Particle Image Velocimetry Applications of Fluorescent Dye-doped Particles

Brian J. Petrosky
1. Introduction

2. Polystyrene Latex (PSL) Particle Characterization

3. Fluorescent Particle Image Velocimetry (PIV) Technique Validation

4. Fluorescent PIV Applications

5. Kiton Red Temperature Sensitivity

6. Summary and Future Work
Traditional PIV Techniques and Shortcomings

- PIV measurements use Mie scattered light of seed particles from a laser source.
- Leads to laser flare at solid boundaries or at liquid/gas interfaces.
Surface Flare Reduction Techniques

- Black paint is quick solution but not completely effective.
- Surface treatments are expensive, fragile, labor intensive, and/or carcinogenic.
- Flare at air/liquid interfaces is essentially unavoidable.

Laser Induced Fluorescence (LIF)

- Stokes shift: fluorescent light at higher wavelengths than the excitation light
- A high pass optical filter used to block reflections and flare.
- Intensity of fluorescent light given by $I_\lambda = I_0 \times \alpha(\lambda_0) \times \varepsilon(\lambda) \times N_M$

1. Introduction

![Energy level diagram and graph showing absorption and fluorescence emission with the Stokes shift highlighted.](image-url)
Past Work Using Fluorescent Light for PIV

- Fluorescent light for PIV is common in water flows [2,3] or micro PIV [4,5].
- In water, acceptable particle diameters are much larger than in air.
- Very few fluorescent PIV measurements conducted in air:
  - Most involve two-phase flow or fuel injection
  - Some used large particles [6]
  - The most successful, by Chennaoui et al., demonstrated the potential benefits of this technique but used dangerous particles[7].

PIV obtained via fluorescent light [8][9].

© IOP Publishing. Reproduced by permission of IOP Publishing. All rights reserved

Manufacture and conduct PIV experiments using fluorescent particles in an airflow.

Requirements:
- Particles must be small (generally < 2 μm).
- Particles must display an adequate fluorescence signal.
- Particles must be relatively safe for use in an open environment.

Flow from a seeded nozzle at 3.5 m/s.

Wind tunnel test section. From NASA.gov [8].

Kiton Red Doped PSL Particles

- Produced at NASA Langley via dispersion polymerization
- Past Virginia Tech research has used Rhodamine B, Dichlorofluorescein (DCF), and Kiton Red 620 PSLs
- Highest signal obtained from Kiton Red particles
- These Kiton Red dye-doped particles are:
  - Small, lightweight, and mono-disperse, with a mean diameter of 0.87 μm
  - Relatively safe to use in an open-air environment, with no carcinogenic effects

Kiton Red molecular structure [9].

Measured Kiton Red emission spectrum at 532 nm excitation.

Particle Image Velocimetry Applications Using Fluorescent Dye-doped Particles

by B Petrosky, P Maisto, K T Lowe, M André, P Bardet, P Tiemsin, C Wohl and P Danehy

Presented at AIAA SciTech 2015
January 5-9, 2015
Kissimmee, FL
Virginia Tech “Free Jet” Fluorescent PIV Setup

- **Equipment:**
  - 2048 x 2048 pixel camera
  - Dual-pulsed 532 nm Nd:YAG laser operating at 200 mJ/pulse
  - Custom nozzle with exit diameter \( d = 14.15 \text{ mm} \ (\sim 0.55 \text{ in.}) \)
  - 560 nm long pass filter
  - Camera and laser controlled by LaVision’s DaVis software, operating at 10 Hz

- **Test conditions and procedure:**
  - Fluorescent and Mie scattered images were taken back to back
  - Lens aperture set at f/22 for Mie images and f/2.8 for fluorescence

- Additional details found in thesis text

3. Fluorescent PIV Technique Validation
Flow is from right to left, ~3.5 m/s
- 45.6 mm x 45.6 mm field of view.
- Fluorescence signal clearly lower than Mie signal.
- Whether this lower signal impacted PIV processing would have to be studied.
What is Peak Ratio?

Example cross correlation result (oversimplified 1D version)

- Peak Ratio: $Q \equiv \frac{\text{Highest Correlation Peak Height}}{\text{Second Highest Correlation Peak Height}} = \frac{P_1}{P_2}$
- A high peak ratio indicates a clear particle displacement
  - $Q > 1.3$ generally used for “valid” peak.
- The lowest uncertainties in displacement occur for $Q > 2.$
- Low peak ratios indicate a weak signal/excessive noise
- Spurious Vector- vector calculated from an invalid correlation peak.

Fluorescent PIV Technique Validation
Spurious Vector Comparison - Background

- Percent of spurious vectors compared for Mie and fluorescent images.
- Spurious vectors identified through two steps:
  - Using a median filter, standard for PIV [10].
  - Deleting all vectors with a peak ratio below 1.3.

Overall, 100% of Mie vectors in the jet were valid, compared to 98.2% of the fluorescent vectors.

- 95% is often considered the threshold for good quality PIV data. [10]

- Spurious vectors are easily replaced by another correlation peak or interpolated over.

Free Jet PIV Processing Results (1)

- Processing Methodology:
  - Multipass technique with 50% overlap
  - Spurious vectors removed and replaced via median and peak ratio filter.

- An average of 6000 total vectors per image with a spatial resolution of 356 μm.

Velocity Magnitude, m/s

Fluorescent processing results

Mie scattering processing results
The horizontal exit velocity averages of the jet are within 3% of each other (seen below).

High peak ratios and correlation values from both image sets.

Velocity profile across nozzle exit compared.

Higher velocity values from fluorescence signal likely due to nozzle unsteadiness.

Mie scattering (left) and fluorescent (right) horizontal velocity averages.
Application: GWU Two-phase Flow Setup

- **Equipment Setup:**
  - Rectangular water tunnel open at the top
  - Planar PIV measurements
  - Dual-cavity, Nd:YLF 527 nm laser operating at 10 kHz for time resolved data.
  - 540 nm longpass filter

- **Test conditions and procedure:**
  - Fluorescent and Mie images taken back to back
  - Lens aperture set at f/11 for Mie images and f/2.8 for fluorescence images

- Additional details found in thesis and references.

---

3. Fluorescent PIV Technique Validation
GWU Two-phase Flow Results

- Reflected light at water surface filtered out
- Velocity vectors obtainable throughout entire air/water interface
- Processing Methodology:
  - Multipass technique with 75% overlap, with a 64x64 pixel first pass followed by 32x32 pixel second pass
  - Spurious vectors deleted via median filters after each pass, replaced via interpolation.

Fluorescent light raw image.

Mie scattering image using reflective particles.

Fluorescent light raw image.

PIV velocity field and vorticity contour plot.

3. Fluorescent PIV Technique Validation
Laser Flare Removal in Particle Image Velocimetry Using Fluorescent Dye-doped Particles

B Petrosky, K T Lowe, P Danehy, C Wohl, and P Tiemsin

To be Submitted to Measurement Science and Technology
PIV Test Setup

- **Equipment:**
  - 1024 x 1024 pixel cameras, 12 bit digitization
  - Dual-pulsed 527 nm Nd:YLF laser operating at 23 mJ/pulse
  - 6 cm nozzle exit diameter
  - 560 nm long pass filter
  - Camera and laser controlled by LaVision’s DaVis software, operating at 2.5 kHz

- Additional details found in thesis text

4. Fluorescent PIV Applications
Traverse and mount allow for translation and rotation of camera, so that FOV’s can match exactly.

4. Fluorescent PIV Applications
The two images are very similar, but slightly off in terms of field of view and orientation.

Images taken in free air at low speed (~ 8 m/s)

Fluorescence $f/2.8$
Mie $f/22$
Cross correlation from fluorescence to Mie images determined offset.

- Fluorescent images deformed by this vector field using DaVis.
- Resulting images nearly exactly overlapped with the Mie images.
50 x 50 pixel image of fluorescence image (above) and Mie-scattered image (below).

4. Fluorescent PIV Applications
Images broken up into square bins
Minimum pixel count threshold used to differentiate valid signal and noise.
Ratio between the Mie and fluorescent signal was taken for 150 images

48 x 48 bin sizes, 10 count minimum signal

- Histogram distribution is lognormal.
- Distribution described using geometric mean and standard deviation.

4. Fluorescent PIV Applications
24 x 24 bin size (highlighted) chosen to describe the particle signal characteristics.

Mean signal is $321 \pm 12$ times stronger in Mie.

Expected individual particle signal ranges from 120 and 870.

Variation suggests a degree of nonuniformity in dye concentration.
Aluminum flat plate placed in 4.5 m/s flow.
Plate used in 2 orientations, as shown. Both were set to approximately a 0° AoA.
Only a single camera was used for these tests.
Fluorescence and Mie data sets taken back to back, rather than simultaneously.

4. Fluorescent PIV Applications
Plate Orientation 1: Plate Perpendicular to Sheet

- Raw images for fluorescent and Mie techniques.

4. Fluorescent PIV Applications
Plate Orientation 1: Processing Results

- Vectors processed with 24 x 24 final pass interrogation window sizes.

4. Fluorescent PIV Applications
The profiles were compared to Falkner-Skan boundary layer profiles.

Falkner-Skan solutions set a pressure gradient through $\beta$.

- Best fit for $\beta = -0.13$.
- Mie PIV at f/2.8 and f/22 inaccurate within 1 mm and 0.5 mm of plate surface, respectively.
- Fluorescent PIV accurate to plate surface.

4. Fluorescent PIV Applications
Plate Orientation 2: Angled Plate Images

- Plate angled 45° to laser sheet and camera.
- Significant flare in Mie images.
- Overall fluorescent background signal is 2+ orders of magnitude lower.
- 32 x 32 final pass interrogation window sizes.
- The stream-wise velocity averages above are calculated from only valid vectors.
- The Mie-scattered velocities are erroneous within 5-10 mm of the plate surface.

4. Fluorescent PIV Applications
Validation rates compared for 100 images.

“Valid” vector:
- High peak ratio
- Passes median filters
- Stream-wise velocity between 2 and 7 m/s.

63 times fewer spurious vectors with Mie-scattered PIV.

<table>
<thead>
<tr>
<th>Region of Interest</th>
<th>Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>x, mm</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>y, mm</td>
<td></td>
</tr>
</tbody>
</table>

Plate Orientation 2: Angled Plate Validation Rates

<table>
<thead>
<tr>
<th>Technique</th>
<th>Percent Valid, Q &gt; 1.3</th>
<th>Percent Valid, Q &gt; 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluorescence</td>
<td>99.0%</td>
<td>95.1%</td>
</tr>
<tr>
<td>Mie</td>
<td>36.6%</td>
<td>24.7%</td>
</tr>
</tbody>
</table>

4. Fluorescent PIV Applications
Initial Studies into the Temperature Sensitivity of Kiton Red PSL Particles

B Petrosky
Background

- Intensity of fluorescent light:
  \[ I_\lambda = I_0 \alpha(\lambda_0, T) \varepsilon(\lambda, T) N_M \]

- The recorded fluorescent intensity at a given wavelength can be written as:
  \[ I_f = K_{opt} K_{spec} I_0 N_M e^{(\frac{B(\lambda, T)}{T})} \]

- A ratio between two wavelength bands taken to eliminate parameters.

- This ratio has been shown to be of the form:
  \[ R_f = e^{\left(\frac{A}{T^2} + \frac{B}{T} + C\right)} \]

- Temperature calculations using this method are well documented, with measurement uncertainties under 1-2°C [11].

Experimental Setup for Calibration

- 1.25 cm Nozzle
- Temperature Probe
- Beam Dump
- Focusing optics
- 532 nm 6W CW Laser
- Collection Optics
- 450 µm optical fiber
- Spectrometer
- 532 nm notch filter

Fluorescent light at nozzle exit

5. Kiton Red Temperature Sensitivity
Selecting the Two Bands

- Tests at room temperature up to 110°, near the particle melting point.
- Spectrometer recorded over a finite period, usually 1-2 s.
- Spectra corrected for sensitivities at different wavelengths.
- Bands selected based on differing temperature sensitivities
  - Further optimized to maximize the two band ratio’s temperature sensitivity.
Initial Calibration Results

- 10 spectra each obtained at 30°, 50°, 70°, and 90° C
- The ratio $R_{f,e} = \frac{B_1}{B_2}$ was taken for each measurement
  - $B$ is the integral of the total measured signal for band

\[ R_f(T) = e^{\left(\frac{-3e6}{T^2} + \frac{2.6e3}{T} - 2.9\right)} \]

Repeatability also an issue
6. Work Summary

- Kiton Red doped PSL particles used meet all requirements of the research.

- Fluorescent particle signal calculated at $321 \pm 12$ times weaker than the Mie signal.

- Using LIF for PIV eliminates flare at surfaces or gas/liquid interfaces.
  - Over 0.5 mm closer to obstacle surface for minimal reflection case.
  - Over 5-10 mm closer to obstacle surface and 63x fewer spurious vectors for high reflectivity case.

- Kiton Red PSL’s did not exhibit sufficient temperature sensitivity.

- Future Work:
  - Improvements in particle polymerization to increase fluorescent signal.
  - Larger scale applications- the end goal is for the ability to use these particles in any PIV or particle tracking application.
In addition to the co-authors of this paper, whose contributions were essential to the success of this work, I would like to thank the support of the NASA ARMD Seedling Fund and NIA Cooperative Agreement NNL09AA00A for making this research possible, as well as Max Verkamp and Jason Danley for their efforts in particle manufacturing and characterization.

Also, a special thanks to all friends and colleagues in the CREATE center, whose day-to-day work and conversations taught me so much about how to conduct quality research and allowed me to develop my project as I did.
Questions?


