EVALUATING THE PERFORMANCE OF A PARTICLE COUNTING SENSOR BASED ON CONTINUOUS WAVE LII

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Performance of a Particle Counting LII Sensor

Motivation

Goal: Development of an optical sensor to determine the (soot) particle number

- Monitoring of particle number concentrations also for the sub-100 nm range
- Creating a compact & low-cost sensor for measurements close to the particle source

State of the art of optical particle sensors:

- Scattering-based optical sensors: limited to particle diameters >100 nm
- Condensation particle counters & LII systems: too bulky for universal, mobile use
Performance of a Particle Counting LII Sensor
Laser-Induced Incandescence

- Heating of nanoparticles to temperatures above 3000 K through absorption of optical energy emitted by a laser
- Heated particles emit broadband incandescence light, which can be captured by a photodetector

Available LII methods:
- Most LII systems rely on bulky (nanosecond) pulsed, high-power Nd:YAG lasers
- Pulsed LII setups cannot count individual soot particles
- Commercially available CW-LII device SP2(-XR)\(^1\) provides this counting capability

**Continuous wave** LII as a possible solution with the potential for a compact realization

\(^1\) Droplet Measurement Technologies
Performance of a Particle Counting LII Sensor

Sensor Demonstrator Design & Setup

- **Laser source: NIR laser diode** (currently: $\lambda=830$ nm, $P=650$ mW)
  - Beam shaping to focus the laser beam to a µm-sized spot to create a particle detection area with high power densities (up to $10^{-6}$ W/cm$^2$)

- **Compact optics design**
  - Collinear guidance of excitation & detection light
  - Intensity difference (laser & LII) requires highly efficient filter systems

- **Detector: Silicon photomultiplier array - SiPM**
  - Highly sensitive for light intensities ranging from several pW to nW
  - Several hundred (parallely connected) pixels operated in Geiger mode
Performance of a Particle Counting LII Sensor

Sensor Characterisation Setup

- **Soot source:** miniCAST 5203C
- **Diluter:**
  - Dekati eDiluter with variable dilution ratios
  - Dekati DI-1000
- **Particle size selection:** DMA or AAC
- **LII laboratory demonstrator:**
  - Easy to align, change & test components
  - Potential for compact setup
- **Reference devices:**
  - CPC (Airmodus), SMPS (TSI)
Performance of a Particle Counting LII Sensor
Determination of the Sensor Performance – Methods

- **Detection limit** as a key performance indicator → measurement capability for soot particles w/ diameters below 100 nm as a goal
- Difficulty of a direct determination due to sensor characteristics & soot properties

**Evaluation of the sensor performance**

1. Indirect procedure for a quick estimation and simple check of cause-effect relationships and parameter variations

2. Measurement of “quasi-monodisperse” particle distributions for a calculation of the sensor’s size-dependent detection efficiency
Performance of a Particle Counting LII Sensor
Determination of the Sensor Performance – Pt. 1

Approach: Indirect ratiometrical measurement procedure for detection limit
- Measurement of particle size distribution with reference equipment (e.g. SMPS)
- Simultaneously measure LII events (#/min) with sensor demonstrator
- Cut of reference data by introducing an artificial detection limit
- Adjust artificial detection limit, until comparison between LII & reference particle concentration data match for several measurements with different CAST particle size distributions
- Assumption of size-independent detection efficiencies gives a rough approximation of sensor performance
Performance of a Particle Counting LII Sensor

Dependencies of the Sensor Performance

- Gain sensor knowledge by evaluating influences of varying parameters:
  - Laser power (power density within focus area)
  - Lens combinations
  - Particle velocity
  - Flow orientation compared to laser beam orientation

Example: Change of laser power from 300 to 700 mW
- Initially strong decrease of the calculated figure of merit (300 to 550 mW)
- Saturation for a further increase of the laser power (density)
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Determination of the size-dependent detection efficiency

Sharp cut-off limit does not reflect the sensor's real behaviour:

- Typically, a transition area with size-dependent detection efficiencies can be observed
- Geometry of the focused laser beam is reason for a size-dependent detection area

**Efficiencies of the SP2(-XR)**

**Detection area of LII sensor**

*Efficiencies of the SP2(-XR)*

[Graph showing detection efficiency vs. BC Mass Eq. Diameter (nm)]

*Detection area of LII sensor*

[Diagram showing detection areas with increasing particle size]

Legend:
- particle detected
- particle not detected
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Determination of the Sensor Performance – Pt. 2

- Detection limit not as a sharp edge, but as a **size-dependent detection efficiency curve**
  - **Cut-off diameter** as the smallest detectable particle size

- Use of a classifier (DMA or AAC) to select a quasi-monodisperse particle size distribution
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Determination of the Sensor Performance – Pt. 2

Estimation of the cut-off diameter

- Selected size: 20 nm – no LII counts
  - Largest particle diameter of this distribution (33 nm) not detectable

- Selected size: 30 nm – **LII counts registered**
  - Largest particle diameter of this distribution (58 nm) detectable

**Cut-off diameter between 33 nm and 58 nm**
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Determination of the Particle Size

**Goal:**
Gain size information directly from registered LII signal shapes w/o additional device (e.g. SMPS)

► Dependency of the emitted LII signal to the soot particle diameter \( Q \downarrow \text{rad} \propto d\downarrow P_3 \)
► Calculation of the distribution's mean diameter through fitting of mean data to calibration values

\[
d\downarrow \text{mean} = (V\downarrow \text{max, mean}/X)^Y \cdot Z
\]

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Mean Peak Voltage (mV)</th>
<th>Mean Diameter (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>383.9</td>
<td>90</td>
</tr>
<tr>
<td>2</td>
<td>311.8</td>
<td>70</td>
</tr>
<tr>
<td>3</td>
<td>286.8</td>
<td>60</td>
</tr>
</tbody>
</table>
Performance of a Particle Counting LII Sensor

Particle Counting Capability

Alternation of PN concentrations

Linear relationship between LII count rates and PN concentration

Size-independency w/ correction function based on mean diameters

1. **Alternation of PN concentrations**
   - Graph showing changes in particle concentration with varying diameters.

2. **Linear relationship between LII count rates and PN concentration**
   - Graph illustrating a linear relationship between LII count rates and PN concentration.
   - Equations:
     - $y = 11.56x + 278.67$
     - $y = 4.57x + 821.28$
     - $y = 2.14x - 760.58$

3. **Size-independency w/ correction function based on mean diameters**
   - Graph showing estimated concentration as a function of LII counts and mean diameters.
   - Formula: $LII\ Counts \times f(d_{\text{Particle, mean}}) = \text{Estimated Concentration}$
Performance of a Particle Counting LII Sensor

Conclusion & Outlook

- Functional sensor demonstrator for measurement of CW-LII signals of soot particles
- Influences on sensor performance investigated
- Detection efficiency curve successfully determined
- Calculation of particle mean diameters

Next steps:
- Transfer gained knowledge to a compact sensor demonstrator
- Online determination of particle size distributions
Performance of a Particle Counting LII Sensor

Literature


BACKUP
Performance of a Particle Counting LII Sensor
Experimental Evaluation of LII Events

- LII events are registered and counted when surpassing a set threshold (voltage + duration)
  - Settings depend on the demonstrator electronics' noise level

- Typical detector events show a duration of **several µs** and pulse heights ranging from 15 mV to >1 V
  - Signal duration depends on the heat-up time and duration of particles propagating through laser focus (and focus geometry)
  - Intensity relates to individual particle size
Performance of a Particle Counting LII Sensor
Determination of the Sensor Performance – Pt. 1

- Ratiometrical method to ensure a fast assessment of the sensor performance

Measurement of particle size distributions w/ SMPS & Record LII events per time

Introduction of an artificial lower limit $d_{\text{L, artificial}}$ for SMPS measurements

Sum of PN concentrations starting at $d_{\text{L, artificial}}$
Performance of a Particle Counting LII Sensor

Determination of the Sensor Performance – Pt. 1

- Ratiometrical method to ensure a fast assessment of the sensor performance

Sum of PN concentrations starting at $d\downarrow L$, artificial

\[
\int_{dx, y} d\downarrow P, c \uparrow \infty \sum \downarrow \# LII
\]

Compare LII count ratio for corresponding measurements to SMPS ratio

\[
\int_{dx, y} d\downarrow P, c \uparrow \infty \sum \downarrow \# LII
\]