EuroBrake® 2018

CFD based Analysis of Particle-Air Interaction within a Sampling Device for Brake Dust Emissions

Prof. Klaus Augsburg, David Hesse, Toni Feißel (Technische Universität Ilmenau, Germany)

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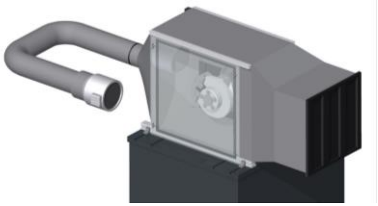
1. Motivation



Main requirement for a sampling system:

- Providing a representative sample for PN/PM-measurement (PM2.5, PM10)

Implementation by (Homologation):

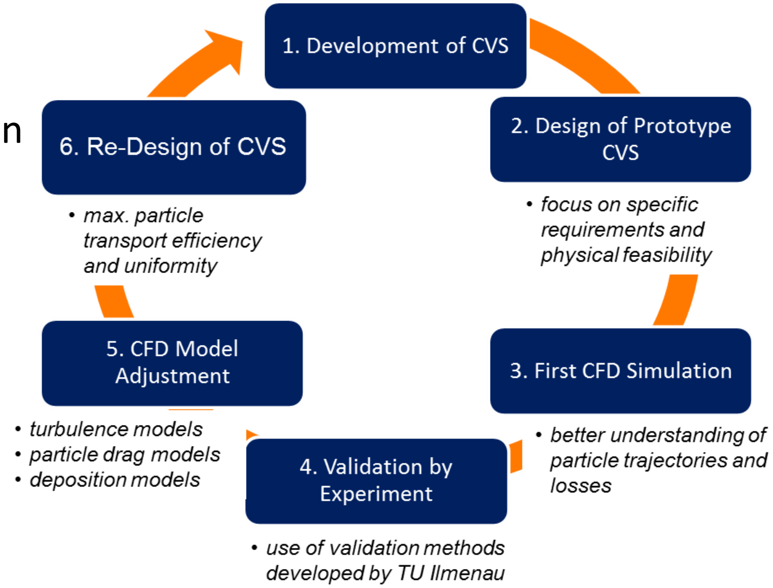
- High sampling- and transport efficiency
- High uniformity of number concentration
- High reproducibility (uniformity, const. Aerosol flow)
- minimizing background concentration (filter)

Influence variables (extract):

- complex geometries → complex flow
- Transport mechanism (external processes)
- injection / initial conditions
- varying parameters over the cycle (rot. speed)
- Disc ventilation

Methodology:

- according to preliminary examinations: the application of empirical models is not sufficient
- The application of complex software (mathematical-physical models)
  - ➢ high quality of results can be achieved
- validation methods for verifying the results of numerical flow simulation are necessary



1. Development of CVS

2. Design of Prototype CVS
- *focus on specific requirements and physical feasibility*

3. First CFD Simulation
- *better understanding of particle trajectories and losses*

4. Validation by Experiment
- *use of validation methods developed by TU Ilmenau*

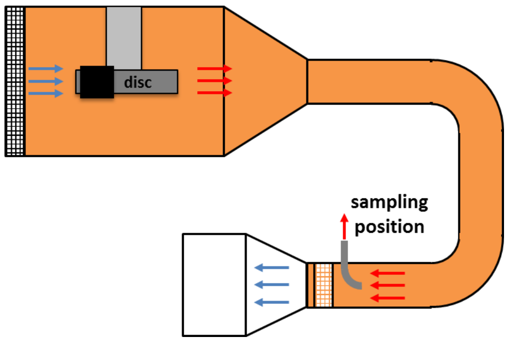
5. CFD Model Adjustment
- *turbulence models*
- *particle drag models*
- *deposition models*

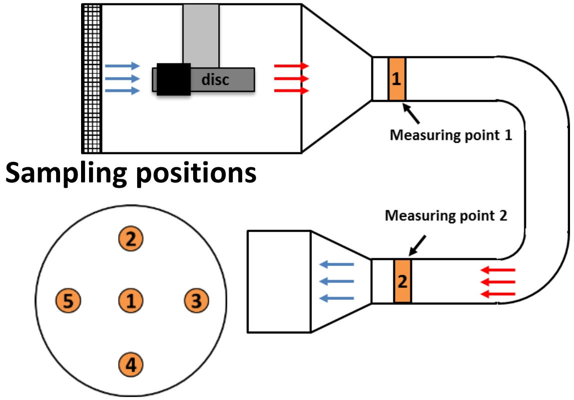
6. Re-Design of CVS
- *max. particle transport efficiency and uniformity*

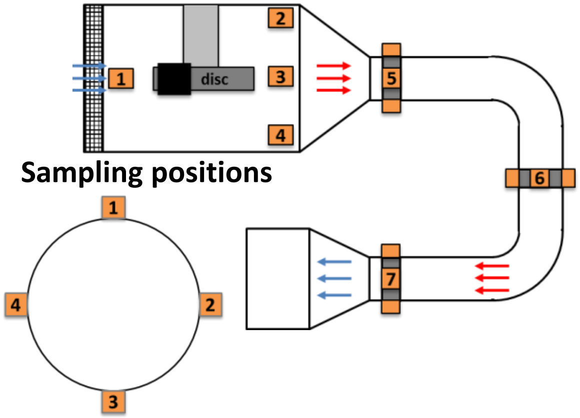
3. Validation methods

Overview

1. Mass balance of deposited particles	2. Verification of the concentration profile	3. Verification of deposited particles
• filter based methodology • Verification of the transport efficiency of a sampling system • Analysis of the influence of different process parameters on the transport efficiency	• verification of the size-resolved number concentration and uniformity • Analysis of the influence of different process parameters on the transport efficiency and uniformity	• Analysis of size-resolved particle deposits and particle loss mechanism • Analysis of the uniformity of number concentration • Analysis of the influence of different process parameters • Analysis of the influence of material properties (electrostatics) or surface texture (roughness)





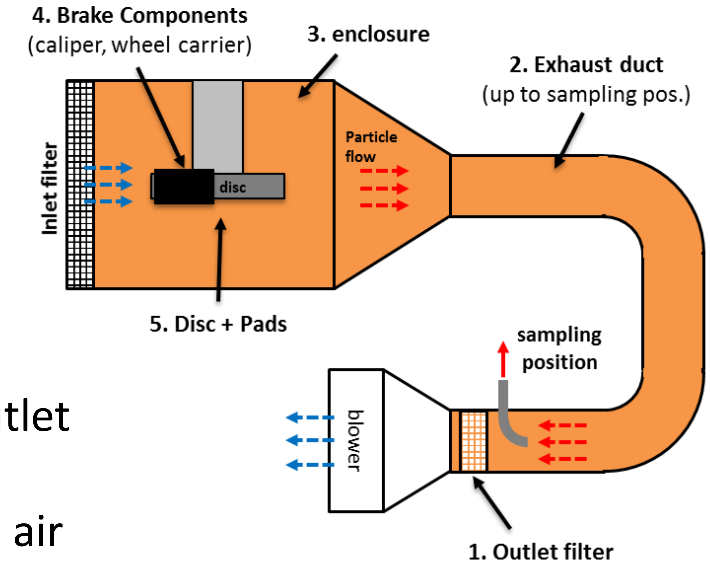


3. Validation methods

Method 1 – Filter-based determination of the particle mass balance

Verification of the transport efficiency of a sampling system (without size resolution)

- ➢ Weighing of deposited particle mass



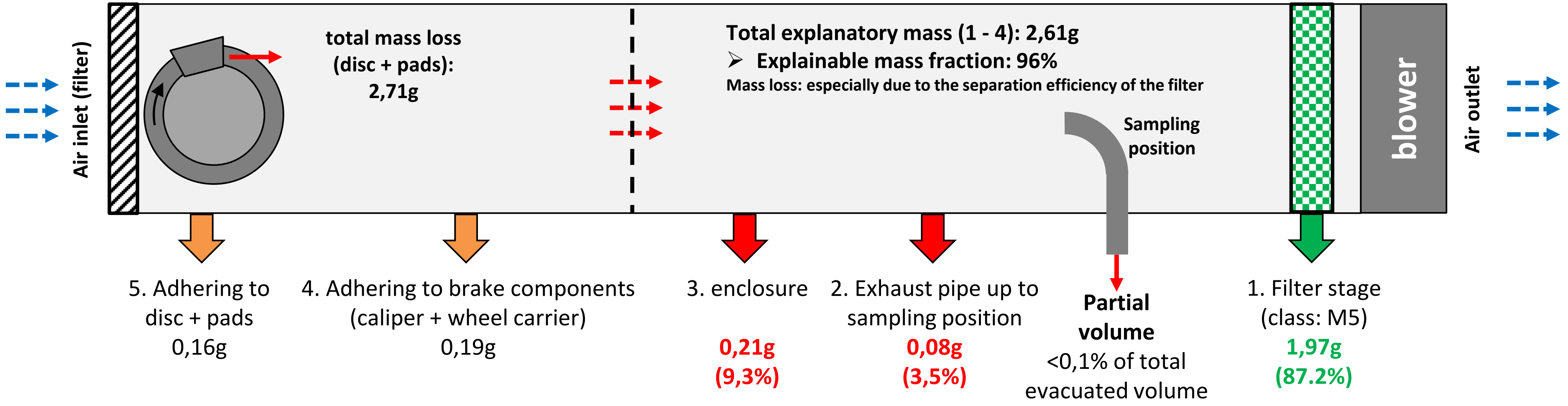
Methodology:

1. Integration of an outlet filer (fine dust - class M5) at the sampling position
2. Execution of the test-cycle as specified (blower activated - evacuation of emitted particles)
3. Determination of mass increase of the loaded outlet filter (Nr. 1)
4. Evacuation of deposited particles by compressed air (blower activated) and integrated filter (Nr. 2 – 5)
5. Weighing of mass increase of the filter stage per section as well as loss of disk and pads
6. Calculation of the mass-based transport efficiency
    - ➢ **Comparison of deposited particle mass vs. evacuated particle mass**

3. Validation methods

Method 1 – Filter-based determination of the particle mass balance

Test conditions: 60x 80→30km/h; 30bar; T_{init} = 100°C



Air inlet (filter)

total mass loss (disc + pads): 2,71g

Total explanatory mass (1 - 4): 2,61g

➢ **Explainable mass fraction: 96%**

Mass loss: especially due to the separation efficiency of the filter

Sampling position

blower

Air outlet

5. Adhering to disc + pads 0,16g

4. Adhering to brake components (caliper + wheel carrier) 0,19g

3. enclosure **0,21g (9,3%)**

2. Exhaust pipe up to sampling position **0,08g (3,5%)**

Partial volume <0,1% of total evacuated volume

1. Filter stage (class: M5) **1,97g (87.2%)**

Calculation of the mass-based transportefficiency (without size resolution):

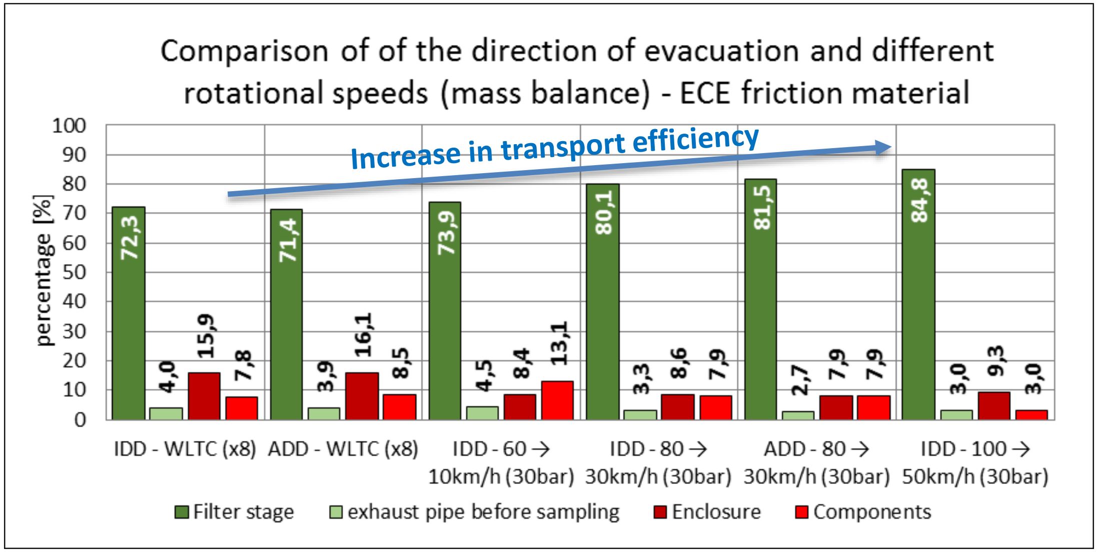
1. Detection of particle mass (deposited / evacuated) per section of the sampling system
2. Comparison of the sum of deposited mass (2 + 3) with the evacuated particle mass (1)

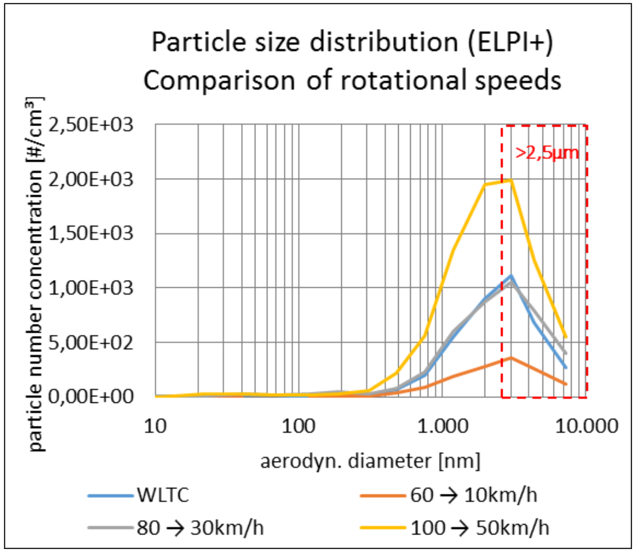
	Total (1-3)	Mass loss fraction (2+3)	Evacuated mass fraction (1)
Σ mass fraction	**2,26g**	**0,29g** ➢ Percentage: 12.8%	**1,97g** ➢ Percentage: 87.2% (**transport efficiency**)

3. Validation methods

Method 1 – Filter-based determination of the particle mass balance

Influence of the direction of evacuation and rotational speed



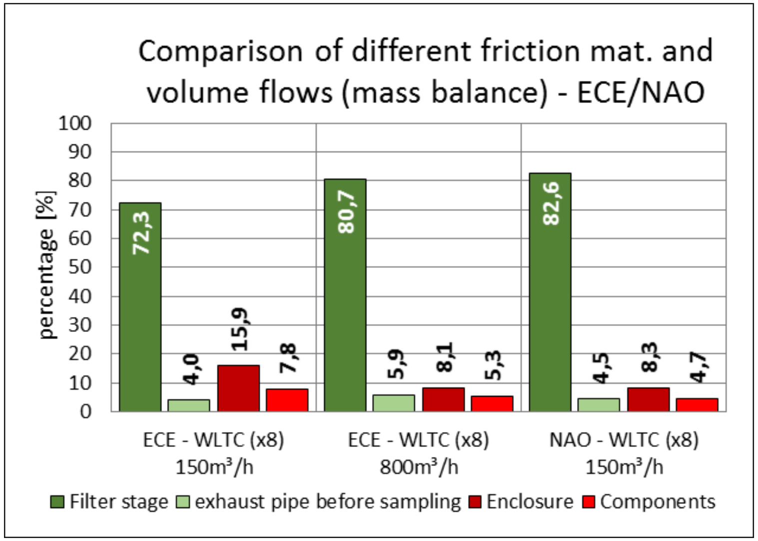


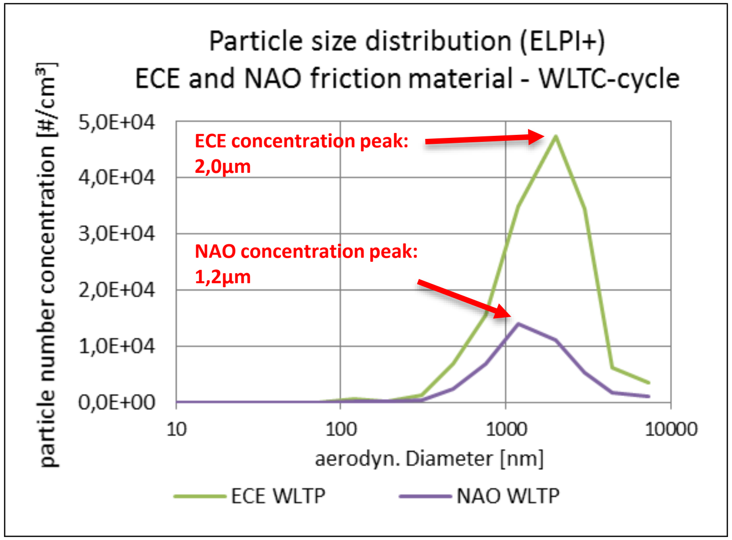
- **IDD: Evacuation in driving direction / ADD: Evacuation against driving direction**
- Mass-based transport efficiency depends on the rotational speed and friction energy
  - ➢ Change of the PSD with increase of the friction energy (red. of the CMD)
  - ➢ Increase in efficiency of evacuation for smaller particle diameter
- Deposition with variation of the suction direction depends on the initial speed
- Deposition at the components (e.g. caliper) depends on the rot. speed and the disc ventilation

3. Validation methods

Method 1 – Filter-based determination of the particle mass balance

Influence of different friction materials and volume flows



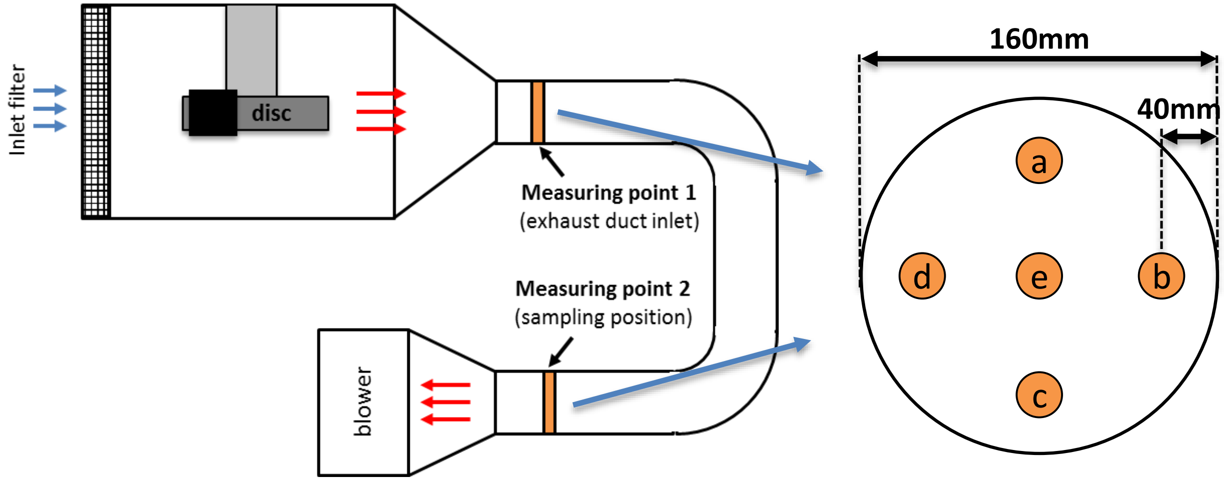


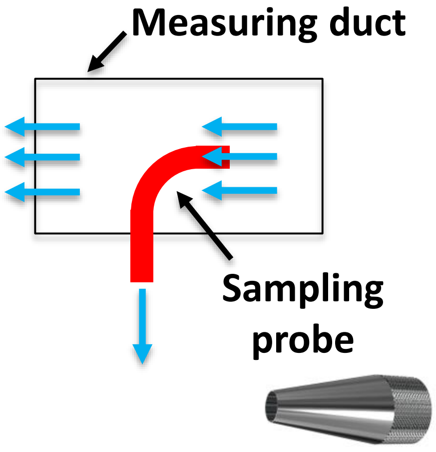
- NAO with a higher transport efficiency due to smaller particle diameter
- Increase transport efficiency with increasing volume flow
  - ➢ higher proportion of deposition in the exhaust duct (influence of transport loss mechanism: impaction / turbulent inertial deposition especially for particles larger than 1µm)

3. Validation methods

Method 2 – Verification of the concentration profile

Methodology





EN 13284-1 and ISO 9096 conform

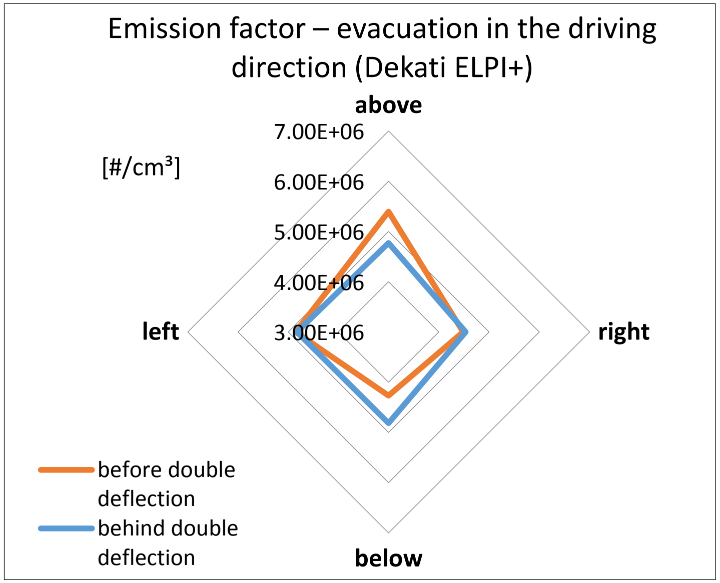
Methodology:

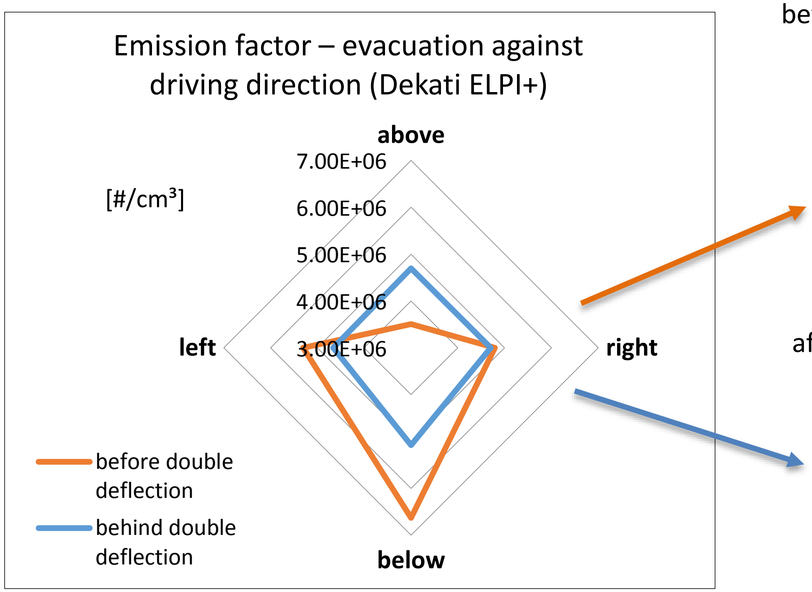
1. definition of the measuring target: Comparison of the concentration profile before and after the double deflection - sampling (isokinetic / isoaxial)
   a. 4 positions offset by 90°
   b. detection at the central point (e) serves as benchmark
2. Execution of the test-cycle as specified (blower activated) and measure the size resolved number concentration over the cross section (Dekati ELPI+: 6 – 10.000nm)

3. Validation methods

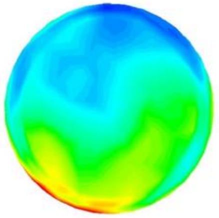
Method 2 – Verification of the concentration profile

Comparison of the number of particles at different suction directions

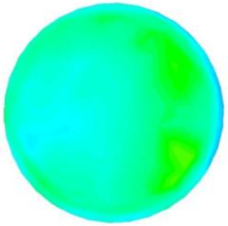

Emission factor – evacuation in the driving direction (Dekati ELPI+)


Emission factor – evacuation against driving direction (Dekati ELPI+)

before double deflection
uniformity: 80,9%



after double deflection
uniformity: 91,4%

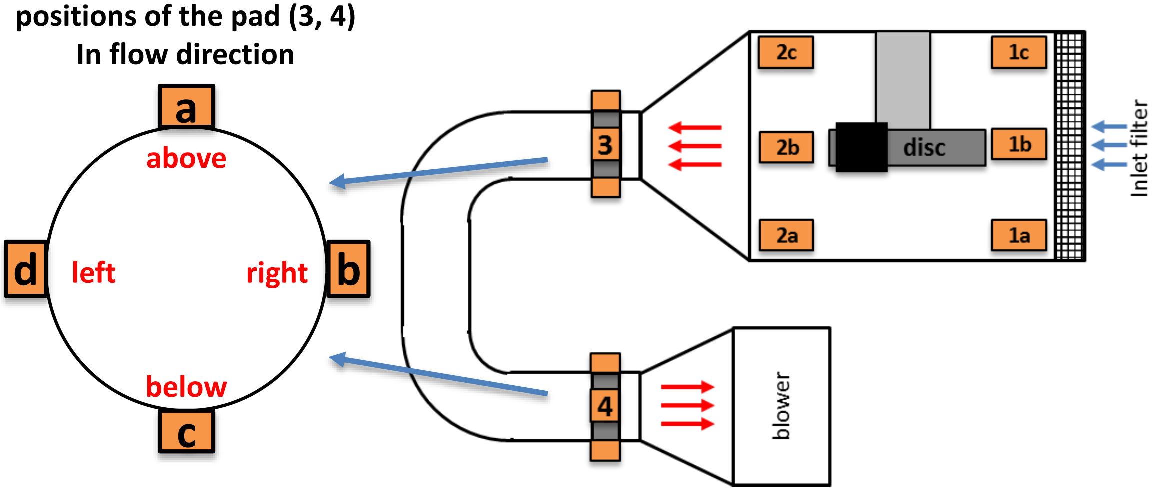


- test conditions: v = 80 → 30km/h, p = 30bar, T_{init} = 100°C; ECE – with copper
- The concentration profile is influenced by the evacuation direction
  - evacuation in driving direction: higher proportion above, lower proportion below
  - evacuation against driving direction: lower proportion above, higher proportion below
- significantly more homogeneous particle distribution due to double deflection

3. Validation methods

Method 3 – Verification of particle deposition mechanisms

Comparison of the size distribution at different suction directions



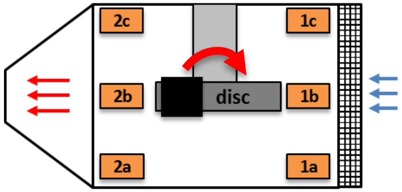
Methodology:

1. adaption of sampling pads in the duct (same material properties and surface texture)
    - ➢ positions: 2x4 pads offset by 90° (analysis of PSD and particle loss mechanism)
2. execution of the test-cycle as specified
3. removal of the collection plates and performing a microscopic analysis (1.000x)
4. analysis of microscopic images by software (e.g. scientific counter) - determination of the particle area and calculation of an equivalent diameter

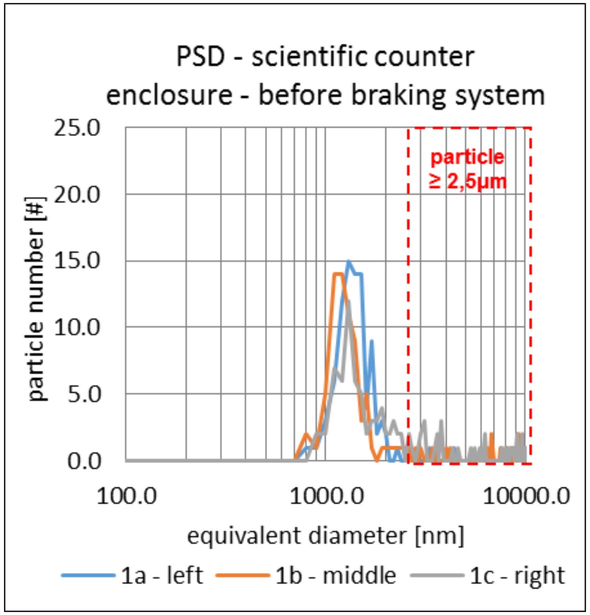
3. Validation methods

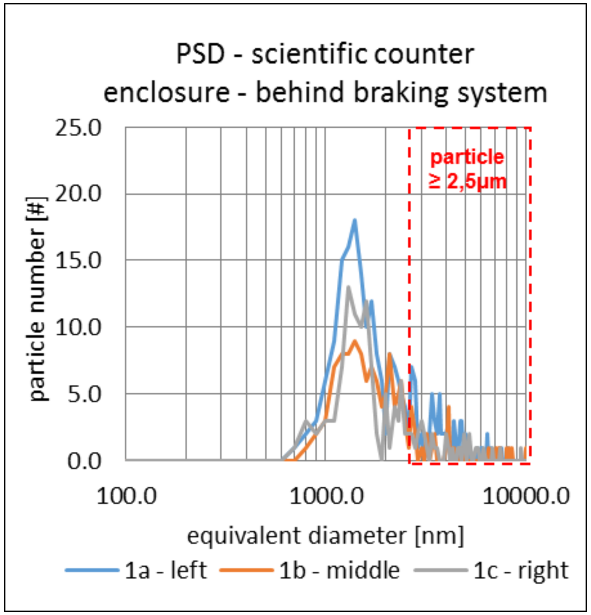
Method 3 – Verification of particle deposition mechanisms

Comparison of the PSD of deposited particles (evacuation against driving direct.)

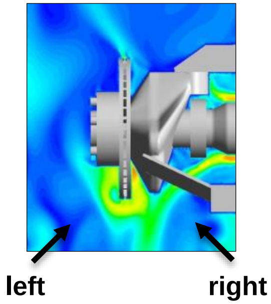


	before braking system (1)		behind braking system (2)	
	PM2.5 to PM10 [%]	CMD [µm]	PM2.5 to PM10 [%]	CMD [µm]
right (c)	65,0	1,74	79,5	1,87
middle (b)	76,1	1,28	80,5	1,92
left (a)	96,5	1,47	75,3	1,92





- Test conditions: v = 60x 80 ⟶ 30km/h, p = 30bar, Tinit = 100°C; ECE-friction mat.
- Significant fraction of deposited particles smaller than 1µm
- High proportion (35,0%) of deposited particles >2.5µm on the right before the braking system, low percentage on the left (3,5%)
  - ➢ influence of “dead water areas” due to the adapted wheel carrier



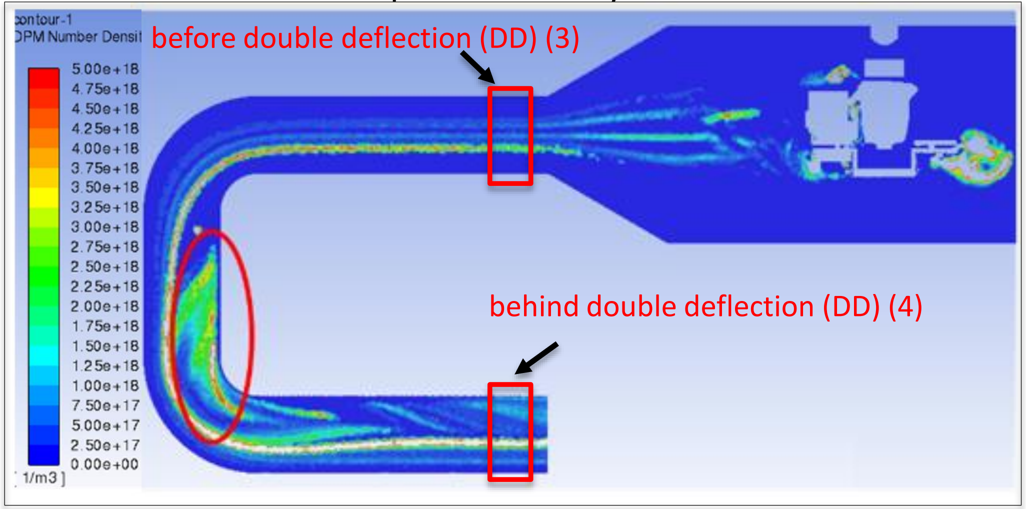
3. Validation methods

Method 3 – Verification of particle deposition mechanisms

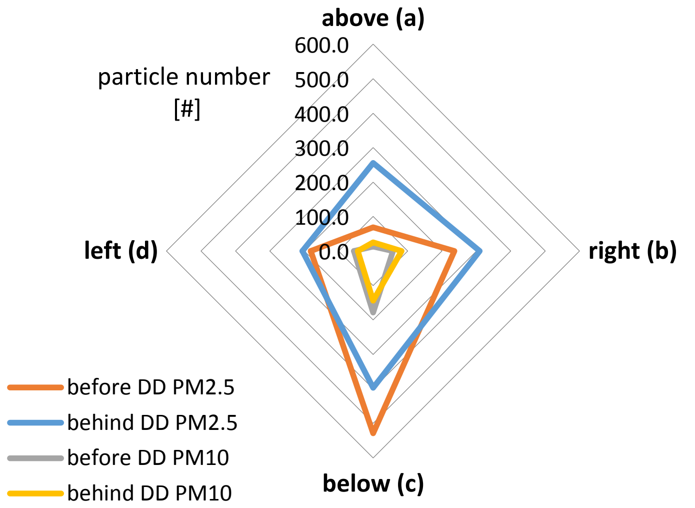
Comparison of the PSD of deposited particles – on collection pads (evac. ADD)

flow simulation – RSM stress omega

particle density



particle number – evacuation against driving direction (PM2.5/PM10)

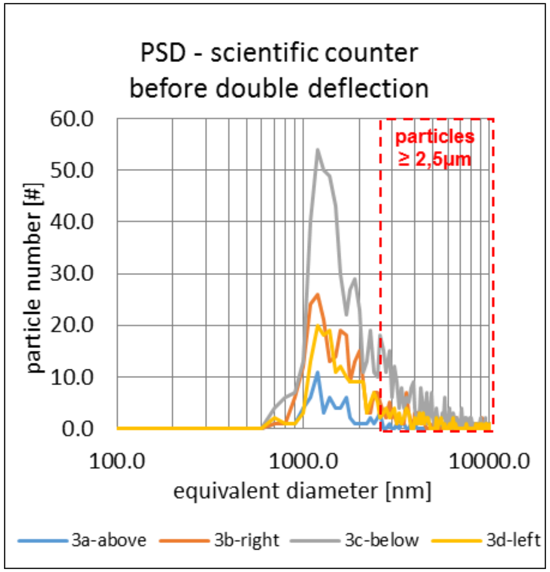


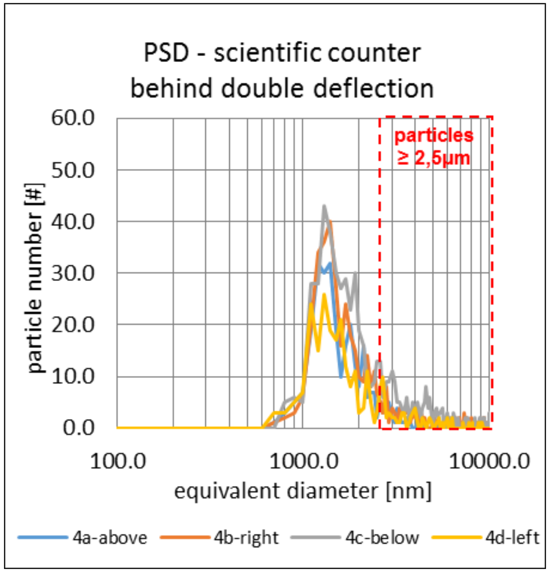
- The expression of a vortex after the first curvature causes an increase in uniformity
- Increase in the homogenization of the flow profile (uniformity) with simultaneous shift of the concentration profile after the double deflection to the right
  - ➢ Comparison of flow simulation and validation: **High degree of agreement at current state of flow study**

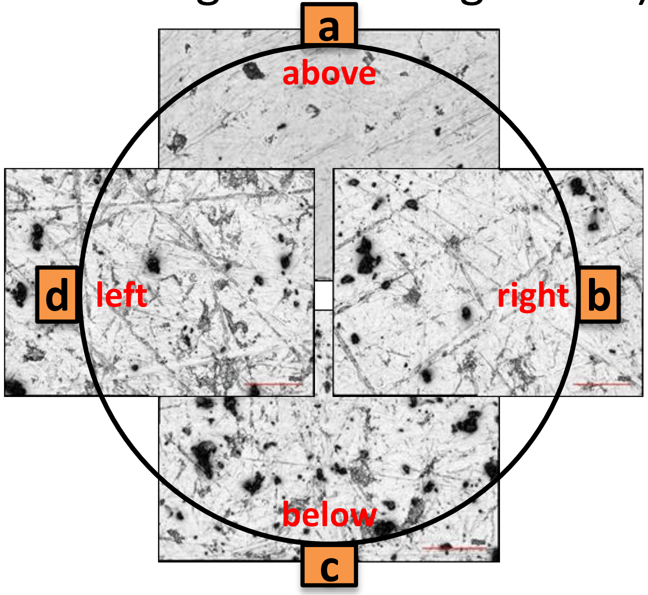
3. Validation methods

Method 3 – Verification of particle deposition mechanisms

Comparison of the PSD of deposited particles (evacuation against driving direct.)







- Influence of the double deflection is also evident with regard to deposited particles in a homogenization of the flow profile
- Highest proportion of deposited particles >2.5µm in the lower area (25,2%/26,6%), lowest in the upper area (15,9%/8,9%)
  - ➢ Proportion is increased with increasing length of the exhaust duct by external processes (e.g. sedimentation, turbulent inertial deposition)

	before double deflection (3)		behind double deflection (4)	
	#-PM2.5 to #-PM10 [%]	CMD [µm]	#-PM2.5 to #-PM10 [%]	CMD [µm]
above (a)	84,1	1,44	91,1	1,40
right (b)	80,3	1,69	78,9	1,62
below (c)	74,8	1,82	73,4	2,01
left (d)	76,4	1,84	82,0	1,63

4. Conclusions

- Application, improvement and validation of CFD models is necessary for the development of a CVS
- By use of the methods presented, the transport efficiency and uniformity of number concentration of different sampling systems (mobile or stationary) can be verified – CFD results can be validated
- The transport efficiency of a sampling systems (CVS) depends from various influence factors (tribological and sampling conditions)
- Geometric adjustments can increase uniformity (double deflection)
  - ➢ **Evaluated and validated methodology for the development of sampling systems is available**

5. Outlook

- Application of the presented methods for the verification of particle deposition / adhesion mechanisms on the transport efficiency and uniformity of the number concentration
  - ➢ stationary and mobile sampling systems
- findings regarding brake dust particle deposition mechanisms and particle properties can be used to improve CFD models
- by using advanced models the CVS design can be enhanced

Thank you for your attention!

TECHNISCHE UNIVERSITÄT
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David Hesse

Technische Universität Ilmenau

david.hesse@tu-Ilmenau.de