Measurement of turbulent dissipation with advanced laser diagnostics

Dr. Peter D. Huck
The George Washington University (Prof. Philippe Bardet)
Los Alamos National Lab (Dr. John Charonko)

NSSC3 Kickoff Meeting and Advisory Board Review
April 19-20, 2022
Introduction

**Department and University:** The George Washington University, *Department of Mechanical and Aerospace Engineering*

**Academic Advisor:** Philippe M. Bardet

**NSSC Research Focus Areas:** Nuclear Engineering

**Planned Graduation Date:** N/A

**Lab Mentor and Partner Laboratory:** Dr. John Charonko, LANL

**Mission Relevance of Research:**

In the case of a global nuclear detonations, detection and disaster mitigation can be accomplished by simulating the rise height and fall out of the resulting buoyant plume. To properly parameterize these simulations, it is imperative to provide the direct measurement of small scale velocity gradients in a turbulent flow. This quantity is necessary to determine the rate at which the turbulence dissipates energy and is a fundamental in developing realistic models of turbulent flows. This research supports the NNSA security mission of nuclear detonation forensics by providing CFD models with data inputs with minimal assumptions regarding the resolved scales of the measurement.

Informing numerical models of buoyancy driven flows requires fully resolved velocity gradients and kinetic energy measurements.
Emergency Response to extreme Events

Kolmogorov scale
\[ \eta = (\nu^3 / \epsilon)^{1/4} \]
Batchelor scale (air)
\[ \eta_\theta = \eta Sc^{-3/4} \]
Schmidt number
\[ Sc = \nu / D = 0.7 \]

Mixing occurs when small-scales of plume are similar to those of turbulence.

Strong need for:
- Experimental determination of \( k \) & \( \epsilon \)
- Experimental determination of potential forcing terms in RANS models

Prediction efforts begin with a RANS \& model

\[
\begin{align*}
\frac{Dk}{Dt} &= P_k + \frac{\partial}{\partial x_j} \left[ (\nu + \frac{\nu_t}{\sigma_k}) \frac{\partial k}{\partial x_j} \right] - \epsilon + \mathcal{F}_k^b \\
\frac{D\epsilon}{Dt} &= C_{\epsilon 1} \frac{\epsilon P_k}{k} + \frac{\partial}{\partial x_j} \left[ (\nu + \frac{\nu_t}{\sigma_\epsilon}) \frac{\partial \epsilon}{\partial x_j} \right] - C_{\epsilon 2} \frac{\epsilon^2}{k} + \mathcal{F}_\epsilon^b
\end{align*}
\]
“The problem of spatial resolution is simply the fact that the sensing element cannot truly respond to scales smaller than its dimensions”
Örlu & Alfredsson, 2010

Dissipation rate: \[ \varepsilon = \nu \left\langle \frac{\partial u_i}{\partial x_j} \frac{\partial u_i}{\partial x_j} \right\rangle \]

Deliverables:
- Develop a compact velocimeter that measures velocity gradients with sufficient resolution to determine \( \varepsilon \)
- Test method in flow configuration where the velocity gradients are known (stagnation point flow)

Hot-wire anemometry

- Spatial filtering of data when wire length \( \Delta/\eta \gg 1 \)
- Indirect measurement velocity gradient

PIV

- Interrogation window (\( \Delta \)) limits resolution of velocity derivative
- Velocity gradient amplifies noise in the dissipation measurement

MTV

- Beamlet width (\( \Delta \)) limits resolution of probe
- Velocity derivative encoded in the time of flight measurement
Operating Principles of μ-MTV

- **Spectroscopy** of molecular tracers (seeded or naturally present)
- **Tracer activation** (tagging) with a first laser (**write**)
- **Time of flight** of tagged pattern with a 2nd laser (**read**)

Spectroscopic determination of thermodynamic state variables:

- **Pressure** (in gas) : Basu et. al., Exp. Fluids (2010)
- **Temperature** (in gas) : Matthew et. al., AIAA (2015)

Simultaneous Concentration/Velocity
Structured Illumination gives a uniform pattern along the optical axis

**Goal:** Instantaneous 3D-2C Velocity measurements at a solid interface

Tagged pattern (black) is deformed (blue) by the fluid flow

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Optical sectioning provides in focus images at different depths
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Talbot Effect Structured Illumination

```
z_T = 254 mm

p = 300 \mu m, w = 33 \mu m
```

Fort et al., *Exp Fluids* (2020a)

Expected wall unit (@ Re=12M), \( y^+ = 5 - 10 \mu m \)
Principle of Microscopic **Integral**Velocimetry (MIV)

Confocal Microscopy: “Emission Pinhole” permits fine optical sectioning at focal planes

**Velocimetry** *(μPIV, Shake The Box)*

**2 Camera Microscopy & Velocimetry**

*Kim et. al., Exp. Fluids (2011)*

Resolution: \( R_{xy} = 32 \, \mu m \)

**6 Camera Tomography – 4D PTV “Shake the Box”**

*Schroëder et. al., Flow Turbulence Combust (2015)*

Resolution: \( R_{xy} = 93 \, \mu m \)
Operational Principles of Integral Imaging

Levoy (2005)

Applications

• Optical aberration, temperature, and density variation characterization
  Clifford et. al., AIAA (2017)

• Sensor fusion – synthetic aperture:

• Optically assisted surgery:

Design Tradeoffs:

Reduce spatial resolution
Increased angular resolution
Microscopic Integral Velocimetry (MIV) Resolution

Design Criteria

\[ l_v(\mu m) \in [5, 11] : \text{viscous length scales} \]
\[ t_v(\mu s) \in [25, 120] : \text{viscous temporal scales} \]
\[ f_s(\text{kHz}) = 2(t_v)^{-1} : \text{sampling frequency} \in [16, 80] \text{kHz} \]

<table>
<thead>
<tr>
<th>type</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Confocal</td>
<td>M=20X</td>
<td>NA=0.4</td>
</tr>
<tr>
<td>FIMic</td>
<td>M=20X</td>
<td>NA=0.4</td>
</tr>
</tbody>
</table>
Optical implementation in a newly designed facility

Validate Schlichting Theory for Axisymmetric Stagnation Jet

*Similarity Solution* \[ f''' + 2ff'' + 1 - f'^2 = 0 \]

*Velocity Profile* \[ u/(\alpha r) = f'(\eta) \]

Validate Prediction for Boundary Layer Thickness

*Boundary Layer Height* \[ \delta = 2.8\sqrt{v/\alpha}. \]
Raw (background subtracted/inverted) images

13 “mini cameras”

Back projection of EIs into physical space (& sum)

\[ R_{ZF} = \left( \frac{f_{M0}f_2}{f_1} \right)^2 \cdot \frac{p}{f_{MLA}D} = 33 \, \mu m \]

(10X, NA=0.28)
First approach to rendering

\[ t = 70 \mu s \]

Theoretical Depth of Field
\[ \Delta_{zF} = 260\mu m \]

Theoretical Axial Resolution
\[ R_{zF} = 33\mu m \]
3D-2C Instantaneous Velocimetry

- Vertical resolution (33 μm), smooth gradients
- Lateral resolution (300 μm), probe
- Probe resolution (30 μm)
- 3D structures apparent

\textbf{Huck et. al., NURETH 19, 2022.}

\textbf{Huck et. al., International Symposium on Applications of Laser and Imaging Techniques to Fluid Mechanics Lisbon, 11-14 July 2022}

\textbf{Huck et. al., Symposium Naval Hydrodynamics 2022.}
The NSSC Experience

NSSC involvement has broadened my scientific culture and opened up doors professionally.

- "Non-destructive testing". NSSC conference series, Dr. Steve Glenn, LLNL.

- Networking and gained understanding of role of hydrodynamics in National Laboratory Research

- Under consideration for "Experimental Physicist Position", Lawrence Livermore National Lab
Acknowledgements

This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003996.

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The geometry of Fourier Integral Microscopy (FIMic)

Principle

Practical implementation

\[ NA_{FIMic} = \frac{NA_{MO}}{N} \]
Three approaches to Integral Microscopy

### Plenoptic 1.0
- High angular (depth) resolution
- Low spatial (lateral) resolution

### Plenoptic 2.0
- High spatial resolution
- Extended depth of field
- Long Working Distance
- Low angular resolution
- Black box post-processing
- High Resolution (>25MP) cameras (low acquisition rate)

### Fourier Integral Microscopy - FIMic
- Higher spatial resolution
- Flexible design and operation. Active community (open source)
- Modest Resolution (~5-16MP) cameras (high acquisition rate)
- Restricted depth of Field. Small working distance

_Huck et. al., NURETH 19, 2022._

_Huck et. al., Provisional Patent - Wall Shear Stress Optical Probe, 2022._
Talbot-effect structured illumination (TESI) generates fine and flexible laser patterns

**Structured Illumination:** intensity modulation of excitation light in the spatial domain.

<table>
<thead>
<tr>
<th>Device</th>
<th>Reference</th>
<th>( p ) (mm)</th>
<th>( w ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam blockers</td>
<td>Roetmann et. al. (2008)</td>
<td>0.48</td>
<td>0.16</td>
</tr>
<tr>
<td>Ronchi gratings</td>
<td>Charogiannis et. al. (2019)</td>
<td>0.2</td>
<td>0.1</td>
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<tr>
<td>Beam Dividers</td>
<td>Chu and Liao (1992)</td>
<td>2</td>
<td>0.15</td>
</tr>
<tr>
<td>Micro lens array</td>
<td>Sheng et. al. (2017)</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Talbot Effect</td>
<td>Fort et. al. (2020)</td>
<td>0.038</td>
<td>0.017</td>
</tr>
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TESI: Interferometric technique for flexible Creation of small-scale patterns

**Talbot distance:**

\[
z_T = \frac{p_0^2}{\lambda}
\]

**Pattern periodicity varies along \( z \)**

\[
p\left(z = \frac{M}{N}z_T\right) = \frac{p_0}{N}
\]

Further uses:

- Sub probe-volume resolution in LDV:
  

- Vibration monitoring and profilometry:
  
  

- Extreme UV Lithography:
  