Short Course: Advanced Flow Diagnostic Techniques for Thermal Fluid Studies

Dr. Hui Hu

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

- This short course aims to give a comprehensive introduction of the advanced measurement techniques widely used for fluid mechanics, aerodynamics, heat transfer and combustion studies.
- Demonstration lab experiments will also be incorporated in this course.

Topics to be covered in this short course:
- Pressure Gauge and Transducers
- Pressure Sensitive Painting (PSP); Temperature Sensitive Painting (TSP)
- Shadowgraph and Schlieren photography
- Hot Wire Anemometry (HWA)
- Laser Doppler Velocimetry (LDV) and Planar Doppler Velocimetry (PDV)
- Particle Image Velocimetry (classic PIV, Stereo PIV, 3-D PIV; Holograph PIV, micro-PIV)
- Laser Induced Fluorescence (LIF) and Planar LIF
- Molecular Tagging Velocimetry and Thermometry (MTV&T).

Schedule of the short course:
- 06-July, Tuesday, 1-4pm at GECD: Introductions and fundamentals, PSP/TSP
- 13-July, Tuesday, 1-4pm at GECD: Schlieren and Shadowgraph, HWA, LDV/PDV
- 20-July, Tuesday, 1-4pm at GECD: PIV; Stereo PIV and 3-D PIV
- 10-Aug, Tuesday, 1-4pm at GECD: LIF, MTV and MTT, QD imaging
- 17-Aug, Tuesday, 1-4pm at ISU Lab: 5–7 demonstration experiments
AFD, CFD and EFD

Computational Fluid Dynamics (CFD)

Flow Physics

Experimental Fluid Dynamics (EFD)

Analytical Fluid Dynamics (AFD)
Basics and Fundamentals about Experiments and Instrumentations
Review of Fundamentals about Experiments and Instrumentations

- Basic concepts and fundamental principles
- Similitude and dimension analysis
- Measurement uncertainty analysis
- Fluid Mechanical apparatus: wind tunnels and water tunnels
Measurable Properties

• **Material Properties:** $\rho, m, \text{specific volume}, \mu, \gamma, D$
  (Most of them can be found in handbooks)

• **Kinematic Properties:** Describes the fluid motion w/o considering the force.
  (Position, $V$, displacement, acceleration, momentum, volume flow rate, mass flow rate, etc)

• **Dynamic properties:** Related to applied forces.
  (Pressure, shear stress, Torque)

• **Thermodynamic properties:** Heat and Work.
  ($T, e, h, S$)
Descriptions of Flow Motion

- **Lagrangian Method**: Focused on fluid particles

\[
V = \lim_{\Delta t \to 0} \frac{\Delta L}{\Delta t}
\]

- **Eulerian Method**: Focused on space location.

\[
U(x_i, t) = V(x_{0i}, t)
\]

**Acceleration:**

\[
\bar{a} = \frac{DV}{Dt} \quad \Rightarrow \quad \text{Langragian domain}
\]

\[
\bar{a} = \frac{\partial \vec{U}}{\partial t} + (\vec{U} \cdot \nabla)\vec{U}
\]

\[
= \frac{\partial \vec{U}}{\partial t} + U_1 \frac{\partial \vec{U}}{\partial x_1} + U_2 \frac{\partial \vec{U}}{\partial x_2} + U_3 \frac{\partial \vec{U}}{\partial x_3} \quad \Rightarrow \quad \text{Eulerian domain}
\]

**Rate of Strain:**

\[
e_{ij} = \frac{1}{2} \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right)
\]

**Shear stress:**

\[
\tau_{ij} = \mu \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right)
\]
Primary Properties and Secondary properties

- **Primary Properties:** Properties which are independent to each other

<table>
<thead>
<tr>
<th>Name</th>
<th>Abbreviations</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>L</td>
<td>M</td>
</tr>
<tr>
<td>Mass</td>
<td>m</td>
<td>kg</td>
</tr>
<tr>
<td>Time</td>
<td>t</td>
<td>s</td>
</tr>
<tr>
<td>Temperature</td>
<td>T</td>
<td>K</td>
</tr>
<tr>
<td>Electric current</td>
<td>I</td>
<td>A</td>
</tr>
<tr>
<td>Amount of substance</td>
<td>mole</td>
<td>mol</td>
</tr>
<tr>
<td>Luminous intensity</td>
<td>Candela</td>
<td>Cd</td>
</tr>
<tr>
<td>Plane Angle</td>
<td>Radius</td>
<td>rad</td>
</tr>
<tr>
<td>Solid Angle</td>
<td>Storadian</td>
<td>Sr</td>
</tr>
</tbody>
</table>

- **Secondary Properties:** Related to other properties through their definition or basic principles
Similitude and Dimensional Analysis

• Similitude:
  • The study of predicting prototype conditions from model observations.

F-22 Raptor Air Superiority Fighter
Similitude and Dimensional Analysis

\[ \Delta p_l = f(D, \rho, \mu, V) \]

\[ \frac{\Delta p}{\rho V^2} = \Phi\left(\frac{\rho V D}{\mu}\right) \]

(a) \( D, \rho, \mu \) – constant

(b) \( V, \rho, \mu \) – constant

(c) \( D, V, \mu \) – constant

(d) \( D, \rho, V \) – constant
Buckingham $\pi$ - Theorem

- **Step 1:** List all the variables that are involved in the problem.
- **Step 2:** Express each of the variables in terms of basic dimensions.
  - Basic dimension: $M, L, T, F$
  - Force - $F = MLT^2$, density - $\rho = ML^{-3}$; or $\rho = FL^{-3}T^2$.
- **Step 3:** Determine the required number of pi-terms.
  - Number of pi-terms is equal to $k-r$, where $k$ is the number of variables in the problem, $r$ is the number of reference dimensions required to describe the variables.
- **Step 4:** Select a number of repeating variables, where the number required is equal to the number of reference dimensions.
- **Step 5:** Form a pi-term by multiplying one of the non-repeating variables by the product of repeating variables, each raised to an exponent that will make the combination dimensionless.
- **Step 6:** Repeat Step 5 for each of the remaining non-repeating variables.
- **Step 7:** Check all the resulting pi terms to make sure they are dimensionless.
- **Step 8:** Express the final form as a relationship among the pi-terms, and think about what it means.

$$\Pi_1 = \Phi(\Pi_2, \Pi_3, \ldots, \Pi_{k-r})$$
Buckingham $\pi$-Theorem

- Example

$\Delta p_1 = f(D, \rho, \mu, V)$

\[ \Delta p_1 = FL^{-3} \]
\[ D = L \]
\[ \rho = FL^{-4}T^2 \]
\[ V = LT^{-1} \]
\[ \mu = FL^{-2}T \]

$K = 5; \quad r = 3 \quad \Rightarrow \quad 2 \pi - \text{terms is needed}$

\[ \Pi_1 = \Delta p_1 D^a V^b \rho^c \]

\[
(FL^{-3})(L)^a (LT^{-1})^b (FL^{-4}T^2)^c = F^0 T^0 L^0 \quad \Rightarrow \quad \begin{cases} 
1 + c = 0 \\
-3 + a + b - 4c = 0 \\
-b + 2c = 0 
\end{cases} \quad \Rightarrow \quad \begin{cases} 
a = 1 \\
b = -2 \\
c = -1 
\end{cases} \quad \Pi_1 = \frac{\Delta p_1 D}{\rho V^2} 
\]

\[ \Pi_2 = \mu D^a V^b \rho^c \]

\[
(FL^{-2}T)(L)^a (LT^{-1})^b (FL^{-4}T^2)^c = F^0 T^0 L^0 \quad \Rightarrow \quad \begin{cases} 
1 + c = 0 \\
-2 + a + b - 4c = 0 \\
1 - b + 2c = 0 
\end{cases} \quad \Rightarrow \quad \begin{cases} 
a = -1 \\
b = -1 \\
c = -1 
\end{cases} \quad \Pi_2 = \frac{\mu}{D\rho V} 
\]
Commonly used dimensionless parameters

- Mach Number, \( M = \frac{V}{c} \propto \frac{\text{inertial force}}{\text{compressibility force}} \)
- Reynolds number, \( Re = \frac{\rho VL}{\mu} \propto \frac{\text{inertial force}}{\text{viscous force}} \)
- Euler number, \( Eu = \frac{\Delta p}{\frac{1}{2} \rho V^2} \propto \frac{\text{pressure force}}{\text{inertial force}} \)
- Drag Coefficient : \( C_D = \frac{D}{\frac{1}{2} \rho V^2} = \frac{\text{Drag}}{\text{inertial force}} \)
- Lift Coefficient : \( C_L = \frac{L}{\frac{1}{2} \rho V^2} = \frac{\text{Lift}}{\text{inertial force}} \)
- Prandtl Number : \( Pr = \frac{V}{\gamma} = \frac{\text{momentum diffusion}}{\text{heat diffusion}} \)
- Schmidt Number : \( Sc = \frac{U}{\gamma_c} = \frac{\text{momentum}}{\text{mass}} \)
- Froude Number, \( Fr = \frac{V}{\sqrt{\frac{g}{c}}} \propto \frac{\text{inertial force}}{\text{gravity force}} \)
- Strohal Number, \( Str = \frac{\omega l}{V} \propto \frac{\text{centrifugal force}}{\text{inertial force}} \)
- Weber Number, \( We = \frac{V^2 l \rho}{\sigma} \propto \frac{\text{inertial force}}{\text{surface tension force}} \)

...
Similitude

- Geometric similarity: the model have the same shape as the prototype:

F-16

F-22
Similitude

- **Kinematic similarity**: condition where the velocity ratio is a constant between all corresponding points in the flow field.
  - The streamline pattern around the model is the same as that around the prototype.
Similitude

- Dynamic similarity: Forces which act on corresponding masses in the model flow and prototype flow are in the same ratio through out the entire flow.

\[
\begin{align*}
\frac{(F_I)_m}{(F_I)_p} &= \frac{(F_p)_m}{(F_p)_p} = \frac{(F_\mu)_m}{(F_\mu)_p} = \frac{(F_g)_m}{(F_g)_p} = \text{constant} \\
\Rightarrow \frac{(F_I)_m}{(F_I)_p} &= \frac{(F_p)_m}{(F_p)_p} \Rightarrow \frac{(F_I)_m}{(F_p)_m} = \frac{(F_I)_p}{(F_p)_p} \Rightarrow Eu_m = Eu_p \\
\Rightarrow \frac{(F_I)_m}{(F_I)_p} &= \frac{(F_\mu)_m}{(F_\mu)_p} \Rightarrow \frac{(F_I)_m}{(F_\mu)_m} = \frac{(F_I)_p}{(F_\mu)_p} \Rightarrow Re_m = Re_p \\
\Rightarrow \frac{(F_I)_m}{(F_I)_p} &= \frac{(F_g)_m}{(F_g)_p} \Rightarrow \frac{(F_I)_m}{(F_g)_m} = \frac{(F_I)_p}{(F_g)_p} \Rightarrow Fr_m = Fr_p
\end{align*}
\]
Wind Tunnels and Water Tunnels

- Producing the desired flow field with controlled conditions
Types of Wind Tunnels

Based on Flow Speed:

- **Subsonic or low speed wind tunnels** ($M << 1.0$)
- **Transonic wind tunnels** ($M \approx 1.0$)
- **Supersonic wing tunnels** ($1.0 < M < 5.0$)
- **Hypersonic wind tunnels** ($M > 5.0$)

Based on Shape:

- **Open circuit wind tunnel**:
- **Closed circuit wind tunnel**:

Other special wind tunnels:

- **Icing wind tunnel**
- **Tornado simulators**
- …
Open Circuit Wind Tunnel

- **Suction wind tunnel:** With the inlet open to atmosphere, axial fan or centrifugal blower is installed after test section.

- **Blow down wind tunnel:** A blower is installed at the inlet of wind tunnel which throws the air into wind tunnel.
Closed circuit wind tunnel
Components of a Wind Tunnel

- Test section
- Contraction section
- Diffuser section
- Setting chamber
- Screens and similar structures
- Cooling system / radiators
- Motors / fans
Function of Contraction


c_1 = \frac{A_1}{A_2} \quad \text{if} \quad \frac{\Delta V_1}{V_1} = 0.1 \quad \frac{\Delta V_2}{V_2} = \frac{1}{c^2} \frac{\Delta V_1}{V_1} = \frac{0.1}{100} = 0.001
Water Tunnels
Towing Tank
**Measurement Uncertainties**

- “Accuracy” is generally used to indicate the relative closeness of agreement between an experimentally-determined value of a quantity and its true value.
- “Error” is the difference between the experimentally-determined value and its true value; therefore, as error decreases, accuracy is said to increase.
- Since the true value is not known, it is necessary to estimate error, and that estimate is called an uncertainty, $U$.
- Uncertainty estimates are made at some confidence level—a 95% confidence estimate, for example, means that the true value of the quantity is expected to be within the $\pm U$ interval about the experimentally-determined value 95 times out of 100.

\[
A_{\text{error}} = A_{\text{measured}} - A_{\text{true}} \quad \Rightarrow \quad E = A_m - A_{\text{true}}
\]

Which Case is more accurate measurement?

$V_i = 10m/s$, Measurement error $\Delta V = 1m/s$

$V_i = 100m/s$, Measurement error $\Delta V = 5m/s$

\[
E_{\text{relative}} = \frac{A_{\text{error}}}{A_{\text{true}}}
\]
Measurement Uncertainties

- **Total error, \( U \), can be considered to be composed of two components:**
  - a random (precision) component,
  - a systematic (bias) component,
  - We usually don’t know these exactly, so we estimate them with \( P \) and \( B \), respectively.

- **Precision Error: Random error**
  - Normal Distribution or Gaussian Distribution

- **Bias Error: Fixed Error, System Error**
  - Constant Throughout the experiment
  - Can be positive or Negative

\[
U^2 = B^2 + P^2
\]
Measurement Uncertainties

- Precise but biased
- Unbiased but Imprecise
- Biased and Imprecise
- Precise and Unbiased

Qualification of measurement error:

\[ E^2 = B^2 + P^2 \]
• **Repeatability** is the variability of the measurements obtained by one person while measuring the same item repeatedly. This is also known as the inherent precision of the measurement equipment.
  - Consider the probability density functions shown in Figure 1. The density functions were constructed from measurements of the thickness of a piece of metal with Gage A and Gage B. The density functions demonstrate that Gage B is more repeatable than Gage A.

• **Reproducibility** is the variability of the measurement system caused by differences in operator behavior. Mathematically, it is the variability of the average values obtained by several operators while measuring the same item.
  - Figure 2 displays the probability density functions of the measurements for three operators. The variability of the individual operators are the same, but because each operator has a different bias, the total variability of the measurement system is higher when three operators are used than when one operator is used.

<table>
<thead>
<tr>
<th>Repeatability</th>
<th>Precision Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reproducibility</td>
<td>Both Bias and Precision Errors</td>
</tr>
</tbody>
</table>
Measurement Uncertainties

• We almost always are dealing with a data reduction equation to get to our final results.
  – In this case, we must not only deal with uncertainty in the measured values but uncertainty in the final results.

• A general form looks like this:

\[
R = R(X_1, X_2, X_3, \ldots, X_J)
\]

  – R is the result determined from J independent variables.
Example

**Uncertainty in velocity \( V \):**

\[
U_R^2 = B_R^2 + P_R^2
\]

\[
B_R^2 = \sum_{i=1}^{J} \left[ \frac{\partial R}{\partial X_i} B_i \right]^2 ; \quad P_R^2 = \sum_{i=1}^{J} \left[ \frac{\partial R}{\partial X_i} P_i \right]^2
\]

\[
B_i = \sqrt{\sum_{j=1}^{M} B_{i,j}^2}
\]

For a large number of samples \((N>10)\)

\[
P_i = 2S_i
\]

\[
S_i = \left[ \frac{1}{N-1} \sum_{k=1}^{N} (X_i)_k - \overline{X}_i \right]^2 ; \quad \overline{X}_i = \frac{1}{N} \sum_{k=1}^{N} (X_i)_k
\]

\[
P_{\text{total}} = p_{\text{static}} + \frac{1}{2} \rho V^2, \quad \text{(Bernoulli)}
\]

\[
V = \sqrt{\frac{2(p_{\text{total}} - p_{\text{static}})}{\rho}} = \sqrt{\frac{2\Delta p}{\rho}}
\]
Technical Basis for Optical Instrumentation
The nature of light

- According to classical electromagnetic theory, light is considered to be radiation that propagates through vacuum in free space in the form of electromagnetic waves, both oscillating transversely to the direction of wave propagation and normal to each other.

\[ E_y(x, t) = E_{y0} \sin 2\pi \left( \frac{x}{\lambda} - \frac{t}{T} \right) \]

\[ B_z(x, t) = B_{z0} \sin 2\pi \left( \frac{x}{\lambda} - \frac{t}{T} \right) \]

- \( \lambda \): is wavelength
- \( T \): is the period of the oscillation
- \( \nu \): The reciprocal of the period, is called frequency, \( \nu = 1/T \)
The nature of light-1

- Light propagation velocity, \( V = f \lambda \)
- Light propagation velocity in Vacuum, \( C = 2.998 \times 10^8 \text{ m/s} \)
- Wave front: the locus of all points along the different paths that have the same phase.
- If all the wave fronts are plane, then, the light is considered to be a plane wave.
- If all the wave fronts are spherical or cylindrical, then, the light is considered to be a spherical or cylindrical wave.
- Light propagation is associated with electric and magnetic fields. They are in phase and their amplitudes are related as:
  \[ E_y^0 = c B_z^0 \]
- It is usually sufficiently to analyze electromagnetic waves by considering only electric field.
- The polarization is associate with the orientation of the plane of the plane of oscillation of the electric field.
- Concepts of linearly polarized light, elliptically polarized light and circularly polarized light, unpolarized or randomly polarized light.
# The nature of light -2

<table>
<thead>
<tr>
<th>RADIATION TYPE</th>
<th>WAVELENGTH RANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmic rays</td>
<td>$\lambda &lt; 10^{-4}$ nm</td>
</tr>
<tr>
<td>Gamma rays</td>
<td>$10^{-4}$ nm &lt; $\lambda$ &lt; $10^{-1}$ nm</td>
</tr>
<tr>
<td>X-rays</td>
<td>$10^{-2}$ nm &lt; $\lambda$ &lt; $10^{2}$ nm</td>
</tr>
<tr>
<td>Disinfecting radiation</td>
<td>$10$ nm &lt; $\lambda$ &lt; $380$ nm</td>
</tr>
<tr>
<td>Visible light</td>
<td>$380$ nm &lt; $\lambda$ &lt; $750$ nm</td>
</tr>
<tr>
<td>Space heating</td>
<td>$750$ nm &lt; $\lambda$ &lt; $10^{7}$ nm</td>
</tr>
<tr>
<td>Microwaves</td>
<td>$10^{6}$ nm &lt; $\lambda$ &lt; $10^{9}$ nm</td>
</tr>
<tr>
<td>Radar</td>
<td>$10^{7}$ nm &lt; $\lambda$ &lt; $10^{9}$ nm</td>
</tr>
<tr>
<td>Radio and Television</td>
<td>$10^{8}$ nm &lt; $\lambda$ &lt; $10^{13}$ nm</td>
</tr>
<tr>
<td>Electrical power waves</td>
<td>$10^{14}$ nm &lt; $\lambda$ &lt; $10^{17}$ nm</td>
</tr>
</tbody>
</table>

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The nature of light -2

- The colors: visible light consists of radiation with wavelength in the range of 380~750nm (1nm=10^{-9} m) which corresponds to the frequency range between 4.0 \times 10^{15} to 7.9 \times 10^{15} Hz.

<table>
<thead>
<tr>
<th>COLOR</th>
<th>WAVELENGTH RANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultraviolet (UV)</td>
<td>0.85 nm &lt; \lambda &lt; 380 nm</td>
</tr>
<tr>
<td>Violet</td>
<td>380 nm &lt; \lambda &lt; 424 nm</td>
</tr>
<tr>
<td>Blue</td>
<td>424 nm &lt; \lambda &lt; 491 nm</td>
</tr>
<tr>
<td>Green</td>
<td>491 nm &lt; \lambda &lt; 575 nm</td>
</tr>
<tr>
<td>Yellow</td>
<td>575 nm &lt; \lambda &lt; 585 nm</td>
</tr>
<tr>
<td>Orange</td>
<td>585 nm &lt; \lambda &lt; 647 nm</td>
</tr>
<tr>
<td>Red</td>
<td>647 nm &lt; \lambda &lt; 750 nm</td>
</tr>
<tr>
<td>infrared</td>
<td>750 nm &lt; \lambda &lt; 1000 nm</td>
</tr>
</tbody>
</table>
The nature of light – as photons

- **Photon scattering.**
  - one finds experimentally that the frequency of the scattered wave is changed, which does not come out of a wave picture of light. However, when the light is viewed as a photon with energy proportional to the associated light wave, excellent agreement with experiment is found.

- **The photoelectric effect:**
  - When light is shone at a metal plate, it is found that electrons are ejected. These electrons then get accelerated to a nearby plate by an external potential difference, and a photoelectric current is established, as below.
  - The photons hit an electron in the metal, giving up its energy. This is enough to free the electron from the attractive forces holding it in the metal, and it is accelerated towards the other side, causing a flow of charges and hence a current.
  - It is found experimentally that the photoelectric current depends critically on the frequency of the light being used. This is a feature of the energy that the electrons gain when struck by the light, but in the wave picture the energy of the light depends on the amplitude, and not on the frequency.
  - However, in the photon picture of light the energy of the photon is proportional to the frequency of the associated wave, which therefore provides a natural explanation of the frequency dependence of the photoelectric current.
  - The explanation, which was first given by Einstein and which won him the Nobel Prize.

\[ \varepsilon = h \nu \]

Planck const \(= 6.624 \times 10^{-34} \text{ Js} \)
Light propagate through media

- **Refractive index:** \( n = c / v = \frac{\lambda_0}{\lambda} > 1 \)

- **Index of refraction of a material generally increasing slightly with decreasing wavelength of the light. Such phenomena is called dispersion.**

\[
n = \sqrt{\frac{1 + 2K_L\rho}{1 - K_L\rho}}
\]

<table>
<thead>
<tr>
<th>Gas</th>
<th>Liquid</th>
<th>n</th>
<th>Solid</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>Water</td>
<td>1.333</td>
<td>Fused quartz</td>
<td>1.46</td>
</tr>
<tr>
<td>He</td>
<td>Ethyl alcohol</td>
<td>1.361</td>
<td>Pyrex glass</td>
<td>1.47</td>
</tr>
<tr>
<td>CO₂</td>
<td>Turpentine</td>
<td>1.472</td>
<td>Crown glass</td>
<td>1.52</td>
</tr>
<tr>
<td>H₂</td>
<td>Benzene</td>
<td>1.501</td>
<td>Flint glass</td>
<td>1.57~1.89</td>
</tr>
<tr>
<td></td>
<td>Benzene</td>
<td>1.501</td>
<td>Plexiglas</td>
<td>1.51</td>
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<td></td>
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<td></td>
<td>Lexan</td>
<td>1.58</td>
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<tr>
<td></td>
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<td></td>
<td>Polystyrene</td>
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<td></td>
<td></td>
<td></td>
<td>sapphire</td>
<td>1.77</td>
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<td></td>
<td></td>
<td></td>
<td>zircon</td>
<td>1.92</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Diamond</td>
<td>2.42</td>
</tr>
<tr>
<td></td>
<td></td>
<td>589nm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Light propagate through media

- **Refraction:**
  - When light propagates through a homogenous medium, its path would be straight, whereas, if the medium is non-homogeneous or if the light across from one medium to another, the path may change direction gradually or abruptly. The change of light propagation direction is called refraction.
  
  - Optically denser medium \((n_1<n_2)\)

\[
\frac{\sin \varphi_1}{\sin \varphi_2} = \frac{n_2}{n_1}
\]
Light propagate through media

- **Total refraction**

  \[
  \frac{\sin \varphi_1}{\sin \varphi_2} = \frac{n_2}{n_1}
  \]

  \[n_1 > n_2 \Rightarrow \varphi_2 > \varphi_1\]

  \[\varphi_{2\text{max}} > \frac{\pi}{2} \Rightarrow \varphi_{1\text{cri}} = \sin^{-1}(n_2 / n_1)\]

- **reflection**
Light propagate through media

- Optical lens

Convex lens

Concave lens
Light propagate through media

\[ n = \frac{c}{v} = \frac{\lambda_0}{\lambda} > 1 \]

Figure 5.4. Interpretation of light refraction at the interface between two media as the rotation of wave fronts.
How does refractive-index-matching help?

- **Optical techniques avoid disturbing the flow to be measured**
- **Typical approaches are LDV, PIV, PTV, flow visualization, PLIF, etc.**

*Example of application of refractive-index-matching*

*Refractive index not matched*

*Unless the refractive indices are matched, the view may be distorted or impossible even with "transparent" materials and position measurements may be incorrect*
Absorption

- Light is transmitted through a material, it will be absorbed by the molecules of the material.

- Beer’s law: 
  \[ I = I_0 \exp(-\alpha L) \]

  - \( \alpha \) is the absorption or attenuation coefficient.
  - \( L_c = 1/\alpha \) is called penetration depth.
  - When \( L = L_c \), \( I/I_0 = 1/e = 37\% \), i.e., 63\% energy was absorbed.
  - Metals have very small \( L_c = 1/\alpha \).
  - Copper, \( L_c = 0.6 \text{nm} \) for 100 nm UV light.
  - Copper, \( L_c = 6.0 \text{nm} \) for 1000 nm infrared light.
  - 2nm copper plate as the high pass filter.
illumination

• **Light source**
  – **Thermal source:**
    • *Lamps: Continuous wave (CW)*
  – **Laser sources**
    • *Continuous wave (CW)*
    • *Pulsed laser*
    • *Single wavelength*
  – **Point source:**
  – **Plane source:**
Light source

- **Thermal light source:**
  - Emit electromagnetic radiation as a result of being heated to high-temperature
  - **Line sources:**
  - **Continuum sources:**
  - **Incandescent lamps:** heated tungsten filament in a evacuated glass container.
  - **Electric discharge lamps:** fluorescent lamps. Filled with mercury vapor at low pressure and utilize an electric discharge through it to produce light in ultraviolet (UV) range. Through fluorescent, it is convert to visible light.
  - **Flash lamps:** tubes containing a noble gas such xenon, krypton or argon. For their operation, high voltage stored in a capacitor is discharged through the gas, producing a highly luminous corona discharge. Light pulse is about 1μs or 1 ms.
  - **Sparks:** produced by the electric breakdown of a gas (helium, neo, argon or air) during an electric discharge between electrodes. The choice of different electrodes produces sparks of different shapes.
Laser

- **Laser: Light Amplification by Stimulated Emission of Radiation (LASER)**
- **Advantages of laser light over thermal light source:**
  - Coherent light (with all light wave front in phase)
  - Collimated and concentrated (parallel light with small cross area)
  - Monochromic (energy concentrated in a very narrow wavelength band)
- **How a laser works:**
  - Radiation energy is produced by an activated medium (can be gas, crystal or semiconductor or liquid solution).
  - The medium consists of particles (atom, ions or molecules).
  - When a photo, having energy $hv$, approaching the particles, the photo may be absorbed causing an electron or atoms to be raised temporarily to high-energy level.
  - When the excited electron or molecule to return ground level, spontaneous emission or stimulated emission would take place.
- **Spontaneous emission**: emit a photo with the same energy as that absorbed one, but in random direction.
- **Stimulated emission**: An electron or atom is already at a higher energy level could become excited by an incident photo, without absorb the photo, it will emission another photo with identical energy (frequency), phase, and direction as the incident photon.
- **External power source** is required to maintain the population of the atoms in higher energy level in order to make to stimulated emission taking place continuously.
- **Optical cavity**.
- **Q-switch**
Commonly used Lasers

- Helium-neon (He-Ne) laser
  - Active medium is helium neon atoms
  - Continuous wave laser
  - Power 0.3 ~15 mW
  - $\lambda = 633\text{nm (red)}$
Commonly used Lasers

- Argon-ion (Ar-ion) laser
  - Active medium is argon atoms maintained at the ion state.
  - Continuous wave laser
  - Power level: 100 mW ~10 W
  - Have seven wavelengths
    - $\lambda = 488$nm (blue)
    - $\lambda = 514.5$nm (green)
  - LDV application
  - LIF in liquid flows
Commonly used Lasers

- Nd-YAG laser
  - **Solid-state laser**
  - **Active medium:** neodymium (Nd$^{+3}$) as active medium incorporated as an impurity into a crystal of Yttrium-Aluminium-Garnet (YAG) as a host
  - **Flash lamp is used as external source**
  - **pulsed laser:** 10 - 400mJ/pulse or more
  - **Pulse duration:** 100ps ~ 10ns
  - **Wavelength of tube** $\lambda$ = 1064nm (infrared)
  - **SHG:** $\lambda$ = 532nm (green), **THG:** $\lambda$ = 355nm (UV), **FHG:** $\lambda$ = 266nm (deepUV)
  - **PIV, MTV, PLIF**
  - **Repetition rate can be as high as 30 Hz.**
Commonly used Lasers

- Copper Vapor laser
  - Active medium: copper vapor
  - Pulsed laser: 10mJ/pulse or more
  - Pulse duration: 15 ~ 60ns
  - \( \lambda = 510.6 \text{nm (green)}, \lambda = 578.2 \text{nm (yellow)} \)
  - Repetition rate can be as high as \( f = 5,000 \sim 15,000 \text{ Hz} \).
  - High-speed PIV, LIF and others
Commonly used Lasers

- **Dye laser**
  - Active medium: complex multi-atomic organic molecules
  - $\lambda = 200\text{nm} \sim 1500\text{nm}$

- **Excimer laser**
  - Gas laser KrF and XeCl
  - High-energy
  - UV wavelength
  - Pulsed laser
  - high repetition frequency
Light Scattering

- **Scattering**
  - Scattering is a general physical process whereby some forms of radiation, such as light, are forced to deviate from a straight trajectory by one or more localized non-uniformities in the medium through which it passes.

- **Elastic Scattering**
  - Excited electron or atoms emits a photo have exact the same frequency as the incident one.

- **Inelastic scattering**
  - Excited electron or atoms emits a photo have a frequency different from the incident one.
Elastic scattering

• Rayleigh Scattering
  – Light scattering from particles that are smaller than 1/15 of the incident light wavelength (d < \(\frac{\lambda}{15}\)).
  – Efficiency of the scattering from a particle is expressed in terms of scattering cross section.

\[
\sigma_R = \sigma_T \left(\frac{\lambda_0}{\lambda}\right)^2
\]

\[
\sigma_T = 6.65 \times 10^{-29} \text{ m}^2
\]

\(\lambda_0\) is the characteristic wavelength of the atom.

• Mie Scattering
  – Light scattering from a particle with its size close on bigger than the incident light wavelength (d > \(\lambda\)).
  – Conservation of polarization direction
  – Angle dependent
    • Forward scattering
    • Back scattering

1. d=1 \(\mu\) m
2. d=10 \(\mu\) m
3. d=30 \(\mu\) m
**Inelastic Scattering**

- **Raman Scattering**
  - Inelastic scattering from molecules.
  - Chance to occur is about $10^{-5}$ to $10^{-2}$ times lower than the Rayleigh scattering.
  - Scattering cross section is several orders smaller than the Rayleigh scattering.
  - Stokes transition: the energy of the emitted photon is higher than the absorbed photon.
  - Anti-stokes transition: the energy of the emitted photon is lower than the absorbed photon.
  - Time between the absorption and emission: $10^{-14}$ s.
  - Anti-stokes line will be stronger when the temperature is low.

---

Table 5.5. Wavelengths of Raman-scattered radiation for some common molecules in air at standard atmospheric pressure and a temperature of 295 K; excitation was provided by a ruby laser.

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Anti-Stokes line (nm)</th>
<th>Stokes line (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incident light</td>
<td>694.30 (Rayleigh line)</td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>638.23</td>
<td>761.17</td>
</tr>
<tr>
<td>CO₂</td>
<td>637.92</td>
<td>762.23</td>
</tr>
<tr>
<td>CO₂</td>
<td>632.42</td>
<td>769.61</td>
</tr>
<tr>
<td>CO₂</td>
<td>626.57</td>
<td>778.44</td>
</tr>
<tr>
<td>O₂</td>
<td>615.50</td>
<td>796.23</td>
</tr>
<tr>
<td>O₂⁻</td>
<td>614.26</td>
<td>798.31</td>
</tr>
<tr>
<td>N₂</td>
<td>604.34</td>
<td>815.73</td>
</tr>
<tr>
<td>CO</td>
<td>603.19</td>
<td>817.82</td>
</tr>
<tr>
<td>N₂⁻</td>
<td>597.57</td>
<td>828.39</td>
</tr>
<tr>
<td>CH₄</td>
<td>577.45</td>
<td>870.46</td>
</tr>
<tr>
<td>H₂</td>
<td>538.67</td>
<td>976.41</td>
</tr>
</tbody>
</table>
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 $10^{-10} \sim 10^{-5}$ s.

Rhoda mine B
Fluorescence and phosphorescence

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

**MTV chemical:** 1-BrNp•Mβ-CD•ROH complex
Light sensing and recording
**Lenses**

- **Focus length:**
- **Depth of focus:**
- **F-numbers or focal ratio:** is defined as the ratio of focal distance of the lens and its clear aperture diameter.

<table>
<thead>
<tr>
<th>12 F2.8</th>
<th>14 F5.6 F8 F11</th>
<th>116 F22</th>
</tr>
</thead>
<tbody>
<tr>
<td>wide aperture</td>
<td>small aperture</td>
<td>less light</td>
</tr>
<tr>
<td>more light</td>
<td></td>
<td>larger number</td>
</tr>
<tr>
<td>small number</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Photo detector

- **Photo detector** is a device to convert light to an electric current through photo electric effect.

- **Quantum efficiency:**
  
  \[ \eta = \frac{N_e}{N_p} \]

  - \(N_e\): Number of absorbed photons
  - \(N_p\): Number of emitted electrons

- **Noise:**
  - **Shot noise:** due to random fluctuation of the rate of photon collection and back ground illumination
  - **Thermal noise:** caused by amplification of current inside the photo detector and by external amplifier.

- **Dark current:** the current produced by the photo detector even in the absence of a desirable light source.

- **Two kinds of photo detectors:**
  - Photomultiplier tubes (PMT)
  - Photodiodes (PD) or photo electric cells
Photo detector

- **Photomultiplier tubes (PMT)**
  - **Photocathode**: absorbs photons and emits electrons.
  - **Dynodes**: increase number of photons
  - **Anodes**: output
Photo detector

- photodiodes (PD) or photo electric cells
  - P-n junctions of semiconductors, commonly silicon-silicon type.
  - High quantum efficiency
  - But not internal amplification
Linearity and Dynamic Range of a Digital Camera

- **Linearity:**
  - Intensified CCD cameras usually need to check its linearity

- **Dynamic Range:**
  - The ratio between the full-well capacity and the dark current noise.
  - For example, for a 8-bit CCD camera, maximum intensity is $2^8=256$, dark current noise is about 25, then Dynamic range is about 10.

- Available bits number:
  - 8 bit, 16 bit, 24 bit
Interlaced Cameras

- The fastest response time of human being for images is about ~ 15Hz.
- Video format:
  - **PAL** (Phase Alternating Line) format with frame rate of $f=25\text{Hz}$ (sometimes in $50\text{Hz}$). Used by U.K., Germany, Spain, Portugal, Italy, China, India, most of Africa, and the Middle East.
  - **NTSC** format: established by National Television Standards Committee (NTSC) with frame rate of $f=30\text{Hz}$. Used by U.S., Canada, Mexico, some parts of Central and South America, Japan, Taiwan, and Korea.

---

Interlaced camera

- **Old field** $(1,3,5\ldots639)$
- **Even field** $(2,4,6\ldots640)$

480 pixels by 640 pixels

1 frame $F=30\text{Hz}$

Odd field

Even field $16.6\text{ms}$

16.6ms

---

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**Progressive scan camera**

- All image systems produce a clear image of the background
- Jagged edges from motion with interlaced scan
- Motion blur caused by the lack of resolution in the 2CIF sample
- Only progressive scan makes it possible to identify the driver

Note: In these examples, the cameras have been using the same lens. The car has been driving at 20 km/h (15 mph) using cruise control.
Mystery of flying rods
Digital camera

- CCD camera and Intensified CCD (ICCD) camera:
  - Spatial resolution: 1K by 1k, 4K by 4K
  - Frame rate: 30 Hz, High speed camera 1khz ~10K hz
  - In a CCD sensor, every pixel’s charge is transferred through a very limited number of output nodes (often just one) to be converted to voltage, buffered, and sent off-chip as an analog signal. All of the pixel can be devoted to light capture, and the output’s uniformity (a key factor in image quality) is high.

- CMOS (Complementary metal-oxide semiconductor) cameras
  - In a CMOS sensor, each pixel has its own charge-to-voltage conversion, and the sensor often also includes amplifiers, noise-correction, and digitization circuits, so that the chip outputs digital bits
  - These other functions increase the design complexity and reduce the area available for light capture. With each pixel doing its own conversion, uniformity is lower. But the chip can be built to require less off-chip circuitry for basic operation

- In summary for CMOS cameras
  - Low cost
  - Operation versatility
  - High speed
  - Quality is not as high as CCD cameras
Pressure Gauge and Transducers
Measurement Techniques for Thermal-Fluids Studies

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

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

Particle-based techniques
- Laser Induced Fluorescence (LIF)
- Molecular Tagging Velocimetry (MTV)
- Molecular Tagging Therometry (MTT)
- Pressure Sensitive Paint (PSP)
- Temperature Sensitive Paint (TSP)
- Quantum Dot Imaging
- etc...

Molecule-based techniques
Pressure, velocity, temperature, density (concentration), etc.
Introduction

• Pressure measurements are the primary measurements made in most practical aerodynamic testing or basic fluid mechanics experiments.

• Surface pressure measurements are used for:
  • Identifying specific flow phenomena (boundary layer separation, shock wave impingement, etc) that are not easily measured by “standard pressure tap” measurements.
  • Validation of computational codes
  • Loads calculations by integration of the surfaces pressures
Pressure measurements

- Pressure is defined as the amount of force that presses on a certain area.
  - The pressure on the surface will increase if you make the force on an area bigger.
  - Making the area smaller and keeping the force the same also increase the pressure.
  - Pressure is a scalar

\[ P = \frac{F_n}{A} = \frac{dF_n}{dA} \]
Pressure measurements

\[ P_{\text{gauge}} = P_{\text{absolute}} - P_{\text{amb}} \]

Manometer

Gage Pressure \( \Delta P = P - P_0 = \rho gh \)
Deadweight gauges:

- High accuracy
- Usually used for the calibration of other instruments
- Application range: 102~108 pa
- Uncertainty is within 0.01% ~0.05% of the reading
Elastic-element gauges:

- Contain an elastic elements that deforms under pressure and creates a linear or angular displacement.
- The displacement is either displayed on a dial by means of purely mechanical linkages or transformed to an electric signal that can be displayed or recorder at will.
- They usually used for monitoring supply pressure.
Electrical Pressure transducers

- These devices provide an electric output signal that is linearly or nonlinearly dependent on the absolute pressure or a pressure difference.
- They can be categorized as:
  - Molecular transducers:
    - Applied pressure or force produces a change (on the molecular level) of a electrical property of material.
    - Piezo-electric material such as quartz crystal: change in internal dipole moments of the molecules of the crystal when the pressure or force is applied.
  - Parametrical transducers:
    - The gross electrical parameter (resistance, inductance, capacitance) of an associate electrical parameter is altered by applied force.
    - Variable-capacitance transducer
Wall Pressure measurements -1

- Making small orifice (pressure tap) facing the flow.
  \[ \Delta p = P_m - P > 0 \]

- Machining small hole could be difficult
- \( d = 0.5\sim3.0\text{mm} \) in practice
- \( l/d = 5 \sim 15 \) is common used

- Potential effect on the wall roughness
- Effects of unsteady shock wave, and shock boundary-layer interactions for transonic and supersonic flows:
- PSP method to be introduced later
Wall Pressure measurements - 2

- For a unsteady flow, the dynamic response of a pressure acquisition system is a key issue!
  - Dynamic response of the pressure transducers
  - Dynamic response of the connection tubing

- Remote connection
  - Dynamic response is low
  - Spatial resolution is high

- Cavity mounting
  - Dynamic response is good
  - Spatial resolution is high

- Flush mounting
  - Dynamic response is high
  - Spatial resolution is low
Pressure Measurements inside Flow Field

- **Non-intrusive technique is unavailable for direct pressure measurements**
  - Based on N-S equation to calculate pressure field using the measured (PIV) velocity field.
- **Static probe:** for static pressure measurements
- **Pitot probe:** for total pressure measurements
- **Pitot-static probe:** for static and total pressures measurements (velocity measurements)
- **Multi-hole probe:**
Pressure Sensitive Paint (PSP) / Temperature Sensitive Paint (TSP)
Introduction

Conventional pressure measurements: Transducers or taps

- Discrete pre-determined locations
- Very high accuracy (< 0.05% FS)
- Well understood with long testing background
- High data rate with scanned systems (1000+)
- Limitations to where they can be installed
- Potential effect on the flow field – intrusive measurements
- Expensive installation costs
Pressure Sensitive Paint (PSP)

- Sprayed over entire exterior surface
- non-intrusive pressure measurements
- high spatial resolution with resolution limited only by detection system
- Limited to optical access applications
- Inexpensive application costs
- Relatively expensive initial costs to setup the system
- High-speed applications
- Newer method that is still being fully explored for low-speed applications.
Basic Principles of Pressure Sensitive Paint (PSP)

- **Composition of Air**: 78.08% $N_2$, 20.95% $O_2$, 0.93% $Ar$, 0.03% $CO_2$, 0.002% $Ne$, plus lesser amounts of Methane, Helium, Krypton, Hydrogen, Xenon.
- **The pressure of air can be determined if the particle pressure of oxygen (i.e. oxygen concentration) can be measured.**
- **A typical pressure sensitive paint is comprised of two main parts: an oxygen sensitive fluorescent molecule and an oxygen permeable binder**
**Basic Principles of Pressure Sensitive Paint (PSP)**

- The pressure sensitive paint method is based on the sensitivity of certain luminescent molecules to the presence of oxygen.
  - When a luminescent molecule absorbs a photon, it is excited to an upper singlet energy state. The molecule then typically recovers to the ground state by the emission of a photon of a longer wavelength (i.e. fluorescence or phosphorescence).
  - In some materials, oxygen can interact with the molecule so that the transition to the ground state is radiationless, this process is known as oxygen quenching.
  - The rate at which these two processes compete is dependent on the partial pressure of oxygen present, with a higher oxygen pressure quenching the molecule more, thus giving off a lower intensity of light.
**Basic Principles of Pressure Sensitive Paint (PSP)**

- For oxygen quenching, the intensity decrease can be described by the well-known Stern-Volmer equation:

\[
\frac{\tau_0}{\tau} = 1 + K_{SV}Q \quad \text{or} \quad \frac{\tau_0}{\tau_{O_2}} = \frac{I_0}{I_{O_2}} = 1 + K_{SV}P_{O_2}
\]

- \( \tau \) is the lifetime, \( I \) is the intensity
- \( K_{SV} \) is the Stern-Volmer constant
- \( Q \) is the quencher or partial pressure of oxygen
Advantages of Pressure Sensitive Paint (PSP)

- Pressure sensitive paint has numerous advantages over conventional pressure taps and transducers.
  - The most obvious is that PSP is a field measurement, allowing for a surface pressure determination over the entire model, not just at discrete points. Hence, PSP provides a much greater spatial resolution than pressure taps, and disturbances in the flow are immediately observable.
- PSP also has the advantage of being a non-intrusive technique.
  - Use of PSP, for the most part, does not affect the flow around the model, allowing its use over the entire model surface.
  - The use of PSP eliminates the need for a large number of pressure taps, which leads to more than one benefit. Since pressure taps do not need to be installed, models can be constructed in less time, and with less money than before.
  - Also, since holes do not need to be drilled in the model for the installation of taps, the model strength is increased, and higher Reynolds numbers can be obtained.
  - Not only does the PSP method reduce the cost of the model construction, but it also reduces the cost of the instrumentation needed for data collection. In addition, the equipment needed for PSP costs less than pressure taps, but it can also be easily reused for numerous models.
- In aircraft design, PSP has the potential to save both time and money.
  - The continuous data distribution on the model provided by PSP can easily be integrated over specific components, which can provide detailed surface loads.
  - Since a model for use with the PSP technique is faster to construct, this allows for load data to be known much earlier in the design process.
Disadvantages of Pressure Sensitive Paint (PSP)

- One of these characteristics is that the response of the luminescent molecules in the PSP coating degrades with time of exposure to the excitation illumination.
  - This degradation occurs because of a photochemical reaction that occurs when the molecules are excited.
  - Eventually, this degradation of the molecules determines the useful life of the PSP coating.
  - This characteristic becomes more important for larger models, as the cost and time of PSP reapplication becomes a significant factor.
- A second undesirable characteristic of PSP is that the emission intensity is affected by the local temperature.
  - This behavior is due to the effect temperature has on the energy state of the luminescent molecules, and the oxygen permeability of the binder.
  - This temperature dependence becomes even more significant in compressible flow tests, where the recovery temperature over the model surface is not uniform.
Implementation of Pressure Sensitive Paint (PSP)

- **Intensity based Methods (most common)**
  - Full-field using camera
  - Point systems using scanning laser

- **lifetime based Methods (lifetime decay)**
  - Full-field using camera
  - Point systems using scanning laser

\[ \frac{\tau_0}{\tau} = 1 + K_{SV} Q \quad \text{or} \quad \frac{\tau_0}{\tau_{O_2}} = \frac{I_0}{I_{O_2}} = 1 + K_{SV} P_{O_2} \]
Intensity based PSP

- The Stern-Volmer equation is rewritten in the popular intensity ratio form:
  \[ \frac{P}{P_{REF}} = A + B \frac{I_{REF}}{I} \]

- \( A \) and \( B \) are highly dependent on the luminophore and binder material as well as the temperature sensitivity of the materials used to make the paint. A 2nd order curve generated from calibration data is most often used.
**Intensity based PSP**

\[
\frac{P}{P_{\text{REF}}} = A + B \frac{I_{\text{REF}}}{I}
\]

- Requires two readings, a reference at constant pressure (wind off) and an unknown data point (wind-on)
- Ratio of intensities \( I_{\text{REF}}/I \) is inversely proportional to the air pressure
- The excitation and detection systems must be spectrally separated, (>10^{-6} attenuation in stop band).
- Simplest technique, most sensitive
- Very sensitive to motion between wind-off and wind-on
- A long period of time can elapse between reference and data.
- Images resulting in significant changes in contamination of paint, light stability, etc that cannot be normalized by the reference condition.
**Intensity based PSP**

\[
\frac{P}{P_{REF}} = A + B \frac{I_{REF}}{I}
\]

- **Advantages:**
  - Eliminate wind off images and image registration problems. It works in theory.
  - In practice, due to homogeneity problems of dispersing of two kinds of molecules, it actually requires a double set of ratios, often called ratio of ratios method.

Self-Referencing paints

- Pressure insensitive molecule
- Pressure sensitive molecule
Intensity based PSP-temperature compensation

Temperature sensitive molecule

Pressure sensitive molecule

- Advantages:
- Measure temperature to compensate for temperature sensitivity of PSP.
- This technique requires all four images to be aligned.
**Lifetime-based PSP**

- **Easiest to do with a point measurement, but can use time resolved cameras to measure lifetime decays of the probe molecules.**
- **Point measurements require a pulsed light source and detector (PMT, PD)**
- **Time resolved imaging requires a double pulse type experiment to measure the decay times (gated camera, interline transfer camera capable of multiple flash integration).**

\[
\frac{I_1}{I_2} = F_1(p, T) \\
\frac{I_1}{I_3} = F_2(p, T),
\]

\[
\frac{\tau_0}{\tau_{O_2}} = \frac{I_0}{I_{O_2}} = 1 + K_{SV}P_{O_2}
\]

---

**Figure 14.** PSP luminescent lifetime images of (a) $I_1$, (b) $I_2$ and (c) $I_3$.

**Figure 16.** (a) Pressure and (b) temperature images on the delta wing at $M = 0.55$, $P_i = 100$ kPa and angle of attack $= 20^\circ$. 

---
**Lifetime-based PSP**

- **Benefits:**
  - Eliminates the need for aligning two or three images since the pair of (or three) images are taken at the same condition relatively close in time (micro-seconds).
  - Pressure and temperature distributions can be determined simultaneously.

- **Disadvantages:**
  - Requires three gates to generate two equations of gate ratios to solve for pressure and temperature at each point (pixel).
  - Camera noise is much higher, especially gated intensified cameras.
  - Paints have tended to be more spatially noisy from lifetime differences between molecules (homogeneity problem).

![Diagram of gate methods](image1.png)

\[
\frac{I_1}{I_2} = F_1(p, T) \\
\frac{I_1}{I_3} = F_2(p, T),
\]

Figure 14. PSP luminescent lifetime images of (a) \(I_1\), (b) \(I_2\) and (c) \(I_3\).
PSP/TSP coatings

**PSP coatings used at NASA GRC**
- Boeing PF2B – ruthenium bathophenanthroline in silicone rubber binder (soft paint, chlorinated solvent)
- UW (ISSI) FIB – PtTFPP in FIB copolymer binder (hard, good steady state paint)
- NASA Langley – PtTFPP in FEM (very hard, very smooth finish)
- ISSI sol-gel – Ru(ph2-phen) and PtTFPP on sol-gels (higher frequency response)
- Anodized aluminum – dip coated Ru(ph2-phen) on anodized surface (very high freq. response)
- UW PtOEP in MAX acrylic copolymer (ice paint)

**TSP coatings**
- Boeing TSP (range: 0 to 100°C, sensitivity ~ -3%/°C)
- EuTTA in commercial clear or shellac (-20 to 80°C, ~ -4%/°C)
- Thermographic phosphors in high temp binders (-20 to >1000°C)
Intensity based PSP

- **Excitation:**
  - Continuous Sources: LEDs, Filtered lamps (Halogen, Xenon), Lasers
  - Pulsed Sources for instantaneous or periodic measurements: LEDs, Xenon, strobes/flash

- **Detectors**
  - Cooled Scientific grade CCD cameras (slow scan, low noise), PMT, PD

Typical PSP absorption and emission spectra [from McLachlan and Bell, 1995]
Calibration for PSP

- **A-priori Calibrations**
- Paints are typically calibrated in a cell that varies pressure and temperature and has a reference measurement – this calibration is used when no on-model instrumentation exists.
- **In-situ Calibration**
  - Uses standard on-model instrumentation to calibrate the paint/images in place
  - Compensates for temperature differences from reference data, spatial temperature differences are averaged among all the points used to generate a calibration
- In practice both calibrations are typically used

![Image of calibration setup](image-url)

*Figure 3. Photo of a multi-gated camera and LED illuminators.*
Calibration setup

- Pressure air pipe to control the pressure in the chamber
- Water recirculation to control the temperature on the sample plate
PSP calibration image process

Reference Intensity: \( I_{\text{ref}} \)

\( \frac{P}{P_{\text{ref}}} = 0.23 \): Intensity

\( \frac{I}{I_{\text{ref}}} \)

\( \frac{P}{P_{\text{ref}}} = 7.2 \): Intensity

\( \frac{I}{I_{\text{ref}}} \)
Calibration curve for the paint positive pressure and error analysis

- Fit function: \( y = 0.00149x^3 - 0.0510x^2 + 0.672x + 0.436 \)
- Error level is below 1%
Calibration curve – Vacuum pressure

Calibration curve for the PSP paint under vacuum pressure and error analysis

- Fit function: \( y = 0.217x^3 - 0.617x^2 + 0.946x + 0.456 \)
- Error level is below 1%
Uncertainty for PSP

- Characterization of the paint and calibration errors (a-priori, in-situ calibration, photo degradation, paint contamination, paint intrusiveness, time response)
- Measurement system errors (detector noise, illumination spectral and temporal stability, spectral leakage)
- Signal analysis errors (registration from model motion and deformation, incomplete temperature compensation, self illumination, resectioning on a non-deformed grid)
- The major contributor is temperature uncertainty which can account for up to 90% of the total uncertainty

Figure 3. Photo of a multi-gated camera and LED illuminators.
Applications of PSP Technique

PSP measurement result

PSP combined with PIV
Application Examples

Rotating PSP/TSP on 22” Fan Model

GRC 9’x15’LSWT
Application Examples

Rotating PSP/TSP

Temperature

Pressure

7875 RPM  C  B  A
Application Examples

Nozzle Test in APL using Lifetime PSP
Application Examples

PSP on Ice

Test setup using PSP on Ice in the IRT
Application Examples

PSP on Ice in the IRT
Application Examples

Inlet Test in the 10’X10’

Pioneer Rocketplane in the 1’X1’

Lifetime PSP F16 Test at ARC

Turbine Cooling Passage simulation
Boundary Layer Control Tests in the 1’X1’ SWT

Methods using suction and blowing for boundary layer enhancement
Dynamic PSP Test: Pulse Detonation Engine Sidewall

Instantaneous image of pressure field of moving pressure wave

Point PSP measurements vs pressure transducer, paint has lag and ~ 1kHz response
PSP Technique for Low Speed Applications

$V_\infty = 50 \text{m/s}$

PSP measurements of a 2002 Ford Thunderbird
Applications of PSP Technique

Time-resolved PSP measurements on the front and lateral side surfaces of a 3-D square cylinder (Yorita et al. 2010)
• Thermodynamic analysis reveals that thermal efficiency and power output of a gas turbine can be increased with higher turbine inlet temperatures.

• Advanced gas turbines are operated at peak turbine inlet temperature about 1700 °C, which is well beyond the maximum endurable temperature for the blade material.
Damaged turbine blades

• Protect the blade against the risk of damage
  – New material to endure higher temperature
  – State-of-art cooling techniques for film cooling and trailing edge cooling

Majority of damages starting at tips and trailing edges
Raw Images for cooling effectiveness

Black image
Reference Image
Air image
Nitrogen image
Cooling Effectiveness measurements by using PSP technique

Cooling Effectiveness

M = 0.43

M = 1.6

C.E.

1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Cooling Effectiveness Measurements by using PSP technique

Graphs showing the relationship between X/H, Z/H, and Cooling Effectiveness η for different Mach numbers (M).

- M=1.6
- M=1.1
- M=0.76
- M=0.64
- M=0.52
- M=0.43
- M=0.25

The graphs illustrate the cooling effectiveness at various X/H and Z/H ratios for the specified Mach numbers.
Thank you for your time!
Questions?