Capture of automotive particulate matter in open substrates

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EXTENDED ABSTRACT.

Background: Open filters (with low pressure drop) have potential for energy efficient reduction of particulate matter (PM) from internal combustion engines. For some applications, open substrates may suffice. Furthermore, the use of a flow-through filter (e.g. an oxidation catalyst) upstream a wall-through filter (i.e. diesel particulate filter, DPF) will decrease the pressure drop build-up, since smaller particles will be captured in the upstream open filter and a narrower particle size distribution (PSD) with a shift towards larger sizes will enter the DPF. Furthermore, the PM from internal combustion engines is prone to changes (via changes in gas composition and temperature) and it is therefore extremely challenging to characterize.

Experimental: In the work reported here, the capture efficiency of PM in open substrates (bare cordierite and alumina-coated cordierite monoliths) has been investigated using PM from a real engine under various flow conditions (varying residence times and temperatures) and sampling settings (dilution ratios) using a DMS500 from Cambustion. However, the capture efficiency was affected by removal of volatiles (hydrocarbons) influencing both size and numbers. In order to quantify these effects, a conceptual model has been implemented that can be used as an in-situ analyzer of the PM properties. This model includes loss of pure volatile particles and shrinkage of semi-volatile particles. Although physically sound, the model is empirical and the parameters needs fitting to experiments.

Results: The observed capture efficiency (CE) confirmed the expected trends that increased residence time and increased temperature gave higher CE. However, the volatile content (assumed to be hydrocarbons, HC) can increase the apparent CE due to rapid evaporation and/or shrinkage of the PM. The results show how exhaust treatment (heating and/or dilution) changes the characteristics of the PM. These properties affect capture efficiency and can be used for subsequent catalyst optimization. In addition, the method developed here was used to analyze nucleation mode PM from a special fuel injection strategy. The results revealed that these particles were mainly non-volatiles, demonstrating the usefulness of this characterization

methodology. Furthermore, an equation for diffusion losses in the rotary dilutor for the DMS500 is presented.

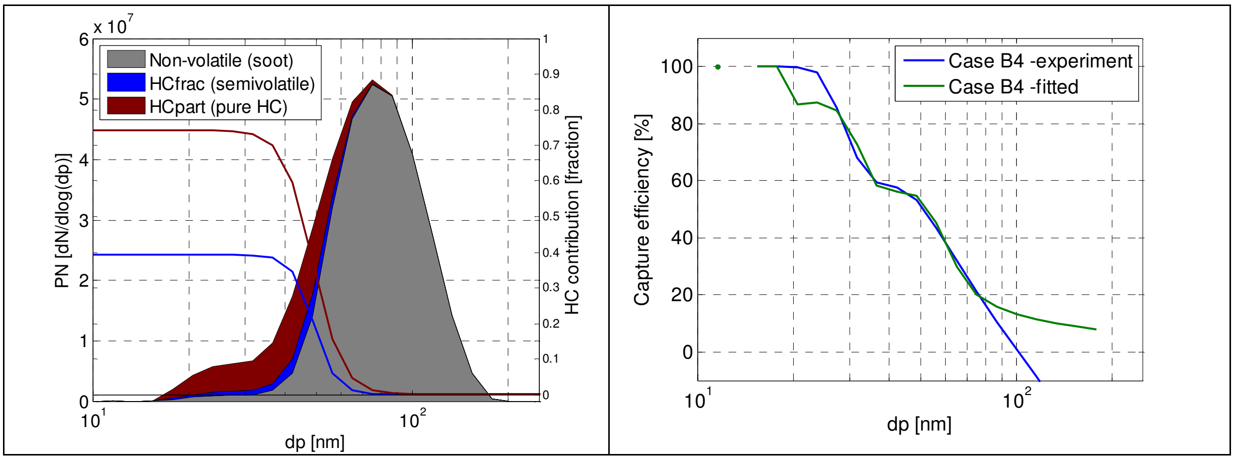

Figure 1. Left: The particle size distribution and the corresponding volatile contribution using a sigmoidal function describing the size-dependent fractions. Right: The experimental and fitted capture efficiencies.

The conceptual model developed here relies upon the assumption that the experimental setup is reliable and that the theory (provided by diffusion equations and/or correlations) hold for inert particles. In order to verify these assumptions a set of experiments was performed using inert NaCl particles generated by an atomizer (Topas ATM230). It could be confirmed that the experimental CE corresponded to the theoretical CE. Thus the experimental setup and methodology was validated.

Conclusions: Although the evaporation model offers a plausible explanation to the phenomena observed, conclusive validation still remains. However, assuming that this model is applicable, a number of important conclusions could be drawn

1. The monolith channel serves as an effective HC trap and thus increases any HC evaporation. The resulting change in PSD should be taken into account when simulating the catalyst reduction in open filters.
2. By analysis of the fitted HC contribution, interferences of the PM characteristics can be made in-situ (in terms of volatile content). This information would be very hard to obtain by other means.
3. The use of partial injection strategy could be a useful way to produce small PM that is suitable for kinetic studies and for the bridging between lab-scale soot (e.g. Printex U) and real diesel PM emissions.

Reference:

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Capture of Automotive Particulate Matter in Open Substrates

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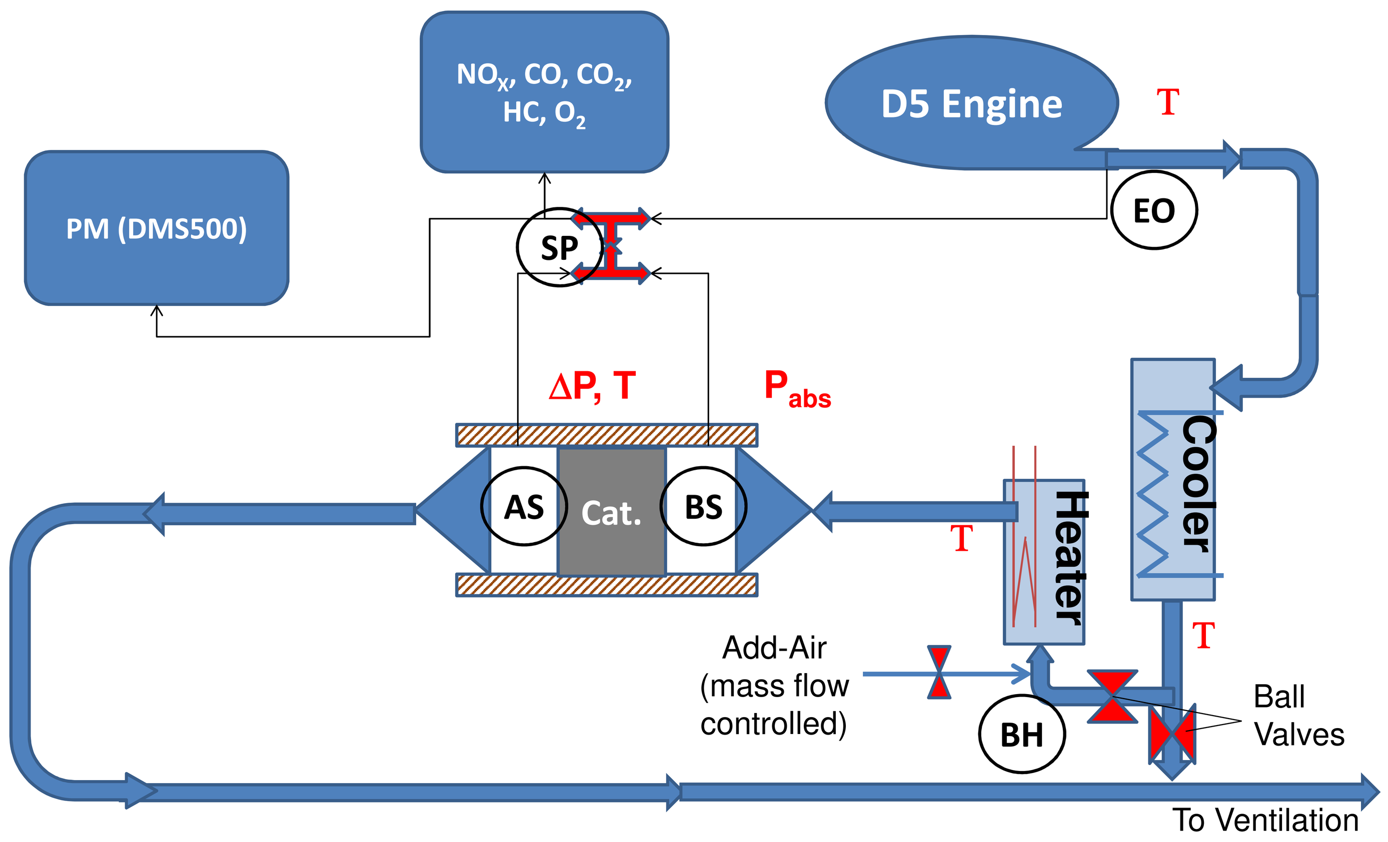
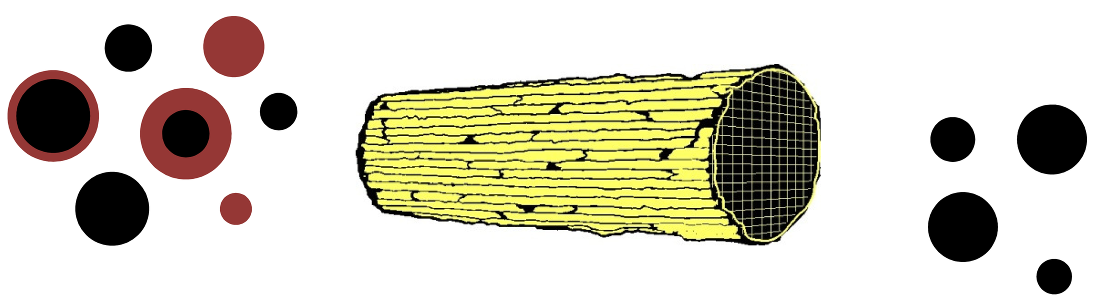
Introduction

- Particulate Matter (PM) emission causes problem for human health as well as for the environment
- PN (particle Number) legislation requires wall-flow filters (DPF) and increases fuel consumption
- To reduce fuel penalty a detailed understanding of capture related phenomena is needed
- Is it possible to use open substrates as the only PM reduction unit?





Objectives

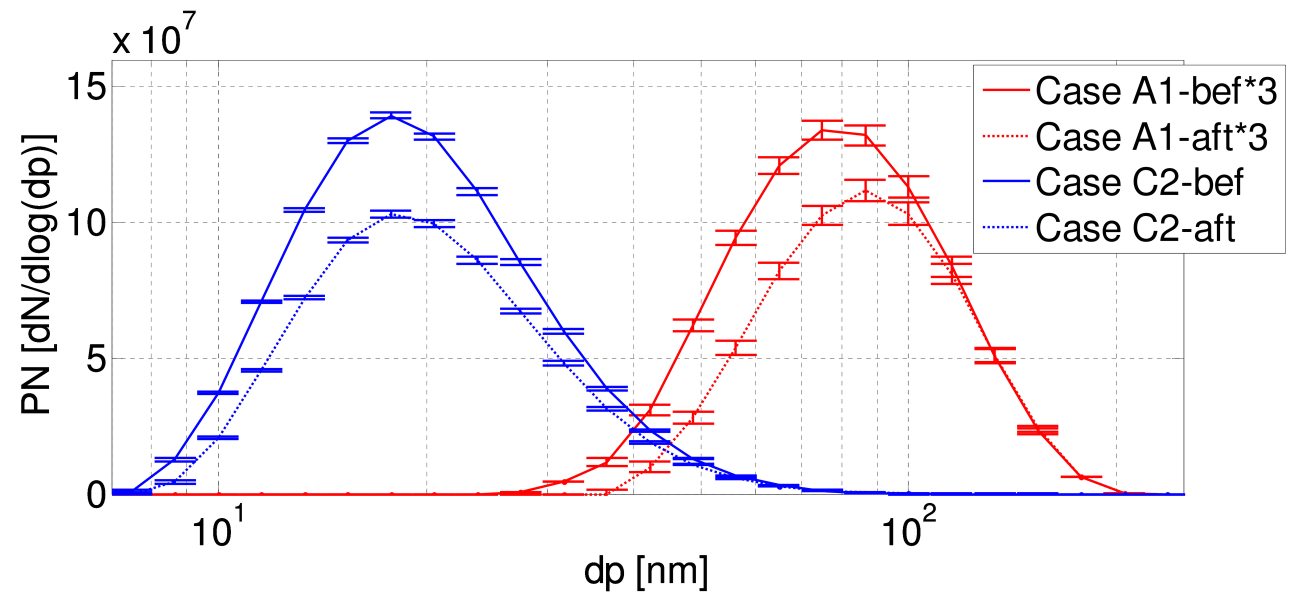
- To assess Capture efficiency by systematic variation of flow conditions
- To increase understanding of PM removal *in situ* (not for regulatory purposes)

Experimental

- EATS (Exhaust Aftertreatment System), for details see [1]
- Insulated, inert substrate (5.66" x 6", 400/6 cpsi)
- Different temperatures and flows
- Addition of air

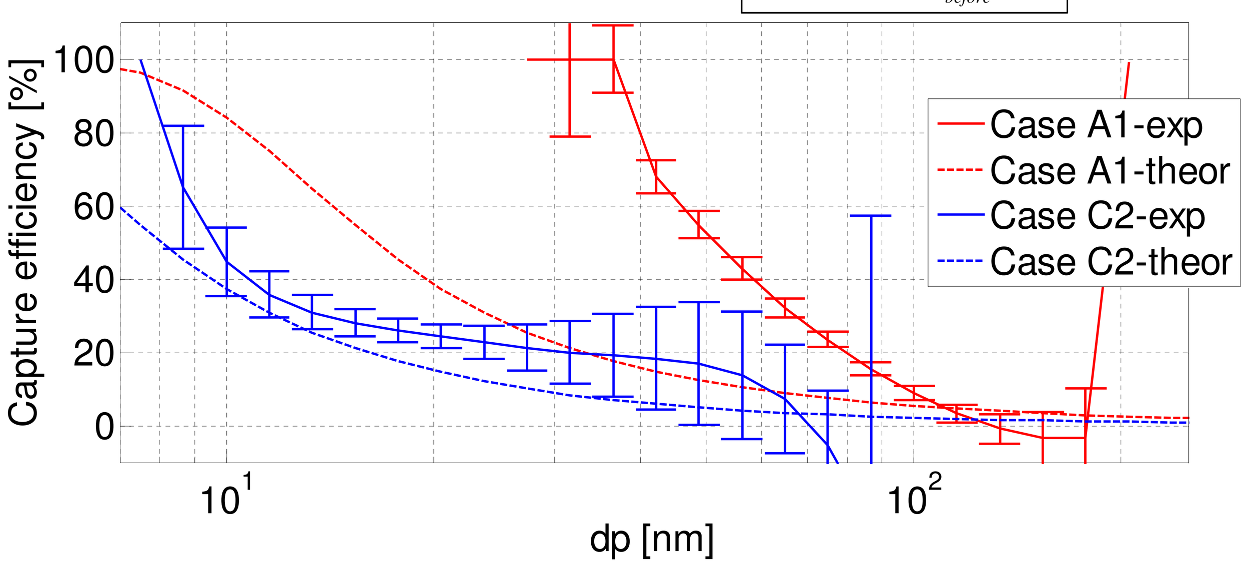
For experimental details, see [2]

Results: Particulate Matter Size Distribution



Capture Efficiency

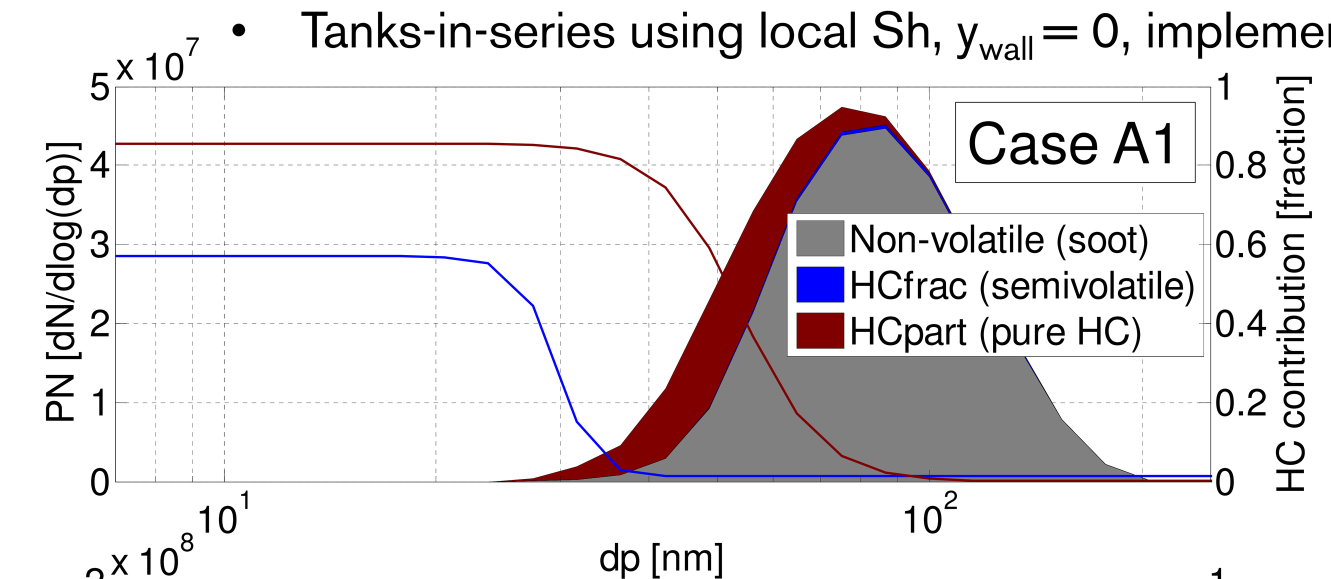
$$CE = \frac{PSD_{before} - PSD_{after}}{PSD_{before}}$$

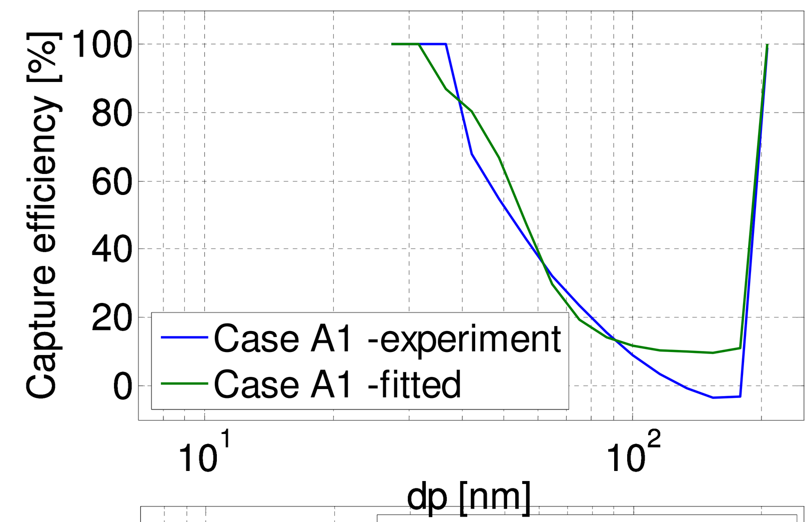


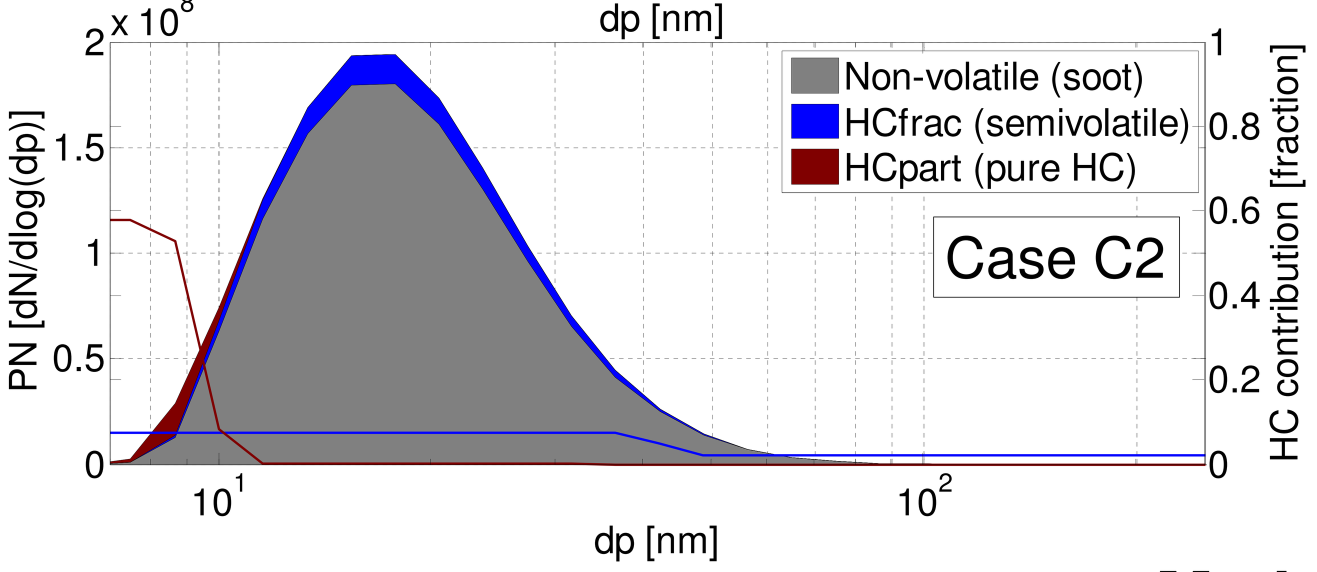
Engine: 5 cyl (2.4 dm³), Low sulfur diesel fuel (MK1), 1200 rpm, PM instrument: DMS 500, $T_{sample\ line}$=75 °C, $P_{instr.}$=0.25 bar Bare cordierite (Case A1), Alumina coated (Case C2)						
PM capture conditions	Engine load [Nm]	T_{substr} [°C]	Add-air [slpm]	Flow [slpm]	$Re_{channel}$ [-]	Dilution (1dil+2dil)
Case A1	30	222	0	66	2.7	1+100
Case C2 (1-cyl)	-25	151	22	286	15.1	1+50

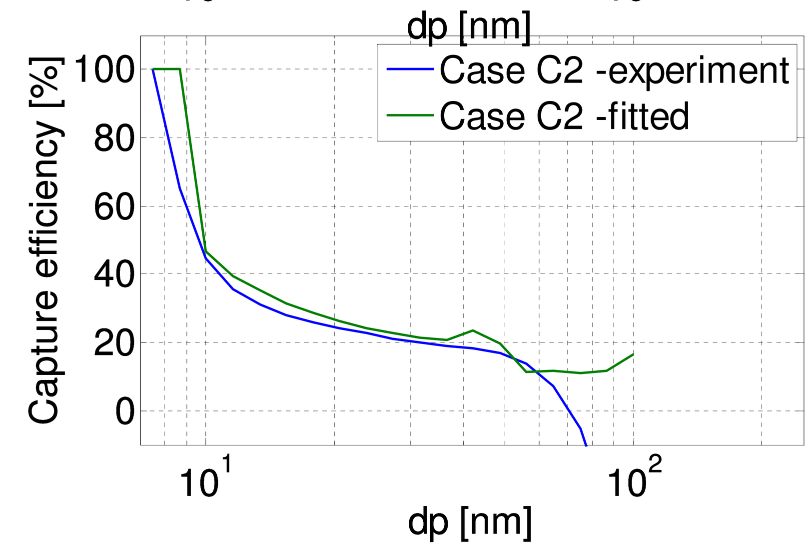
Development of a Conceptual Model

- Assuming heavy hydrocarbon ($C_{40}H_{82}$)
- Evaporation from [3] simulating total evaporation and shrinkage
- Sigmoid function to describe pure volatiles and semivolatile HC
- Tanks-in-series using local Sh, y_{wall} = 0, implemented in Matlab



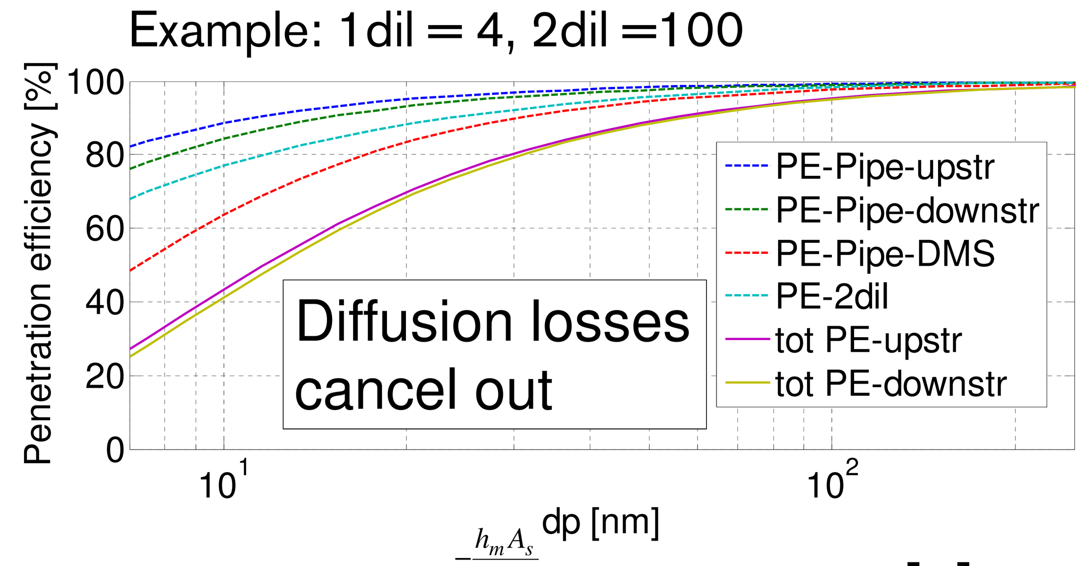






Diffusion Losses

Example: 1dil = 4, 2dil =100



$$CE_{channel} = 1 - e^{-\frac{h_m A_s}{Q}} \quad [4]$$

$$PE_{pipe} = e^{-\frac{4 V_d L}{d_t U}} \quad [5]$$

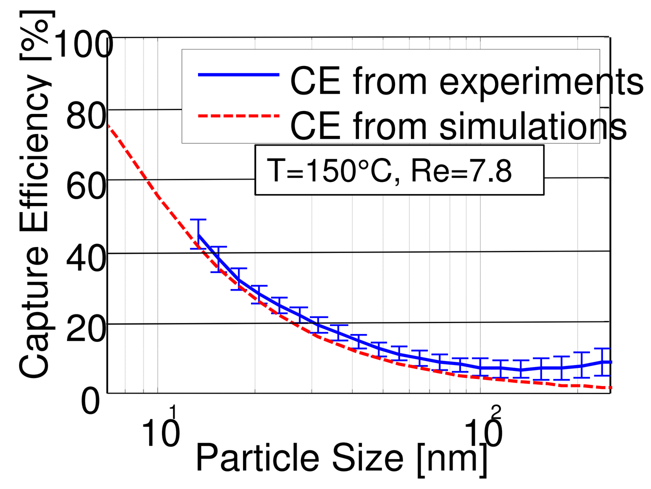
$$PE_{2nd\ dilutor} = 1 - \frac{2A_W}{V}\sqrt{\frac{\alpha\tau}{\pi}}$$ Adapted from [6]

$$\alpha = \frac{b_1}{d_p^2}\left(1 + b_2 e^{-b_3 d_p}\right) \quad [2]$$

$$\mathbf{b} = \begin{bmatrix} b_1 & b_2 & b_3 \end{bmatrix} = \begin{bmatrix} 1.71\cdot 10^{-23} & 1.05 & 1.89\cdot 10^{-11} \end{bmatrix}$$

Methodology Verification

Atomizer Topas ATM230
NaCl-particles
Varying T & flow
Also compare w CFD
- **Demonstrates that measurement method is reliable !**



Conclusions

- Capture efficiency trends agree with theory, but differ in numbers
- Conceptual model implemented to account for HC evaporation
  => channel acts as "HC sink"
- Methodology useful for in situ analysis of PM characteristics

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