A. DREIZLER

Diagnostics Laser

1/2

Samedi 29 Mai 2010, 16h30 - 18h00
Experiments in Turbulent Combustion

Andreas Dreizler
Institute Reactive Flows and Diagnostics
Mechanical Engineering
TU Darmstadt
Germany

Reaktive Strömungen + Messtechnik
Motivation

• 90% of primary energy conversion by combustion
• Global agreement on reduction of green-house gases and pollutants
  ➢ Improved combustion technology
• More detailed understanding of physical-chemical processes in combustion processes
  – Experiments
  – Detailed modeling
  – Numerical simulation
• Focus here is on gaseous combustion
Interplay between experiments and simulation

Experiments
- Design of experiments
- Analysis of systematic errors

Simulation
- Design
- Control

Fundamentals, Model-development, Validation

Practical combustion process
Interplay between experiments and simulation

Experiments
- Design of experiments
- Analysis of systematic errors
- Practical combustion process

Simulation
- Design
- Control
- Verification

Fundamentals, Model-development, Validation

Numerics
- Data-postprocessing
Focus in this lecture

- Experiments for improved understanding and validation purposes
- (Interconnection of experiments and numerical simulation)
- Topics
  - Benchmark flames
  - Measurands of interest and laser-based methods
  - Selected applications
Validation numerical simulation

- Numerical simulations are based on models
- Combustion LES requires
  - Subgrid-scale model
  - Combustion model
  - ...

→ Comprehensive and reliable data sets for validation and improved understanding are a prerequisite

→ (Quantitative) Experiments in Combustion
  - Gaseous flames
  - Laser-based diagnostics
Contents: Experiments in Combustion

• Bench mark flames
  – Requirements for optical diagnostics
  – Inflow and boundary conditions
  – Bench mark configurations and flame sequences

• Laser diagnostic methods
  – Flow field diagnostics
  – Scalar field diagnostics
  – Combined flow/ scalar field diagnostics

• Applications/ diagnostics at high repetition rates

• Comparison of experiments with LES-quantities
Bench mark flames/ configurations

- Requirements for optical diagnostics
  - Optical access from three sides to enable application of different laser diagnostics
  - Nozzle exit accessible, such that radial profiles can be recorded as close as possible (~1mm)
  - Optical access to interior of nozzle (if possible)
  - In case of atmospheric flames shielding from the lab (co-flowing air)
  - Decoupling of the flame from the exhaust gas system
  - Fuel composition that does not interfere with the laser/detection wavelength
Bench mark flames/ configurations

- Requirements for validation of numerical simulations
  - Known or measurable inflow conditions
  - Well-defined boundary conditions
  - Parametric variation ("flame sequence") of key-quantities such as
    - Fuel composition, equivalence ratio
    - Reynolds-number, thermal load
    - Swirl intensity
    - Pressure
    - Geometry
Bench mark configurations

• 3 Examples of bench mark flames
• 1 Example of optically accessible IC-engine

• Example 1: Turbulent opposed jet flame
Turbulent opposed jet flame

- Two identical opposed nozzles, D=H=30mm
- Turbulence intensity ~0.1 at nozzle exit, enhanced by tgp
- N₂ coflow prevents ambient air mixing
- Access laser beam along burner axis → no beam steering
- Horizontal stagnation plane → symmetric influence of gravity
- Water cooling for stable long term operation
- Parametric variation
  - Fuel composition
  - Reynolds-No. (stable to extinction)
Turbulent opposed jet flame

- Variation of fuel and Re

<table>
<thead>
<tr>
<th>$Re_{\text{air}}$</th>
<th>$a_m$(1/s)</th>
<th>$\Phi = 3.18$</th>
<th>$\Phi = 2.0$</th>
<th>$\Phi = 1.6$</th>
<th>$\Phi = 1.2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3300</td>
<td>115</td>
<td>TOJ1A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4500</td>
<td>158</td>
<td>TOJ1B</td>
<td>TOJ2B</td>
<td>TOJ3B</td>
<td>TOJ4B</td>
</tr>
<tr>
<td>5000</td>
<td>175</td>
<td>TOJ1C</td>
<td>TOJ2C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6650</td>
<td>235</td>
<td>TOJ1D</td>
<td>TOJ2D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7200</td>
<td>255</td>
<td></td>
<td></td>
<td>TOJ2E</td>
<td></td>
</tr>
</tbody>
</table>
Turbulent opposed jet flame

- Flow field quantities for TOJ2D

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk velocity $W_b$</td>
<td>3.4m/s</td>
</tr>
<tr>
<td>Turbulent Re-number $Re_t$</td>
<td>90</td>
</tr>
<tr>
<td>Bulk strain rate $a_b = (-W_{b, o} + W_{b, F})/H$</td>
<td>231s $^{-1}$</td>
</tr>
<tr>
<td>Residence time in mixing layers $t_{res} = a_b^{-1}$</td>
<td>4.3ms</td>
</tr>
<tr>
<td>Large-eddy turnover time $t_{ov} = l_0/(2k)^{1/2}$</td>
<td>16.2ms</td>
</tr>
<tr>
<td>Integral time scale $T$ at nozzle exit</td>
<td>1.6ms</td>
</tr>
<tr>
<td>Integral length scale $l_0$ at nozzle exit</td>
<td>4.7mm</td>
</tr>
<tr>
<td>Kolmogorov length scale $\eta_K$ at nozzle exit</td>
<td>0.16mm</td>
</tr>
<tr>
<td>Batchelor scale at nozzle exit $\eta_c$</td>
<td>0.18mm</td>
</tr>
</tbody>
</table>
Turbulent opposed jet flame

- Visual impression

Time-averaged flame luminosity

Transient flame luminosity

@ 500 Hz
Turbulent opposed jet flame

- Extinction monitored by temporally resolved chemiluminescence, 10 kHz

Time=-451300usec
Bench mark configurations

• Example 2: Swirling lean premixed flame
Swirling lean premixed flame

- Nozzle closer to practical applications
- Need for reliable data sets of premixed flames
- Parametric variation of
  - Reynolds number
  - Swirl number
  - Equivalence ratio
Swirling lean premixed flame

- **Swirl number**

  \[
  S = \frac{G_\theta}{\frac{d}{2} \cdot G_x}
  \]

  - \(G_\theta\) Axial flux of tangential momentum
  - \(G_x\) Axial flux of axial momentum

- **Variation by moveable block** *(motor driven, gear reduction)*
Swirling lean premixed flame

- **Parametric variation: Re**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PSF-30</th>
<th>PSF-90</th>
<th>PSF-150</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{0,\text{th}}$</td>
<td>-</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>$P$ [kW]</td>
<td>30</td>
<td>90</td>
<td>150</td>
</tr>
<tr>
<td>$\phi$ [-]</td>
<td>0.833</td>
<td>0.833</td>
<td>1.0</td>
</tr>
<tr>
<td>$Q_{\text{gas}}$ [m$_3$/h]</td>
<td>3.02</td>
<td>9.06</td>
<td>15.1</td>
</tr>
<tr>
<td>$Q_{\text{air}}$ [m$_3$/h]</td>
<td>34.91</td>
<td>104.33</td>
<td>145.45</td>
</tr>
<tr>
<td>$Re_{\text{tot.}}$ [-]</td>
<td>10000</td>
<td>29900</td>
<td>42300</td>
</tr>
<tr>
<td>$s_L$ [m/s]</td>
<td>0.36</td>
<td>0.36</td>
<td>0.42</td>
</tr>
<tr>
<td>$l_F$ [m]</td>
<td>0.26·10$^{-3}$</td>
<td>0.26·10$^{-3}$</td>
<td>0.18·10$^{-3}$</td>
</tr>
</tbody>
</table>
Swirling lean premixed flame

- Classification in regime diagram

Small eddies penetrate only in preheat zone $\rightarrow$ flamelet-like structure preserved

Laminar flame: T-profile

Turbulent length scale/ laminar flame thickness
Swirling lean premixed flame

• Visual impression
Swirling lean premixed flame

- Transition into flashback
  - Variation of swirl number
  - Variation of equivalence ratio
- Slight adaptation of nozzle geometry
  - Extension of bluff body

(b) Z=0mm

Steel or glass

Air + methane

Moveable-block

Steel or glass

Air + methane

Air

Air
Swirling lean premixed flame

• Three states of operation

(a) Stable: stabilization at the edge of the bluff body

(b) Spinning: flame precesses around the shell of the bluff body

(c) After flashback: the flame is stabilized at the swirler
Swirling lean premixed flame

- Precessing flame
Swirling lean premixed flame

- Precessing flame
Swirling lean premixed flame

- After flash back: view from top (slightly tilted)

- Flame luminescence monitored by intensified CMOS-camera at a frame rate of 7kHz
- Only 6 exposures of a full cycle are shown
- Cycle duration ~7.5±0.6ms.
Swirling lean premixed flame

- After flash back: view from top (slightly tilted)
Swirling lean premixed flame

- Transition from spinning into flashback
  - Transparent nozzle
  - Chemiluminescence recorded at high repetition rates (kHz-regime)
Swirling lean premixed flame

- Stability map
  - For fixed geometrical swirl number

- Flashback is favored by
  - Higher swirl intensity
  - Higher laminar flame speeds
Swirling lean premixed flame

- Inflow conditions
  - Characterization by optical methods: transparent nozzle and laser diagnostics
  - Characterization for non-reacting conditions: Hot-wire anemometry (HWA)
Bench mark configurations

• **Example 3: enclosed pressurized flames**
  – Non-premixed natural gas flames
  – Spray flames
Enclosed pressurized flames

- Modular setup
  - Pressure housing
  - Optically accessible flame tube
  - Complex infrastructure
    - Pressurized air supply
    - Electrical heating of combustion air to mimic inlet conditions of GT-combustor
    - Pressurized fuel supply (natural gas compressor, for liquid fuels high pressure pump and large storage capacity)
    - Exhaust gas treatment (cooling)
    - Safety equipment (sensors and explosion protection)
Enclosed pressurized flames

- Rig
Enclosed pressurized flames

- **Optically accessible combustor**
- “Can-combustor-concept”
- \( P_{\text{max}} = 10 \text{bar}, \ T_{\text{max}} = 773 \text{K} \)
- Modular to adapt different geometries/combustion concepts
- Optical access from three sides for LDA/PDA, PIV, LIF, CARS, etc.
- No disturbance of primary reaction zone by cooling air
- CAD-design for computational meshes
Enclosed pressurized flames

- **Nozzles**
  - Spray flames: n-heptane / air
  - Surrogate n-heptane advantageous compared to kerosene due to chemical kinetics modeling and spectroscopic properties
Enclosed pressurized flames

- Nozzles
  - Non-premixed gaseous flame: Natural gas / air

  - Simple, generic design
  - Non-reactive conditions: Mixture of helium and air to match density
  - Swirl number from geometry $S=1$
Enclosed pressurized flames

- **Operational conditions**

<table>
<thead>
<tr>
<th></th>
<th>2bar</th>
<th>4bar</th>
<th>6bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combustion air temperature</td>
<td>623K</td>
<td>623K</td>
<td>623K</td>
</tr>
<tr>
<td>Fuel temperature</td>
<td>373K</td>
<td>373K</td>
<td>373K</td>
</tr>
<tr>
<td>Combustion air mass flow</td>
<td>30g/s</td>
<td>60g/s</td>
<td>90g/s</td>
</tr>
<tr>
<td>$Re_{\text{Air}}$</td>
<td>46000</td>
<td>92000</td>
<td>138000</td>
</tr>
<tr>
<td>$Re_{\text{Fuel}}$</td>
<td>33000</td>
<td>67000</td>
<td>100000</td>
</tr>
</tbody>
</table>
Enclosed pressurized flames

- Visual impression
Enclosed pressurized flames

- Visual impression – spray flame
Generic bench mark configurations

- Example 4: Optically accessible IC-engine
1-cylinder Diesel engine (Bosch)

- Non-reacting conditions
- Spray propagation and evaporation
1-cylinder Diesel engine (Bosch)

- View from bottom
1-cylinder Diesel engine (Bosch)

• Piston geometries

1. Flat piston

2. Piston bowl
## 1-cylinder Diesel engine (Bosch)

### Engine data

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piston geometry</td>
<td>Bowl / Flat</td>
</tr>
<tr>
<td>Rail pressure</td>
<td>300, 500, 800, 1350, 1800 bar</td>
</tr>
<tr>
<td>Pilot injection</td>
<td>1.5 mm³ at 21°CA</td>
</tr>
<tr>
<td>Main injection</td>
<td>30 mm³ at 2°CA (corresponds 7 bar p_{mi})</td>
</tr>
<tr>
<td>Engine speed</td>
<td>1500 1/min</td>
</tr>
<tr>
<td>Boost pressure</td>
<td>1200 mbar (abs), 1600 mbar (abs)</td>
</tr>
<tr>
<td>Coolant temperature</td>
<td>85 °C</td>
</tr>
<tr>
<td>Liner temperature</td>
<td>140 °C</td>
</tr>
</tbody>
</table>
1-cylinder Diesel engine (Bosch)

- Spray penetration and parameter of interest
Conclusions – bench mark configurations

- Configurations of rising complexity and different geometries necessary to study different phenomena
- Optical access in atmospheric flames no problem
- Pressurized combustion (GT-combustor or IC-engine)
  - causes large investments for reliable, safe and reproducible operation
  - realization of optical access more difficult
- Improved characterization of inflow conditions needs more attention
Validation sequence

• Bench mark flames
  – Requirements for optical diagnostics
  – Inflow and boundary conditions
  – Bench mark configurations and flame sequences

• Laser diagnostic methods
  – Flow field diagnostics
  – Scalar field diagnostics
  – Combined flow/ scalar field diagnostics

• Applications/ diagnostics at high repetition rates

• Comparison of experiments with LES-quantities
Comprehensive data set – demands

- Investigation of different geometries, Reynolds-numbers, swirl intensities, fuel compositions, ...
- Flow field
  - Mean velocities, fluctuations, Reynold-stresses
  - Strain, dilatation, vorticity
  - Integral length and time scales
  - Power spectral densities
- Scalar field
  - Means and fluctuation of temperature and chemical species concentrations
  - Structural information based on 2D- or quasi 3D-diagnostics
  - Scalar gradients
  - Wall/ nozzle temperatures
- Inflow conditions
- Information on unsteadiness, temporal sequences of flow/ scalar fields
Laser based diagnostics

- Non-intrusive
- Extremely high temporal and reasonable spatial resolution
- Flow field
  - Laser Doppler Velocimetry (LDV)
  - Particle Imaging Velocimetry (10 Hz – 30 kHz)
- Two-phase flows
  - Mie scattering
  - Phase Doppler Anemometry (PDA)
- Scalar field
  - Mie scattering
  - Planar Laser-Induced Fluorescence (PLIF)
  - 1D Raman/Rayleigh scattering
  - Coherent anti-Stokes Raman Spectroscopy (CARS)
  - Thermographic Phosphors (TG)
Spatial resolution

- **Laser properties**
  - Coherent radiation → well focusable → small spot sizes = small probe volumes
  - For TEM\textsubscript{00}-mode operation:
    - Typical values $f=350\text{mm}$, $d=10\text{mm}$, $\lambda=532\text{nm}$
    - Spot size diameter $2R\sim45\mu\text{m}$
  - In practice for pulsed lasers worse ($\sim200\mu\text{m}$)
Spatial resolution

- **Typical spatial scales in turbulent flows**

  - Integral length scale
    \[ L_{ij,k}(\bar{x}, t) = \frac{1}{2} \int_{-\infty}^{\infty} \rho_{ij}(\bar{x}, t, r_k, 0) dr_k \]

  - Spatial correlation
    \[ \rho_{ij}(\bar{x}, \bar{r}, t) = \frac{\sqrt{u'_i(\bar{x}, t)u'_j(\bar{x} + \bar{r}, t)}}{\sqrt{u_i'^2(\bar{x}, t)} \sqrt{u_j'^2(\bar{x} + \bar{r}, t)}} \]

  - Kolmogorov (smallest) length scale (\(\nu\) kinematic viscosity m\(^2\)/s)
    \[ \eta_k = \left( \frac{\nu^3}{\varepsilon} \right)^{1/4} \quad \varepsilon = \frac{k^{3/2}}{L} \]
    \[ \eta_k = \frac{L}{Re_t^{0.75}} \quad Re_t = \frac{k^{1/2}L}{\nu} \]
Spatial resolution

- Full optical resolution:
  \[ 2R \text{ (spot diameter)} < \eta_k \text{ (Kolmogorov scale)} \]
- Example non-reacting swirling flow

\[
\begin{align*}
\rho_{11,x} & \quad \text{for } dx / x \\
\rho_{11,r} & \quad \text{for } dr / x
\end{align*}
\]

\( 30\text{iso} \; (\text{Re}=10000) \)
\( L_{11,x}=10\text{mm} \)

\( 30\text{iso} \; (\text{Re}=10000) \)
\( L_{11,r}=6\text{mm} \)

\[ \eta_k \sim 50\mu m \]
Spatial resolution

- Comparison optical resolution and Kolmogorov scale
  - Spot size $2R \approx 45\mu m$ (f=350mm, d=10mm, $\lambda=532nm$)
  - Kolmogorov scale $\eta_k \approx 50\mu m$ (air flow at Re=10000)
  - Same order of magnitude but in practice often not fully resolved
  - Smoothing of measurands is an important issue
Temporal resolution

• **Pulsed laser operation**
  - Quality (q-) switch allows ns-pulses (10^{-9} s)
  - 1ns pulse corresponds to ~30cm
  - Pulsed operation increases intensity dramatically → non-linear optical methods become feasible (most prominent method CARS)

• **Typical time scales in turbulent flames**

  - Integral time scale
    \[
    T_{ij}(\bar{x}, t) = \frac{1}{2} \int_{-\infty}^{\infty} \rho_{ij}(\bar{x}, t, 0, \tau) d\tau
    \]

  - Temporal auto-correlation
    \[
    \rho_{ij}(\bar{x}, t, 0, \tau) = \frac{u'_i(\bar{x}, t)u'_j(\bar{x}, t + \tau)}{\sqrt{u'^2_i(\bar{x}, t)} \sqrt{u'^2_j(\bar{x}, t + \tau)}}
    \]

  - Kolmogorov time scale
    \[
    \tau_k = \left(\frac{\nu}{\varepsilon}\right)^{1/2}
    \]

    \[
    \varepsilon = \frac{k^{3/2}}{L}
    \]
Temporal resolution

- Example reacting swirling lean premixed flame

- Comparison optical resolution and Kolmogorov time scale
  - Laser pulses are much shorter than any time scales in turbulent flames
  - Temporal resolution is no problem
  → Comparison of calculated and measured power spectra better in frequency domain

\[ \tau_k \sim 170 \mu s \]

PSF-30 (Re=10000)
T=1.2ms
0D – 3D measurements by laser diagnostics

- **Up to 3 spatial dimensions are observable**
  - 0D/1D: generation of a thin laser beam
  - 2D: generation of a laser light sheet
  - Quasi-3D: multiple and parallel laser light sheets
Flow field measurements

- **Spectroscopic methods**
  - Doppler-shift of absorption/ emission line
- **Particle based methods**
  - Doppler shift during Mie scattering process (Laser Doppler Velocimetry, LDV)
  - Sequential exposures of instantaneous particle positions by Mie scattering (Particle Image Velocimetry, PIV)
Particle-based flow field measurements

- Gaseous flames need appropriate seed material for Mie scattering
- Mie scattering
  - Intensity of Mie scattered light in dependence of particle diameter

For $n=1.51 \Rightarrow d=1\mu m$

Rayleigh-domain $d_p < \lambda$
Mie-domain $d_p \sim \lambda$
Geometrical optics $d_p >$
Particle-based flow field measurements

- **Mie scattering**
  - Intensity of Mie scattered light in dependence of scattering angle
  - Example: transparent glass bead, 1µm diameter

![Diagram](image)

- Forward scattering highest intensities
Particle-based flow field measurements

- **Seeding material for turbulent flame research**
  - Chemically inert
  - Melting point exceeding adiabatic flame temperatures (>2500K)
  - Sufficiently small to reduce slip $s$ between particle ($u_p$) and gaseous fluid ($u_f$)

\[ s = \left| \frac{u_f - u_p}{u_f} \right| < 1\% \]

- Cut-off frequency exceeding slip of 1%

\[ f_c = \frac{\sqrt{2s - s^2}}{2\pi\tau_0 \sqrt{\left(1 - s^2\right) \left(1 + \frac{\rho_f}{2\rho_p}\right)^2 - \left(\frac{3\rho_f}{2\rho_p}\right)^2}} \]

\[ \tau_0 = \frac{\rho_p d_p^2}{18\eta} \quad \eta: \text{dynamic viscosity} \]
Particle-based flow field measurements

- Seeding materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Short notation</th>
<th>Density [kg/m$^3$]</th>
<th>Melting point [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnesium oxide</td>
<td>MgO</td>
<td>3500</td>
<td>2800</td>
</tr>
<tr>
<td>Zirconium silicate</td>
<td>ZrSiO$_4$</td>
<td>3900 - 4700</td>
<td>2420</td>
</tr>
<tr>
<td>Titanium dioxide</td>
<td>TiO$_2$</td>
<td>4000</td>
<td>1780</td>
</tr>
</tbody>
</table>
Particle-based flow field measurements

- Example
  - MgO
  - $f_c$: maximal turbulent fluctuations that can be resolved, slip < 1%

$\rightarrow$ Smaller particles and higher viscosity (higher $T$) expand the range of resolvable velocity fluctuations
Particle-based flow field measurements

- Addition of seed material to the flow
  - All gas feeds must be seeded, **otherwise results can be biased**
  - Volume fraction of seed material must be variable
- Bypass, controlled and variable mass flow
- Appropriate assembly for addition of seed (“seeding-generator”)
Laser Doppler Velocimetry

• **Principle**
  – Pictorial explanation, correct derivation in text books

\[ \Delta x \times \text{particle flight time} = \Delta t \text{(measured)} \]

\[ |\vec{V}_{\perp \text{Interference pattern}}| = \frac{\text{distance between stripes}}{\text{particle flight time}} = \frac{\Delta x}{\Delta t} \]

Instantaneous velocity, temporal resolution ~µs
Laser Doppler Velocimetry

• Measurement of absolute values = ambiguity in direction
  → Use of moving interference stripes (generated by Bragg cell, phonon-photon interaction)
    – Burst frequency versus velocity
Laser Doppler Velocimetry

Without shift

With shift
Laser Doppler Velocimetry

- Practical realization
  - Continuous wave (cw) laser: argon ion laser
Laser Doppler Velocimetry

- Two velocity component measurement
  - Two colors from argon ion laser
  - Two photomultiplier tubes equipped with interference filters
Laser Doppler Velocimetry

- **Commercial setup**
  - Optical fibres
  - Simple alignment
Laser Doppler Velocimetry

- Single-point, 2-component LDV: Measured variables
  - Mean velocity
    - \( t_i \): transit time, weighting by \( t_i \) to avoid bias by “fast particles”
    \[
    \bar{u} = \frac{\sum_{i=1}^{N} u_i \cdot t_i}{\sum_{i=1}^{N} t_i}.
    \]
  - Velocity variance
    \[
    \left< u'^2 \right> = \frac{\sum_{i=1}^{N} u_i'^2 \cdot t_i}{\sum_{i=1}^{N} t_i}
    \]
  - Standard deviation, root-mean-square
    \[
    \sigma_u = \sqrt{\left< u'^2 \right>}
    \]
  - Turbulent kinetic energy
    \[
    k = \frac{1}{2} \left( \sigma_u^2 + 2 \cdot \sigma_v^2 \right)
    \]
  - Reynolds stresses
    \[
    \left< u'v' \right> = \frac{\sum_{i=1}^{N} u_i'v_i' \cdot t_i}{\sum_{i=1}^{N} t_i}
    \]
Laser Doppler Velocimetry

- Single-point, 1-component LDV (→higher data rates): Measured variables
- Data base consisting of time-series
  - Temporal covariance: $\Delta x=0, i=j$
    \[
    R_{ij}(\bar{x}, \Delta x, t, \Delta t) = u_i'(\bar{x}, t)u_j'(\bar{x} + \Delta x, t + \Delta t)
    \]
  - Integral time scale
    \[
    T_{ij}(\bar{x}, t) = \frac{1}{2u_i'(%x, t)u_j'(\bar{x} + \Delta \bar{x}, t + \Delta t)} \int_{-\infty}^{\infty} R_{ij}(\bar{x}, t, 0, \Delta t) d(\Delta t)
    \]
  - Power spectral density
    \[
    \Psi_{ij}(\bar{x}, \kappa, t) = \frac{1}{(2\pi)^3} \int_{-\infty}^{\infty} \exp(-i\kappa\Delta \bar{x}) R_{ij}(\bar{x}, \Delta \bar{x}, t) d(\Delta \bar{x})
    \]
Laser Doppler Velocimetry

- Single-point, 1-component LDV: Measured variables
- Example isothermal jet
Laser Doppler Velocimetry

- **Two-point, 1-component LDV:** Measured variables
- **Data base consisting of time-series**
  - Spatial covariance: $\Delta t=0$
    $$R_{ij}(\bar{x}, t, \Delta \bar{x}, \Delta t) = u'_i(\bar{x}, t)u'_j(\bar{x} + \Delta \bar{x}, t + \Delta t)$$
  - Integral length scale
    $$L_{ij}(\bar{x}, t) = \frac{1}{2u'_i(\bar{x}, t)u'_j(\bar{x} + \Delta \bar{x}, t)} \int_{-\infty}^{\infty} R_{ij}(\bar{x}, t, \Delta \bar{x}, 0)d(\Delta x)$$
Laser Doppler Velocimetry

- Two-point, 1-component LDV: Measured variables
- Example: Isothermal jet, time-space correlation

\[ \rho_{ij}(\bar{x}, t, \Delta z, \Delta t) = \frac{u'_i(\bar{x}, t)u'_j(\bar{x} + \Delta z, t + \Delta t)}{\sqrt{u'^2_i(\bar{x}, t) \cdot u'^2_j(\bar{x} + \Delta z, t + \Delta t)}}. \]
Particle Image Velocimetry

- Principle
Particle Image Velocimetry

- Movie of particles in reacting turbulent opposed jet flow
Particle Image Velocimetry

- Imaging

- Full-frame interline transfer CCD
Particle Image Velocimetry

- **Cross-correlation**

  Frame 1: \( t = t_0 \)

  Frame 2: \( t = t_0 + \Delta t \)

  Full frame

  Interrogation windows, they determine spatial resolution
Particle Image Velocimetry

- Cross-correlation

\[ R_{II'} (x, y) = \sum_{i=-K}^{K} \sum_{j=-L}^{L} I(i, j) I'(i + x, j + y) \]
Particle Image Velocimetry

• Practical realization

Interrogation volume size
Here: 32 x 32 pixel

\[ \hat{R}_{II}(i, j) = \hat{I}_1(i, j) \cdot \hat{I}_2(i, j) \]
Particle Image Velocimetry

- Practical realization

\[ \Delta x = \Delta \frac{x}{\Delta t} \]

\[ u = \Delta x / \Delta t \]

- Result: instantaneous 2-component velocity field in a plane
Particle Image Velocimetry

- Example:
  - PIV at 6 kHz repetition rate to study in-cylinder flow field
  - Single cycle out of 70
Particle Image Velocimetry

- **Measured variables**
  - Mean, variance and Reynolds stresses as in 2-component LDV
  - Instantaneous velocity gradients (w velocity in z-direction)

- Out-of-plane vorticity
  \[ \omega = \frac{1}{2} \left| \frac{\partial w}{\partial r} - \frac{\partial v}{\partial z} \right| \]

- 2D-Dilatation
  \[ (\nabla \cdot V)_{2D} = \left( \frac{\partial w}{\partial z} + \frac{\partial v}{\partial r} \right) \]

- Less suited for time and space correlation measurements
Particle Image Velocimetry

- **LDV versus PIV**
  - Seeding density
    - PIV: needs at least 10 particles per interrogation volume → for a fixed spatial resolution a minimal seeding density is required
    - LDV: seeding density can be as low as required (on the expense of data acquisition time), seeding density and spatial resolution are decoupled
  - Calibration/ data post processing
    - PIV: cross-correlation algorithm required, long CPU-times (→good statistics not feasible), calibration needed
    - LDV: fast online data processing by optimized CPUs, no calibration required
  - Measured variables
    - LDV: reliable “point-data”, investigation of local neighborhood by two-point LDV cumbersome
    - PIV: instantaneous velocity gradients in different directions

→ LDV and PIV are complementary techniques