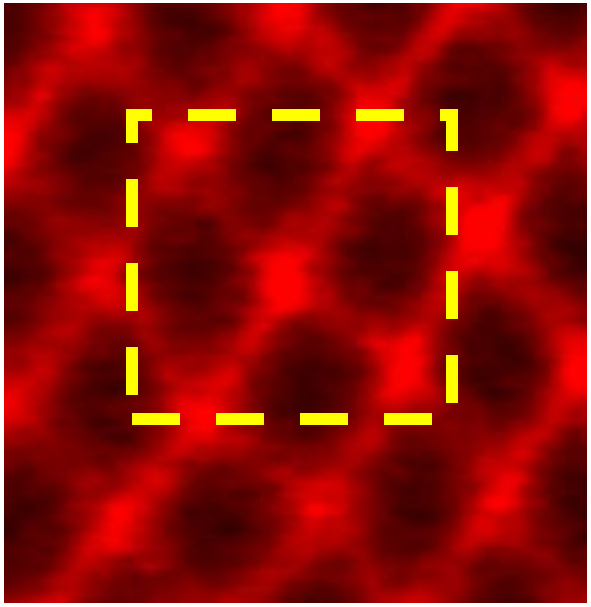
Results taken from (Bohl et al. 2001)

❑ Image Processing for Planar MTV

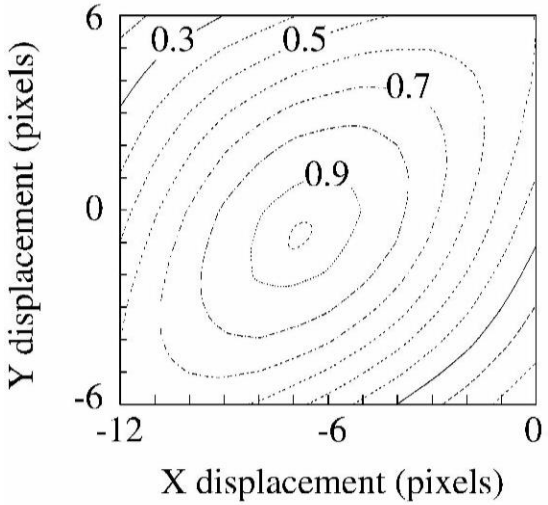
- Create a 2-D contrast field
- Select a region in the first image (green)
- Search in the second image for the matching pattern (red)
- Pattern is matched via direct correlation technique



undelayed image
at time $t=t_0$



delayed image
at time $t=t_0+\Delta t$

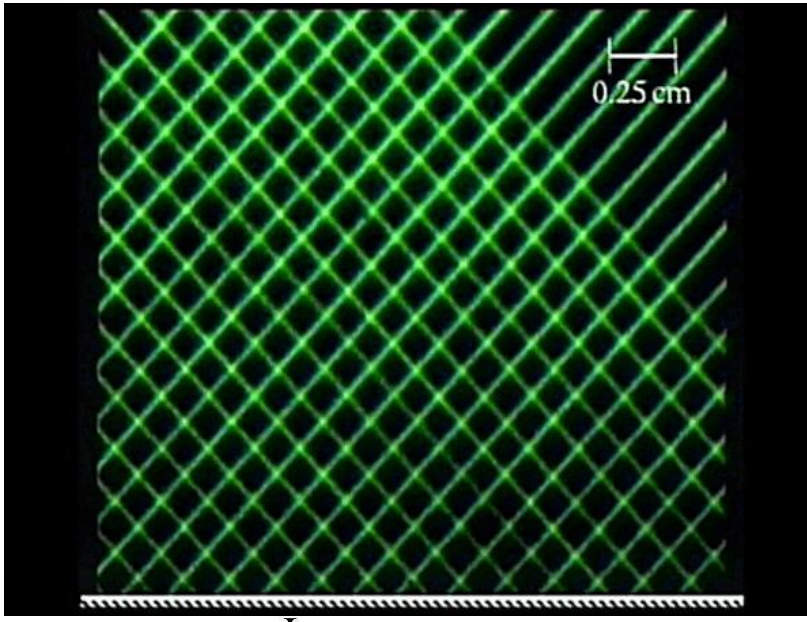


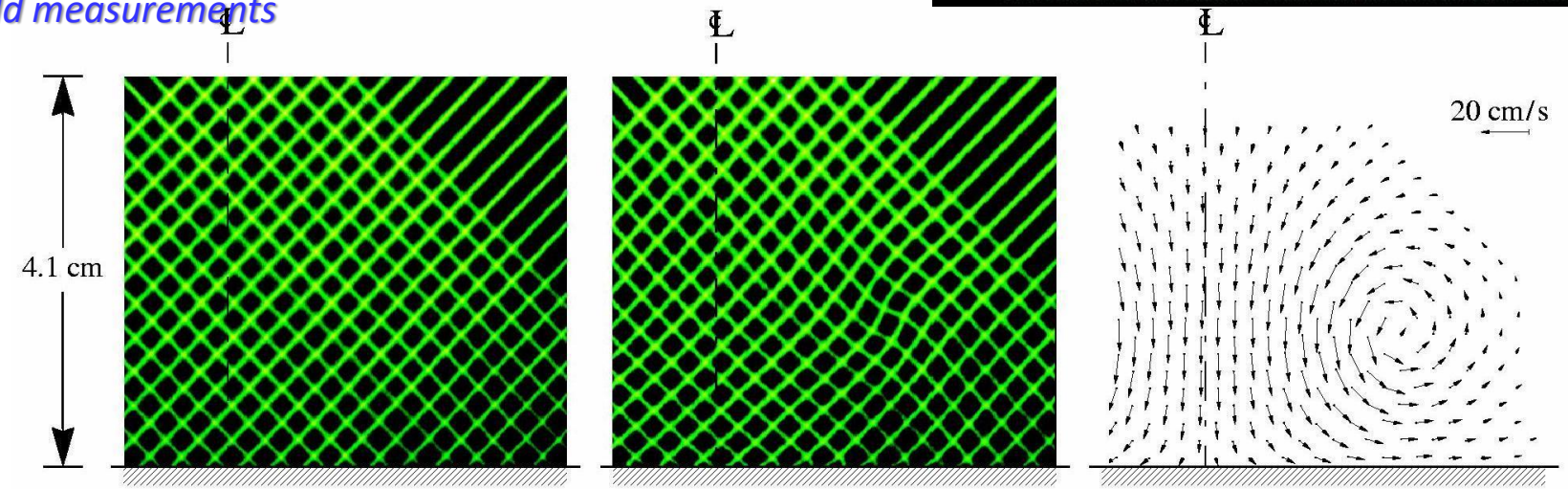
Correlation coefficient distribution

Results taken from (Bohl et al. 2001)

❑ Molecular Tagging Velocimetry (MTV): General Description

- *Whole field, non-intrusive, optical diagnostic technique*
- *Use special chemical molecules premixed in fluid flows as long lifetime tracers*
- *A pulsed laser is used to "tag" small regions of interest*
- *Tagged regions are imaged twice with pre-set time delay*
- *The displacement vectors of the tagged regions provide the estimate of the velocity vectors of the fluid flow.*
- *Line (1-d), Grid (2-d), Stereoscopic (3-d) MTV*
- *Flow visualization and quantitative measurements*
- *Scalar field measurements, simultaneous velocity/scalar field measurements*





Tagged regions imaged right after the laser pulse

Tagged regions imaged 8 ms later

The velocity field derived using a spatial correlation procedure

❑ Comparison between MTV and PIV

	PIV	MTV
Tracer:	particles (~μm)	molecules (~nm)
Image photon source:	scattering light	emission (fluorescence/phosphorescence)
Laser source:	conventional laser	UV laser
signal intensity:	strong	weak

Advantage of MTV

- Flows are hard to seed by particles
  - boundary layers or vortex cores
- Particles may change flows
  - micro-flows
- Particles do not follow flows
  - high speed flows, shock waves
- Particles may change the physics of phenomena
  - solidification
- Simultaneous vector/scalar distribution measurements.

Disadvantage of MTV

- Less light compared to PIV
  - Emission rather than scattering
  - May require intensified cameras
- Chemicals
- Photon Source
  - UV and/or deep UV
  - High Energy
  - Some require multiple photon sources
- Equipment Cost

❑ Components of Molecular Tagging Visualization / Velocimetry

- **Long Lifetime Molecular Tracers**

  The tracer photophysics dictates the type and number of lasers needed

- **Tagging Methods**

  Single-line, Multi-line

  Grid, Laser sheet

- **Detection**

  Standard CCD Cameras

  Gated Image-Intensified Cameras

  Dual Detector for Increased Accuracy

  Multi-Camera for Stereo MTV

- **Processing**

  Line Center Methods

  Direct Spatial Correlation

Liquid Phase

Photochromic Molecules (*Hummel, Falco*)

Caged Laser Dyes (*Lempert*)

Phosphorescent Supramolecules

Gas Phase

Vibrationally Excited O_2 (*Miles*)

Ozone (O_3) (*Pitz*)

OH (dissociation of H_2O) (*Boedeker, Pitz*)

NO (dissociation of Tert-butyl nitrite) (*Grünefeld*)

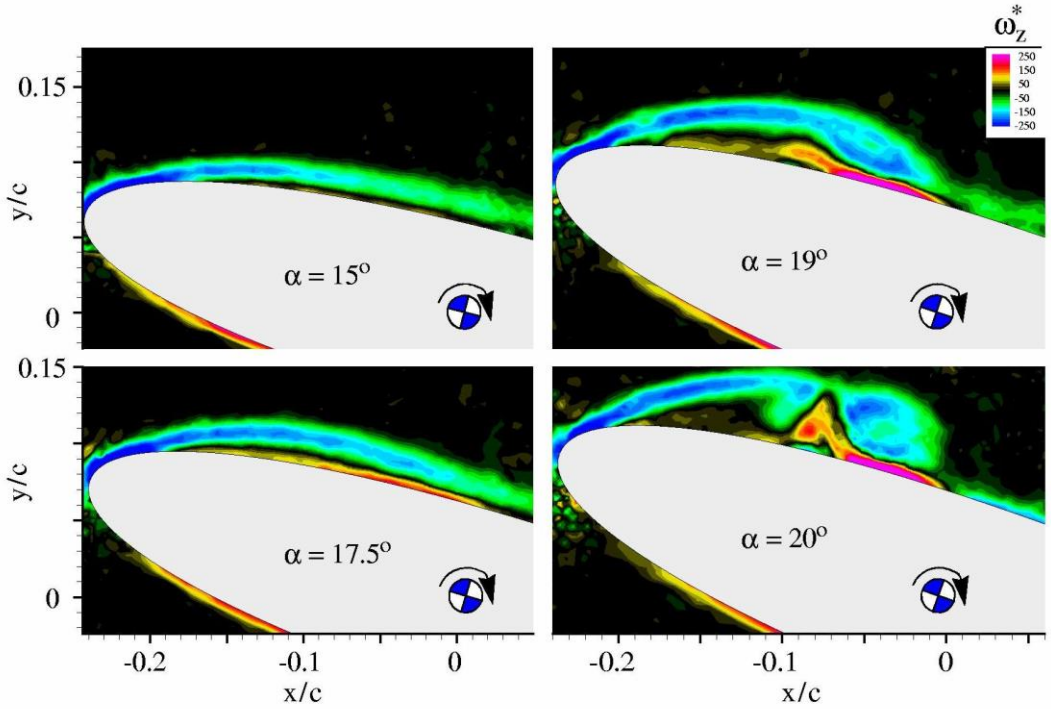
NO (air photolysis) (*Sijtsema et al.*)

Ionic Strontium Fluorescence (*Rubinsztein-Dunlop et al.*)

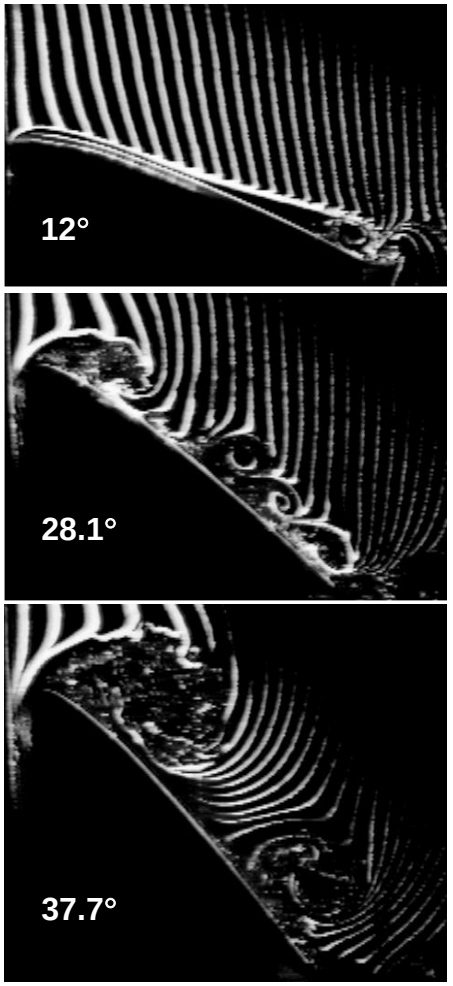
Phosphorescent Molecules
(Biacetyl, Acetone, etc.)

❑ Applications: Unsteady Flow Separation on Airfoils

- Airfoils moving to high angles of attack undergo dynamic stall, characterized by large excursions in lift and pitching moment.



Boundary layer resolved vorticity measurements have revealed the flow physics at the onset of the separation process, and its spatial and temporal scales.

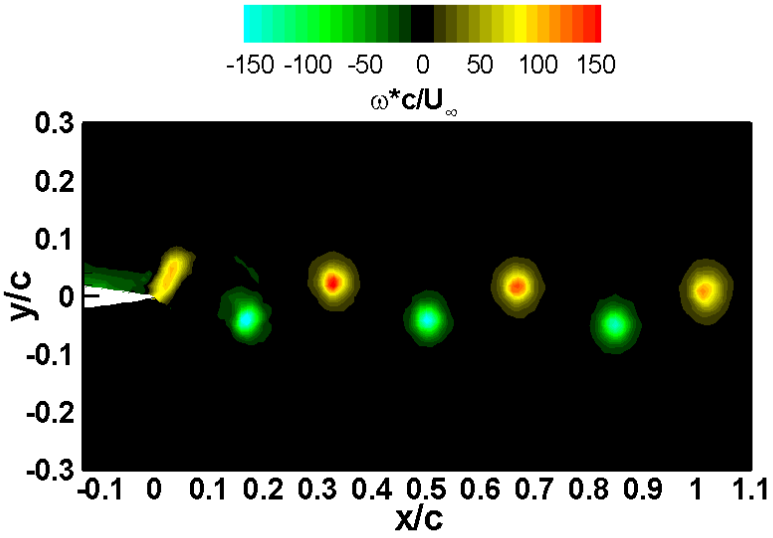


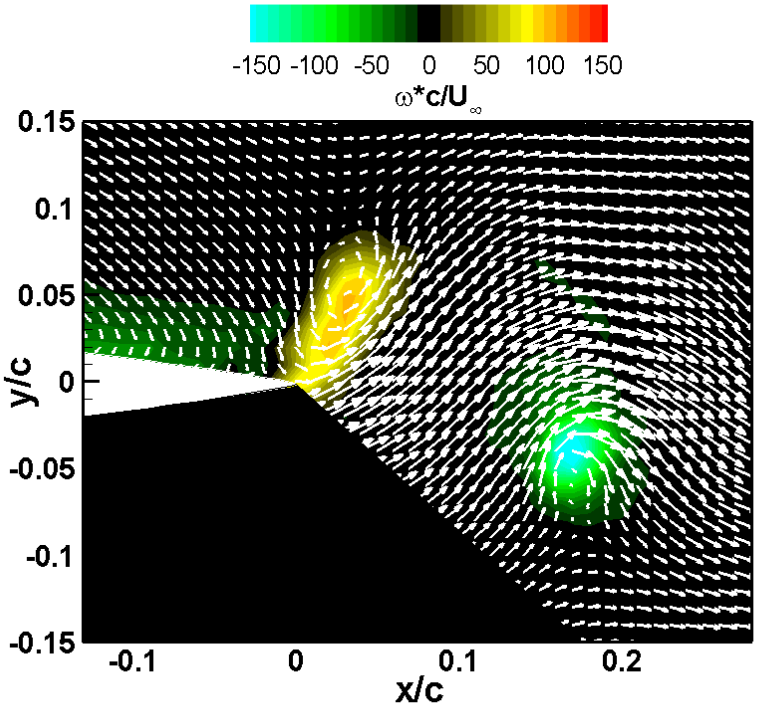
NACA-0012 airfoil pitching to high angle of attack

hydrogen-bubble visualization

❑ Quantitative MTV Measurements

Using the grid tagging method, the in-plane velocity components and the vorticity field are mapped. Data below are for k = 11.5.

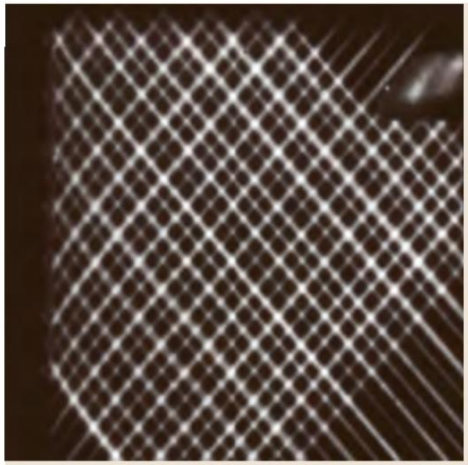




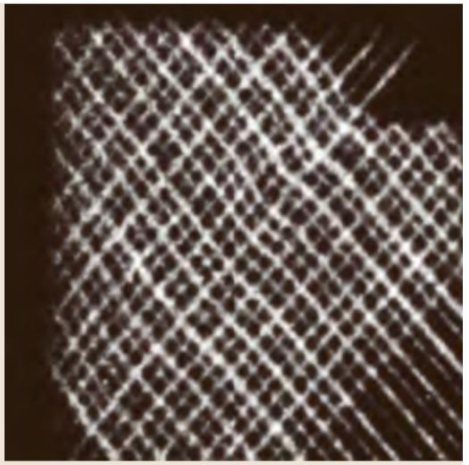
Strong concentrated vortices are formed immediately at the trailing edge.
Instantaneous streamlines are highly curved near the trailing edge.
Note the location and sign of the vortices formed at the trailing edge.

(Bohl et al. 2004)

❑ Applications: MTV Measurements in a Motored IC Engine

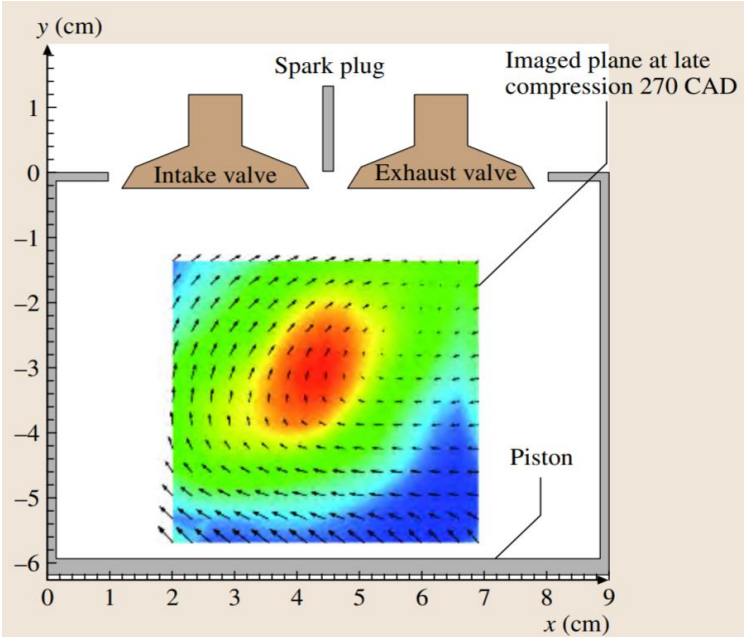


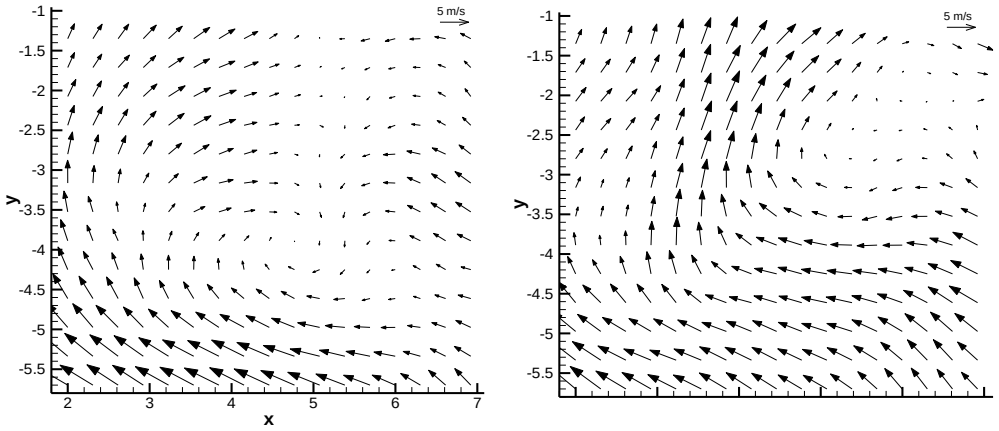
Tagged regions right after the laser pulse



Tagged regions 50 μs later; 3 cm × 3 cm field of view

- ***Optically accessible Ford 4-valve, 4.6L engine***



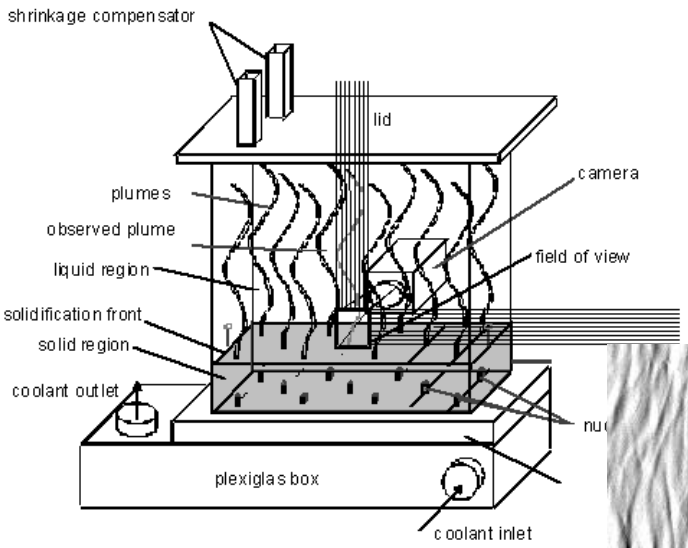


Two instantaneous realizations showing the large cycle-to-cycle variability of the flow field.

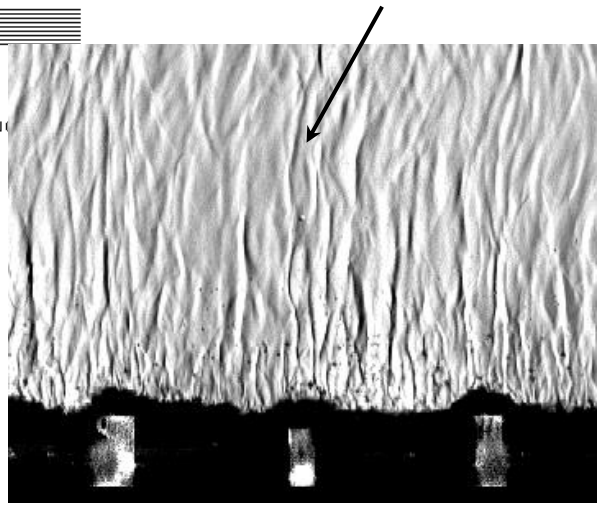
Goh, Koochesfahani & Schock (2001)

Applications: Uni-Directional Solidification of Optically Transparent Binary Alloy Analog, NH_4Cl

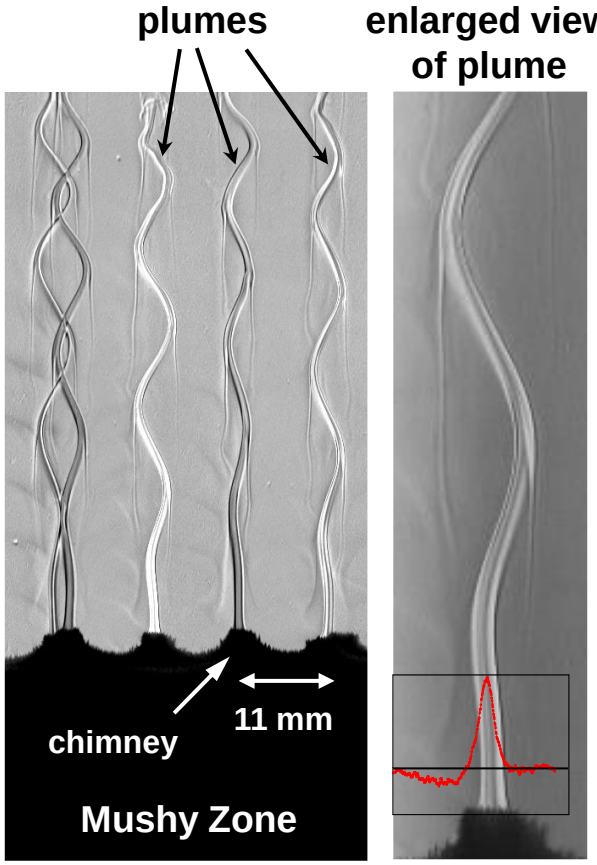
- Uni-directional solidification provides increased resistance to creep rupture and thermal fatigue in the final solidified ingot.
- Solutal and thermal forces produce imperfections in the final solidified ingot in the form of solute-rich channels.



(Lum et al. 2004)

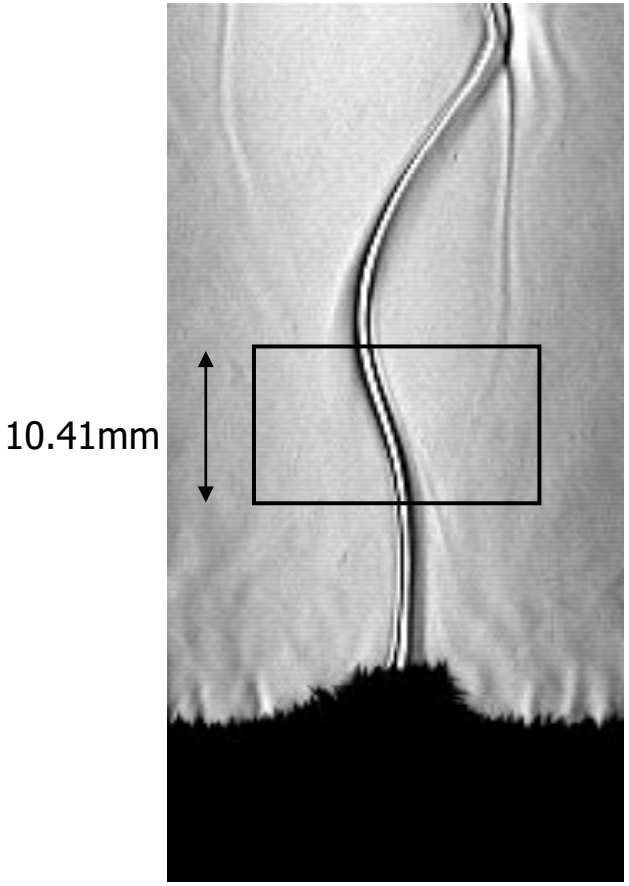


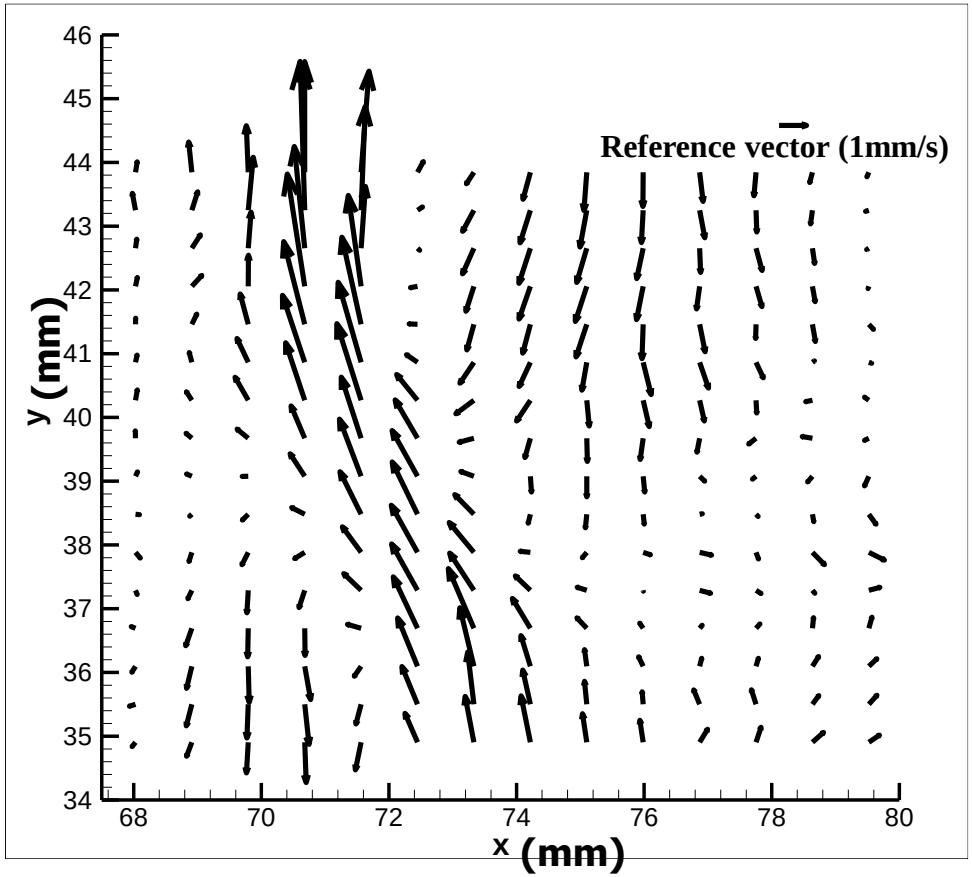
Early stage of solidification



Later stage of solidification

Applications: Uni-Directional Solidification of Optically Transparent Binary Alloy Analog, NH_4Cl





- Velocity vector of plume (79 min into the solidification process)
- Maximum magnitude of velocity is ~7mm/s within the plume

(Lum et al. 2004)