Combustion Laser Diagnostics

Lectures presented

By Professor Marcus Aldén, LU

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by
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Background
Lund – the City

- A creative crossroads with a down-town area dominated by history
- Founded in the late 10th century
- A leading religious, academic and cultural centre in all of Scandinavia in the 12th century
- Became Swedish in 1658
- 100,000 inhabitants – half of them with ties to the University
One of Europe’s Leading Universities

• Founded in 1666
• 38,000 students
• 2,300 postgraduate students
• 5,200 employees
• 560 professors (16% women)
• Eight faculties
• Several campuses
• 5,300 SEK million turnover
Lund University

Eng. Faculty

18 Departments

Dept. of Physics

9 Divisions

Div. of Comb. Physics
Division of Combustion Physics

Main research areas
- Combustion diagnostics
- Chemical kinetics

Economy
- ca 10 % faculty resources
- ca 90 % external resources (STEM, VR, EU, MISTRA, Wallenberg, SSF, industry).
  Approximate budget: 27 MSEK/year

Courses
- Fundamental Combustion
- Laser-based combustion diagnostics
- Molecular spectroscopy

Personal
- 3+1 professors (fulltime/adj)
- 4 ass. prof (docents)
- 4 post.doc
- 3 T/A
- 19 doctorate students

Examination (since 1991)
- 44 PhD
- 18 Tekn. Lic
Division of Combustion Physics

• Participating in ~6 European projects
• Truly world unique instrumentation:
  – ~6 complete Nd:YAG/ dye lasers, 2
    Multi:YAG laser clusters, OPO laser, single
    mode Alexandrite laser, picosecund laser,
    2 DFDL, femtosecund laser, LDV, PIV
  – ~6 ICCD’s, 2 framingcammers, 1
    streakcamera
• Several burners; laminar, turbulent,
  atmospheric-high pressure
Marcus Aldén - Short CV

• Diploma work for M.S in laser diagnostics 1977
• U.S visit to G.E R&D Centre, 1978/79
• PhD in laser diagnostics of combustion proc. 1983
• Professor in combustion laser diagnostics, LU 1991
• Chairman GRC laser diagnostics of comb. proc. 2003
• Program co-chair of CI Symp. 2006
• Vice president CI, 2010
• Invited talk at the CI Symp. 2004, 2010

Member of Swedish Royal Academy of Science, KVA
Member of Swedish Royal Academy of Engineering Sci., IVA
Course outline

Hour 1: Introduction to combustion laser diagnostics, definitions
Hour 2: Molecular spectroscopy: Definitions, rotational, vibrational, electronic structures
Hour 3: Laser diagnostic instrumentation: Lasers, detectors, optical components
Hour 4: Semi intrusive techniques: LII and LIBS
Hour 5: Laser-induced fluorescence: Introduction/theory, basic definitions
Hour 6: Laser induced fluorescence: Applications - engines, gasturbines, furnaces
Hour 7: Rayleigh scattering: Introduction, potential, limitations, filtered Rayleigh Scattering
Hour 8: Raman scattering: Basic theory, thermometry, species concentration measurements
Hour 9: Surface thermometry: Thermographic phosphorescence – definitions, applications
Hour 10: Non-linear techniques I: CARS Spectroscopy – Theory, definitions, applications
Hour 11: Non-linear techniques II: Polarization spectroscopy and Degenerate four-wave mixing – Theory, potential, applications
Hour 12: New techniques for future challenges:
   - “New” species detection
   - Single ended experiments - ps Lidar, Structured illumination
   - Measurements in optical dense media (sprays) - Ballistic imaging, SLIP
Motivation for combustion research

By an improved fundamental understanding of combustion processes there will be a potential to;

• Improve efficiency
  lower fuel consumption
• Reduce emissions
  NO\textsubscript{x}, SO\textsubscript{x}, particles, CO\textsubscript{2} ,,
• Improve reliability
  increased competitiveness
• Develop combustion on alternative fuels and new technology
  hydrogen combustion, biomass, syngas
• Improve safety
  suppress fire initiation and spread
Combustion situations/applications

For specified tasks
- Candle light
- Welding flame
- Bunsen burner
- Log fire
- Liquid gas stove

For efficiency, reliability and low emissions
- Furnace
- Fluidised bed
- Diesel engine
- Gasoline engine
- Rocket engine
- Jet engine
- Gas turbine

Unwanted events
- Fire
- Explosion
- Detonation
1. Combustion diagnostics

- Probing methods:
  - gas chromatography
  - thermocouple
  - hot wire
  - mass spectrometry

- Optical methods

- Spectroscopic
  - (natural) emission
  - Laser-spectroscopic
    - Incoherent
      - ...
      - ...
      - ...
    - Coherent
      - ...
      - ...
      - ...

- Non-spectroscopic:
  - Schlieren/Shadowgraphy
  - Interferometry/Holographic interferometry
  - LDV/PIV/LDA

- Laser?
- CRDS?

- absorption
  - broadband
Short history: Combustion Laser Diagnostics

- First papers on combustion applications in the early seventies; Raman/Rayleigh applications
- First conference in 1974 in Schenectady, NY
- First Engine /GT applications during the eighties; LIF developments
- Multidimensional visualization, non-linear techniques during the nineties
- Multiple technique applications, quantitative real-world applications during 2000-
Suitable reading:


- M. Aldén, J. Bood, Z-S Li and M. Richter, Visualization and understanding of combustion processes using spatially and temporally resolved laser diagnostic techniques, Comb Inst, 33 (2011) 66-97
Combustion diagnostics

Diagnostics used for measurements of:

- Species concentrations
- Pressure
- Temperatures
- Velocities
- Particle characteristics (number density/size)
- Surface characteristics
Objectives with Diagnostic Techniques for Combustion Characterization

- Development of new diagnostic techniques as well as fundamental studies of these new as well as established techniques (e.g. investigations of spectral behaviour at 30 bar, 3000 K)

- Applications of the more developed techniques for measurements of relevant parameters, e.g. species concentrations, temperatures, velocities and particle characteristics for phenomenological studies (e.g. investigations of turbulent combustion)

- Applications of mature techniques for characterisation, optimisation and control of industrial processes (e.g. investigations of IC engine performances)
# Probe techniques

<table>
<thead>
<tr>
<th>Advantages:</th>
<th>Disadvantages:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Relatively cheap (some)</td>
<td>• Intrusive</td>
</tr>
<tr>
<td>• Robust and easy to use (some)</td>
<td>• May be difficult to estimate measuring errors</td>
</tr>
<tr>
<td>• Do mostly give quantitative results (correct?)</td>
<td>• Do not easily measure atoms and radicals</td>
</tr>
<tr>
<td>• Can measure larger molecules</td>
<td>• Often low (unclear) temporal and spatial resolution</td>
</tr>
</tbody>
</table>
Examples of intrusivness of a probe
Possible disturbances during probe (extraction) measurements

- Aerodynamic effects
- Effects of concentration gradients
- Thermal effects
- Catalytic effects
- Quenching effects

Example on probe influences on NO measurements

## Optical techniques

<table>
<thead>
<tr>
<th>Advantages:</th>
<th>Disadvantages:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Non-intrusive with high temporal/spatial resolution (laser techniques)</td>
<td>• Mostly expensive and complicated equipment, theory (laser techniques)</td>
</tr>
<tr>
<td>• Can measure simultaneously in many points</td>
<td>• May have difficulties to give quantitative data</td>
</tr>
<tr>
<td>• Simple (not laser techniques!)</td>
<td></td>
</tr>
</tbody>
</table>
Non-spectroscopic optical techniques

- Refractive index techniques
- Laser doppler velocimetry, LDV
- Particle induced velocimetry, PIV
Refractive index techniques
(Interferometry, shadography, schlieren techniques)
Referens: *Optics of flames* by F.J. Weinberg (Butterworths London 1963)

Shadography measures; $y_1 - y_0$

Schlieren measures; $\Theta$

Interferometry measures; $\frac{2\pi (t_1-t_0)c}{\lambda}$
Set-up schlieren/shadography
Some examples from the web

2.bp.blogspot.com/.../s400/.44+magnum.JPG

Laser doppler velocimetry, LDV

Velocity = distance/time

Flow with particles

\[ d = \frac{\lambda}{2 \sin \frac{\theta}{2}} \]

Signal

Time

t (measured)

measuring volume

backscattered light

Bragg Cell

Laser

Detector

Processor

Image from www.dantec.com
Particle Image Velocimetry, PIV

- PIV is capable of simultaneous velocity measurements at many points in a plane.

- PIV involves the illumination of a plane of the flow under investigation with two thin, pulsed sheets of light. The flow is seeded with particles.

- The light scattered from the particles and from successive pulses are being recorded either on film or a CCD array, forming a multiple exposure of each particle image. If the time between the pulses is known, velocity can be determined as the ratio of the particle displacement and the elapsed time.
PIV, principles

Image from www.dantec.com
Comparison of velocity measurements

**PIV:**
- Instantaneous velocity vectors in a plane
- Correlation within interrogation area reduces spatial resolution, mean velocities only
- Large amount of data in limited measuring time
- High number density of seeding required

**LDA:**
- Measures time series of velocity in a point
- High spatial resolution, suitable for turbulence investigations
- Measurement of entire flowfield time consuming
- Particles arrive randomly, data is not time equidistant
Emission spectroscopy 1: Planck radiation
Emission spectroscopy 2: Chemiluminiscence

- Line of sight
- Qualitative inf.
Emission spectroscopy 2: Chemiluminiscence

- Line of sight
- Qualitative inf.
Absorption spectroscopy

\[ I_t = I_0 \exp(-N \sigma L) \]

- Line of sight
- Quantitative information
Absorption measurement
Why lasers in combustion diagnostics?

- Non-intrusive
- High spatial resolution (<0.001 mm³)
- High temporal resolution (<10 ns)
- High spectral resolution (~MHz)
- Multiplex (multi-species, multi-point)
- Can measure non-thermal equilibrium
Potential drawbacks with lasers in combustion diagnostics?

- Complicated
- Expensive
- Eye safety
- Optical access required
- Intrusive?
  - Laser-induced breakdown (LIBS!)
  - Creation of molecular fragments; atoms
  - Optical pumping
Laser diagnostics in combustion

What can be measured?

- Temperatures (rotational/vibrational/translational/electron)
- Species concentrations (molecules, radicals, atoms)
- Velocities
- Particle number densities/diameters
- Surface characteristics
- Two-phase characterization
Set-up incoherent scattering
Incoherent measurements
Laser techniques

Incoherent techniques:

• Mie/Rayleigh scattering (incl. LDV, PIV)

• Laser-induced fluorescence (LIF)

• Laser-induced incandescence (LII)

• Raman scattering
Set-up coherent scattering
Coherent measurement
Laser techniques

Coherent techniques:

• CARS

• Polarisation spectroscopy

• DFWM

• Stimulated emission, SE