“Analysis of influence parameters during sampling of brake dust particle with a constant volume sampling system”

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Analysis of Influence Parameters for CVS Measurement

1. Introduction: CFD Modelling

- flow set up validated by PIV (Particle Image Velocimetry)
- visualization of brake dust particle behavior depending of pariticle properties (i.e. aerodynamic diameter)
- analysis of influence parameters for sampling of brake dust particle with a constant volume sampling system (CVS).
Analysis of Influence Parameters for CVS Measurement

1. Introduction: Measurement Strategy

**Inertia Brake Dyno**
- reproducible load parameters and environmental conditions
- stationary emission measuring systems

**Chassis Dynamometer**
- reproducible load parameters and environmental conditions
- maneuver based RDE-testing
- portable (PEMS) and stationary emission measuring systems

**Road Tests / RDE**
- dynamic driving conditions
- investigation the influence of the driver
- PEMS measuring systems
- investigation the influence of different road conditions

- realistic emissions behaviour
- complexity / poor reproducibility
- investigation costs
Analysis of Influence Parameters for CVS Measurement

1. Introduction: Measurement Strategy

- **Blower**: 400-800 m³/h
- **Probe**: Partial volume measurement
- **Braking system**
- **Measurement tunnel Ø160 mm**
- **Flow meter**
- **Enclosure**
- **HePA filter**

**Process-Related Parameters (CVS)**

1. **Enclosure (chamber)** placed around the brake system
2. **Evacuation of the particle-volume** by a constant and controlled air flow
3. **Sampling (partial volume)** in the transport line
### Analysis of Influence Parameters for CVS Measurement

#### 1. Introduction: Measurement Requirements

**Aim:** Dyno-Measurement of PN and PM

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Physical Processes</th>
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<tbody>
<tr>
<td>• high inlet efficiency</td>
<td>• high Transport efficiency: Low particle deposition on CVS-chamber walls</td>
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<td>• high sampling efficiency: Isokinetic sampling</td>
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<td>• high reproducibility</td>
<td>• well premixed aerosol</td>
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<td>• constant aerosol flow</td>
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<td>• minimized aerosol modification (agglomeration)</td>
<td>• reduced particle-particle interaction (particle residence time)</td>
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<td>• multi-device-measurement</td>
<td>• flow splitter</td>
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<td></td>
<td>• multiple probes</td>
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<td>• minimized background concentration</td>
<td>• filtered inlet air</td>
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<td>• fully sealed chamber</td>
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Analysis of Influence Parameters for CVS Measurement

1. Introduction: Measurement Requirements

**Aim:** Dyno-Measurement of PN and PM

**Approach**
- analysis of particle behaviour within an existing CVS for brake dust emissions
- insight on how influence factors effect the measurement result

**Solution**
- development of a newly designed CVS based on CFD-Simulation results
- additional: Fully sealed chamber design / HEPA-filtered inlet air

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**CVS - 1st Generation**

Cross-section of sampling
Air outlet

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**CVS - 2nd Generation**

Sample point 1
Sample point 2
Blower
Chamber
HEPA-Filter
Analysis of Influence Parameters for CVS Measurement

2. Analysis: Roadmap – Improved CVS / CFD Model

1. CFD based investigation of a CVS

2. flow optimized CVS design

3. assessment of transport efficiency / uniformity

4. comparison with (validated) empirical data

5. improved of CFD particle models

6. validation by experiment

7. CFD model adjustment

CFD Simulation of Brake Dust Particles for CVS Measurement
Investigation of particle transport efficiency $\eta_m$ and particle uniformity $U_p$ across the measurement tunnel diameter, where the particles sample is abstracted by the probe. (particle size range 0,1-4µm)

**Results:**

- Highly turbulent flow inside the enclosure leads to inconsistent particle-air mixing as well as inconsistent particle deposition, which results in a nosy measurement signal (observed during measurement).
- High particle residence time inside the chamber up to 8s (diffusion losses / agglomeration).

→ Development of improved CVS 2nd generation with streamline flow design.
Measurement Tunnel:
• well premixed particle flow: Strongly improved uniformity

Chamber Outlet:
• improvement of transport efficiency

Chamber Inlet:
• linearized air flow
• Integration of a particle filter (H13)
Analysis of Influence Parameters for CVS Measurement
2. Analysis: Development CVS 2nd Generation

CVS - 1st Generation

• complex assessment of particle behaviour
• slow evacuation / high particle residence times

CVS - 2nd Generation

• Foreseeable particle trajectories
• fast and direct evacuation
→ TU Ilmenau focus
CFD based results indicate a significant dependence of transport losses and particle uniformity form:

- volume flow
- suction direction
- disc rotation speed

→ **Challenge:** Indirect proportional correlation between particle mixing and transport efficiency.

→ **Compromise needed:** Evacuation in reverse particle stream initial direction (depending on disk rotation and caliper layout) with maximum air flow, to ensure maximum particle mixture and transport efficiency at the same time.
Disc Rotation Speed:

- Disc rotation velocity is the only influence factor that varies during measurement.
- Centrifugal forces affect the initial particle velocity, which leads to additional particle mixing but also has a negative effect on particle deposition as particles are forced against the chamber walls.
- The CFD models show optimal particle uniformity across the measurement tunnel diameter for 60-150 km/h while transport efficiency decreases linearly with increasing rotational speed.

→ CFD Simulation offers the possibility to assess the amount of particles lost inside the CVS depending on the test cycle.
Analysis of Influence Parameters for CVS Measurement
2. Analysis: Probe and Flow Splitter

- *Isokinetic sampling*: Probe inlet diameter has to be adjusted with regard to the measurement device sample flow.

- For PM$_{2.5}$ no considerable measurement deviation (<5%) due to partial volume sampling was found (validated by experiment). For bigger particle sizes deviation increases significantly due to inertia (CFD).

- For coarse particles (>2.5µm) parallel measurement by means of a flow splitter should be avoid, as coarse particles tend to keep their initial path, which leads to over / under representation.

→ **CVS 2$^{nd}$ Generation is PM$_{2.5}$ ready**

→ **Better solution for PM$_{10}$: Multi-Probe?**
Empirical model (validated by experiment) shows transport efficiency optimum between 0,01-1µm for CVS.

Below 0,01µm diffusion losses and above 1µm inertia losses are observed. Due to inertia, sufficient measurement of particles >5µm is not possible.

Currently there is no CFD particle deposition model available to match the empirical results.

→ CVS 2nd generation is PM2,5 ready / New Approach for PM_{10} needed

→ Advantage CFD: Contemplation of brake system specific effects / assessment of PN and PM measurement

→ Current work: Development of an CFD-deposition model for brake dust emissions
### Analysis of Influence Parameters for CVS Measurement

#### 3. Summary and Conclusions

**Aim: Dyno-Measurement of PN and PM**

<table>
<thead>
<tr>
<th>Summary</th>
<th>Conclusions / Limitations</th>
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<tbody>
<tr>
<td>• investigation of CVS 1(^{st}) generation regarding particle-air interaction</td>
<td>• highly turbulent flow: Inconsistent uniformity and transport losses, high particle residence time</td>
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<tr>
<td>• development of an advanced CVS 2(^{nd}) generation</td>
<td>• linearized particle behaviour, enhanced uniformity and transport efficiency</td>
</tr>
</tbody>
</table>
| • investigation of Influence factors | • **CVS 2\(^{nd}\) Generation is PM\(_{2.5}\) ready**  
| | • indirect proportional correlation of uniformity and transport efficiency  
| | • CFD provides possibility to assess particle losses depending on the test cycle |
| • comparisons with empirical models | • development of an CFD-particle deposition model fitted for brake dust emissions  
| | • further validation necessary |
Analysis of Influence Parameters for CVS Measurement

3. Summary and Conclusions

1. CFD based investigation of a CVS
2. flow optimized CVS design
3. assessment of transport efficiency / uniformity
4. comparison with (validated) empirical data
5. improved particle models
6. CFD model adjustment
7. validation by experiment
8. CFD Simulation of Brake Dust Particles for CVS Measurement
Analysis of Influence Parameters for CVS Measurement

4. Outlook: Open Questions

**Aim: Dyno-Measurement of PN and PM**

- Influences of particle deposition
- **PM$_{10}$-Measurement**
- *further influences*

**Open Questions**

- material properties: particle chemical composition (Hamakar-constant, density etc.)? material and surface condition of the CVS?
- particle shapes: depending on particle size?
- electrostatic effects?
- thermophoresis: heated particles / cold chamber walls?
- transport efficiency: Sufficient measurement possible? (inertia)
- Uniformity: Multi-Probe?
- background concentration: cleaning of chamber walls?
Analysis of Influence Parameters for CVS Measurement

4. Outlook: RDE Testing

Aim: Real Drive Emission Measurement of PN and PM

Outlook

• Use lessons learned under reproducible conditions at the brake inertia dynamometer to develop a RDE system.

→ Challenge: Fully enclosed system in proximity to rotating components (brake disk / rim), exposed to heated brake disk as well as environmental influences (moisture).

RDE-Box design

Geometry optimization

RDE Testing

CFD:
• Max. transport efficiency
• Max. uniformity
• Min. pressure difference
Analysis of Influence Parameters for CVS Measurement

4. Outlook: RDE Testing

Aim: Real Drive Emission Measurement of PN and PM

Outlook

Measurement set up

- Fully enclosed brake system: Complete collection of brake dust / exclusion of environmental influences.
- A H13 filter is used to eliminate external influences / battery powered blower is supplying volume flow.
- Particle loaded air is passed into the measurement tunnel / probe.

→ Current work: Further CFD investigation for improved transport efficiency

RDE Testing
Thank You for Your Attention!