Physikalisch-Technische Bundesanstalt
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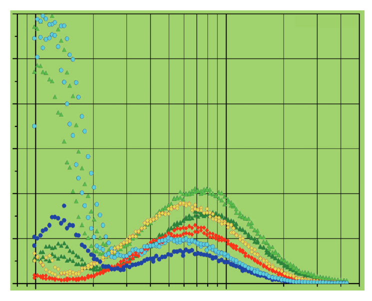

An accompanying CFD-study on partial flow sampling from a soot aerosol dilution setup

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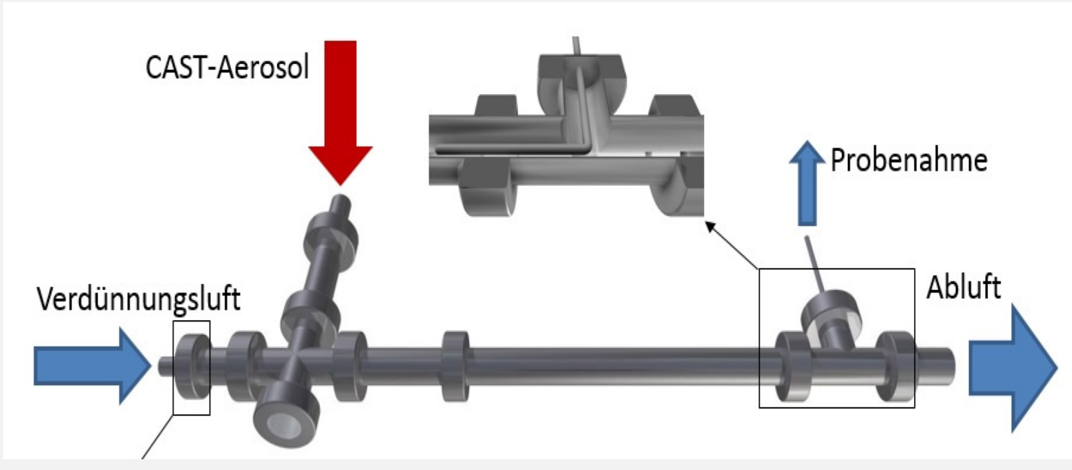
Objectives

- Verify the main flow variables, special attention is paid to the property of conservation of mass
- To ensure a stable and spatially homogeneous mixing and dilution of CAST soot aerosol
- Generate an inside view of the gas-flow-soot-aerosol interaction process, in particular around the sampling tube
- The aerosol sampling is collected at higher flow velocity due to small cross section, indicated by hyperkinetic flow regime between flow velocity in the main pipe versus sampling sub-tube
- To estimate the amount of soot particles which are trapped by probe section (aspiration- or collection efficiency)
- Is the particle number size distribution (PNSD) of the particle collective influenced?
- To achieve tracking information about the soot aerosol which was collected in the small sample tube

Inline Sampling



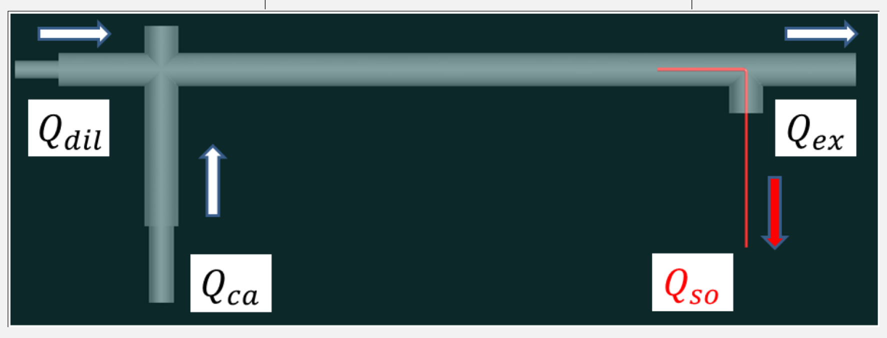
View on dilution and conditioning unit with the additional sampling sub-tube system in the experimental setup [1] [3].

The located field variables are Q_{ca}=CAST (Injection), Q_{dil}=dilution, Q_{so}=sample_out and Q_{ex}=exhaust.

Three Flow Cases

- Volume flow rate Q in l/min, $Q_{so} = -4$ l/min, $\overline{\boldsymbol{u}}$ in m/s (main pipe)
- Conservation of mass: $Q_{ex} = Q_{dil} + Q_{ca} + Q_{so}$
- Reynolds number $\mathrm{Re}_{\mathrm{ch}}$ indicates a turbulent regime
- Equilibrium mass fraction: $\xi_\infty = Q_{ca}/(Q_{dil} + Q_{ca})$

	Q_{dil}	Q_{ca}	Q_{ex}	ξ_∞	$\overline{\boldsymbol{u_{ch}}}$	$\mathrm{Re}_{\mathrm{ch}}$	$\overline{\boldsymbol{u_{so}}}$	Q_{ca}/Q_{dil}
# 1	24	24	44	1/2	0.71	1736	5.32	100 %
# 2	48	24	68	1/3	1.06	2604	5.32	50 %
# 3	48	48	92	1/2	1.41	3471	5.32	100 %



Construction of the dilution and conditioning unit in the domain.

Numerical Modeling

- Stationary incompressible Navier-Stokes equations

$$\nabla \cdot u = 0, \qquad u \cdot \nabla u = -\frac{1}{\rho}\nabla p + \nu \Delta u.$$

with:

- Velocity field u, pressure p, density of the fluid ρ and kinematic viscosity ν.

- Standard no-slip boundary conditions on the walls, zero-gradient boundary condition at the outlet ex
- Turbulence is modeled by RANS equations and applying the well-known standard SST-model
- Hexahedral mesh consisting of 2.7 million elements, solved with ANSYS CFX in three dimensions

Quantifying Mixing

The intensity of segregation was introduced with I_s as the normalization of the variance by its maximum value.

$$I_s(x) = \frac{\sigma^2(x)}{\sigma^2_{max}(x)} \quad \text{with} \quad \sigma^2_{max}(x) = \sigma^2(x=0) \quad \text{with}$$
$$\sigma^2(x) = \frac{1}{|A|}\int_A \left(\xi(x,y,z) - \bar{\xi}(x)\right)^2 dA\,. \qquad (1)$$

This implies integrating of the mass fraction over the surface area about the cross plane $|A|$ respectively $\forall x$ where $\bar{\xi}(z)$ denotes the mean value of mass fraction and $\sigma^2_{max}(x)$ is the maximum possible variance given at x=0.

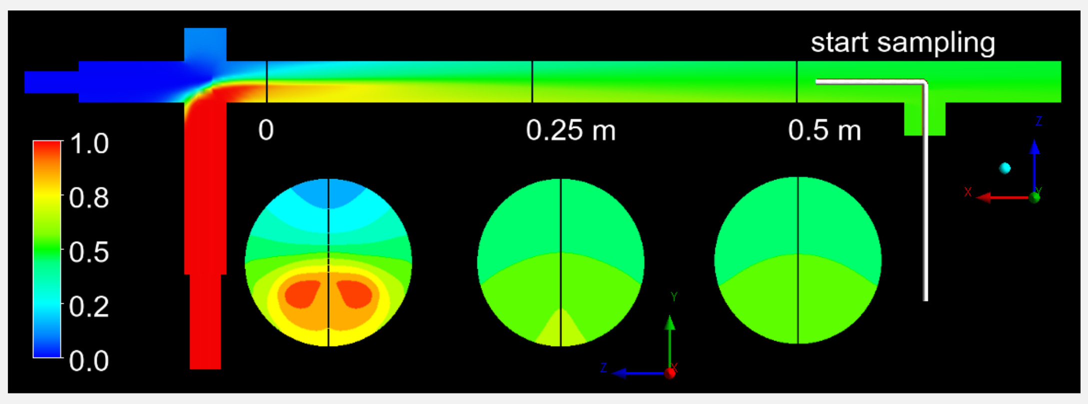
- Assess the quality of the mixing process along the tube
- A threshold level $I_{sl} = 1/10$ is fixed

Particle Injection

- Mass flow rate $\dot{m} = \iint_A \rho u \, dA = 0.1$g/h
- Morphologie: Gas-Solid (Particle-laden flow)
- The soot loading was considered smaller than 10^{-7}
- One-way coupling between gas and particles. That means the carrier fluid allows to influence trajectories, but particles doesn't affected the gas fluid itself
- Considering only drag forces and turbulent dispersion
- Coalescence, breakup or deposition are not modeled
- Zero Slip causes the particles to be injected at the local fluid velocity of the coupled continuous phase.
- Particle locations equally spaced, 2.0×10^5 tracks should be integrated
- Discrete PNSD were chosen from experimental data measured with SMPS-system

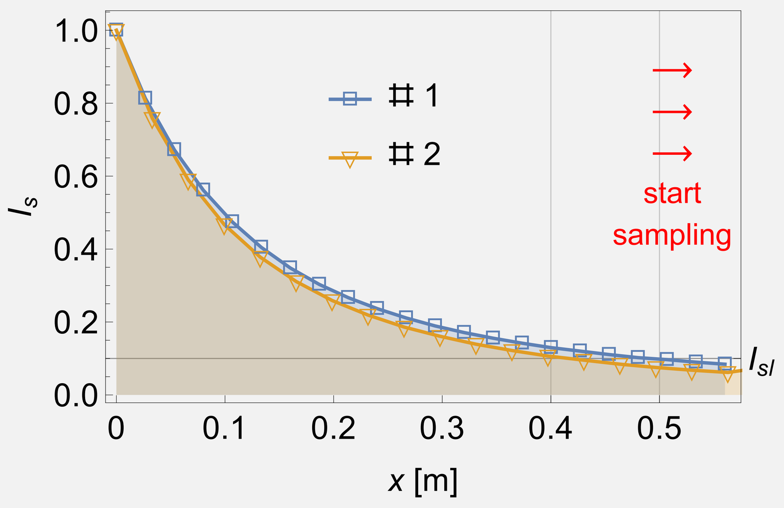
Mixing Behavior

An addional transport equation is used to indicate the mixing behavior of the fluid



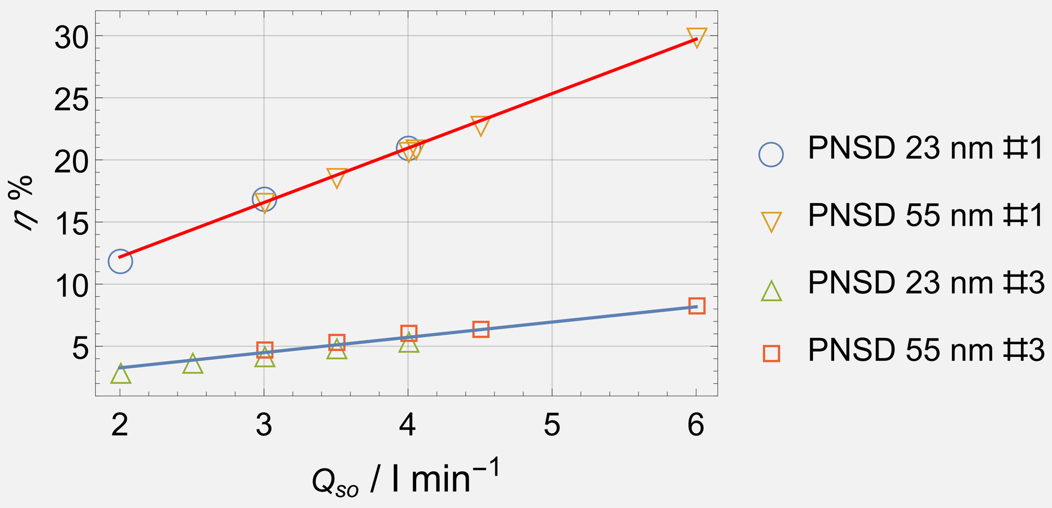
Top: Contour plot of the mass fraction ξ on axial plane. Middle: Plots of ξ for cross sections at different x-positions, $x = 0$ m, $x = 0.25$ m and $x = 0.5$ m. The flow direction is from left to right.

Mixing Length



A mixing length [2] of 0.4 m is obtained for flow case #2 of higher volume flow, whereas a distance of 0.5 m is required to rich I_{sl} for the lower flow case #1.

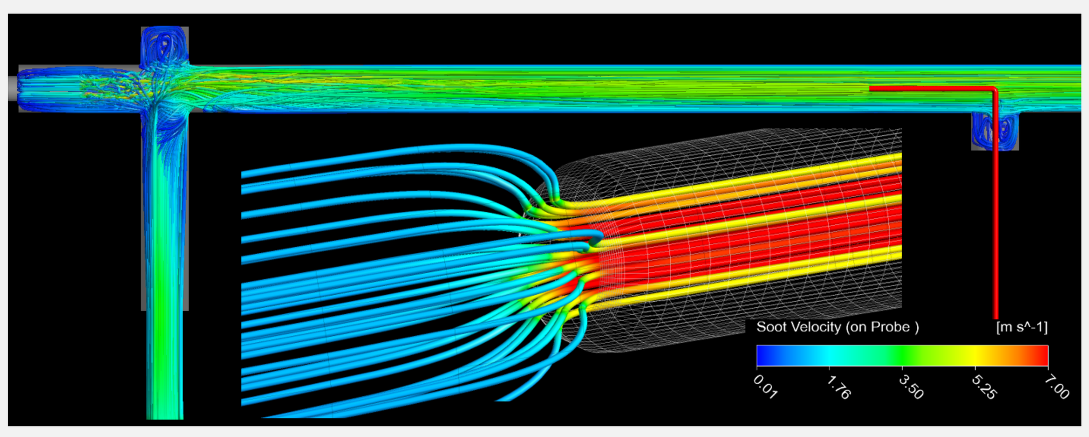
Aspiration Efficiency



Aspiration Efficiency $\eta = pr_{so}/pr_{ca}$ with Particle Number Rate pr. pr_{ca} on inlet (100 %) for flow cases #1 and #3 are shown. Additional two PNSD of 23 nm and of 55 nm are compared.

Particle Tracking (PT)

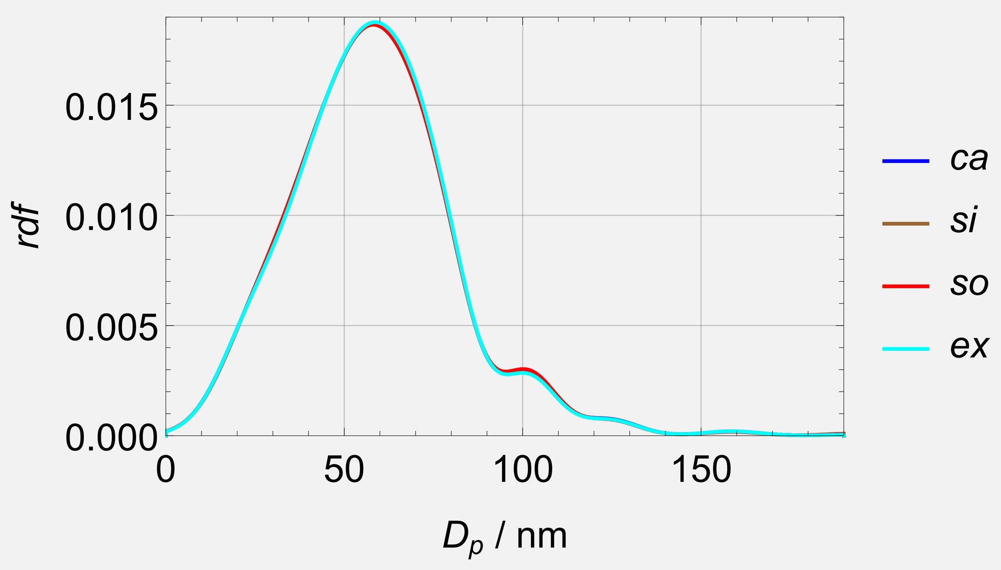
- The application of Eulerian-Lagrangian tracking involves the integration of the particle paths through the discretized domain. A representative ensemble is tracked from the injection inlet (si) until particles escape the domain.
- PT can be describe the mean flow behavior.
- PT can be used to display turbulence induced properties such as re-circulation (see the mixing process in the blind T area).



Top: View of particle paths on axial plane colored by its soot velocity. Middle: Collecting particles into sampling sub-tube showing a hyperkinetic regime. This means, the velocity in the sub-tube is higher (red) than the velocity of the carrier fluid in the main tube.

Comparing PNSD

A discrete PNSD at different locations of the domain were reconstructed to show variation for experimental data. For this aim a measured PNSD was applied to the inlet Q_{ca}. At the moment effects like coalescence or breakup are neglected, because there is an absence of measurement capabilities. Therefore the expected deviations are small.



Example of reconstructed density function rdf for a particle number size distribution (PNSD) around 55 nm on different locations of the setup like ca=CAST (Injection), si=sample_in behind CAST, so=sample_out and ex=exhaust.

Conclusions

- The mean field variables like mass fraction were in the expected range and showed a well mixed process by the self made dilution system.
- The mixing process variable like mixing length induced a threshold value of below $I_{sl} = 0.1$ for an optimized mixing in the main tube to guaranteed the best position of the sampling tube.
- A higher sampling flow leads to an increased aspiration efficiency on sample outlet.
- Discrete PNSD measured with SMPS could be reconstructed in the model domain.

References

[1] A. Kuntze, M. Hildebrandt, A. Nowak, A. Jordan-Gerkens, D. Bergmann, E. Buhr, and V. Ebert. Characterization of a PTB-Standard for Particle Number Concentration of Soot Particles. In 18th ETH-Conference on Combustion Generated Nanoparticles, Zurich, Switzerland, Zurich, 2014.

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