Inter-Laboratory Validation of the Method to Determine the Filtration Efficiency for Airborne Particles in the 3–500 nm Range and Results Sensitivity Analysis

Panagiota Sachinidou, Yeon Kyoung Bahk, Min Tang, Ningning Zhang, Shawn S.C. Chen, David Y.H. Pui, Bruno Araújo Lima, Gabriele Bosco, Paolo Tronville, Thomas Mosimann, Mikael Eriksson, Jing Wang

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

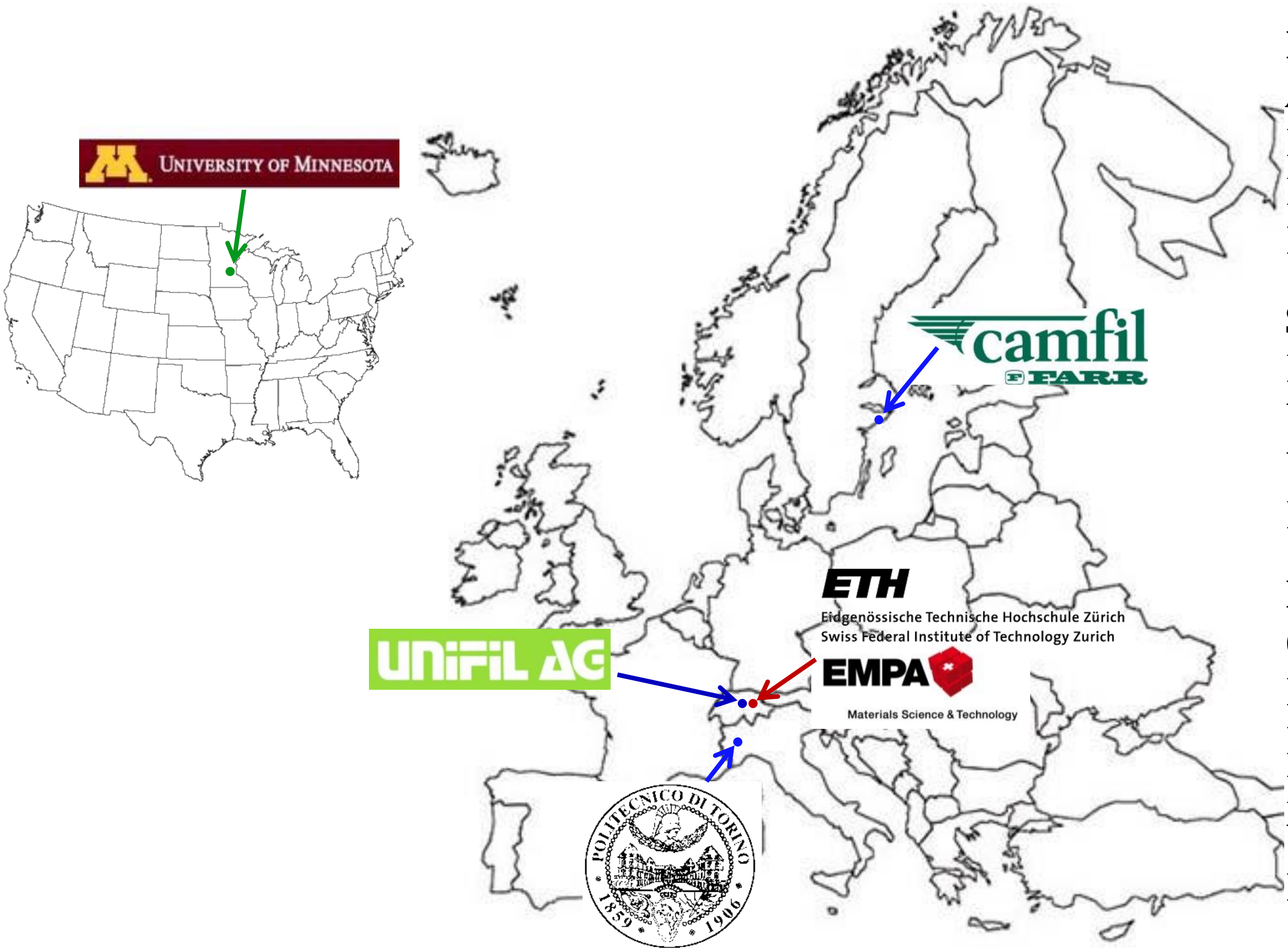
EMPA
Materials Science & Technology

Outline

- Project background
- Pre-normative research
- Qualification of the setup
- Inter-laboratory tests
- Sensitivity analysis
- Summary

Project consortium

Methodology to Determine Effectiveness of Filtration Media against Nanoparticles in the Size Range of 3 to 500 Nanometer



Reference lab
Air Quality & Particle Research
ETHZ/EMPA, Switzerland
Prof. Jing Wang

Supporting lab
Particle Technology Lab
University of Minnesota, USA
Prof. David Y.H. Pui

Round-robin test labs
Camfil, Sweden
Mr. Mikael Eriksson
Politecnico di Torino, Italy
Prof. Paolo Tronville
Unifil, Switzerland
Mr. Nägeli Andreas

Summary of relevant air filtration standards

Background

Pre-norm Research

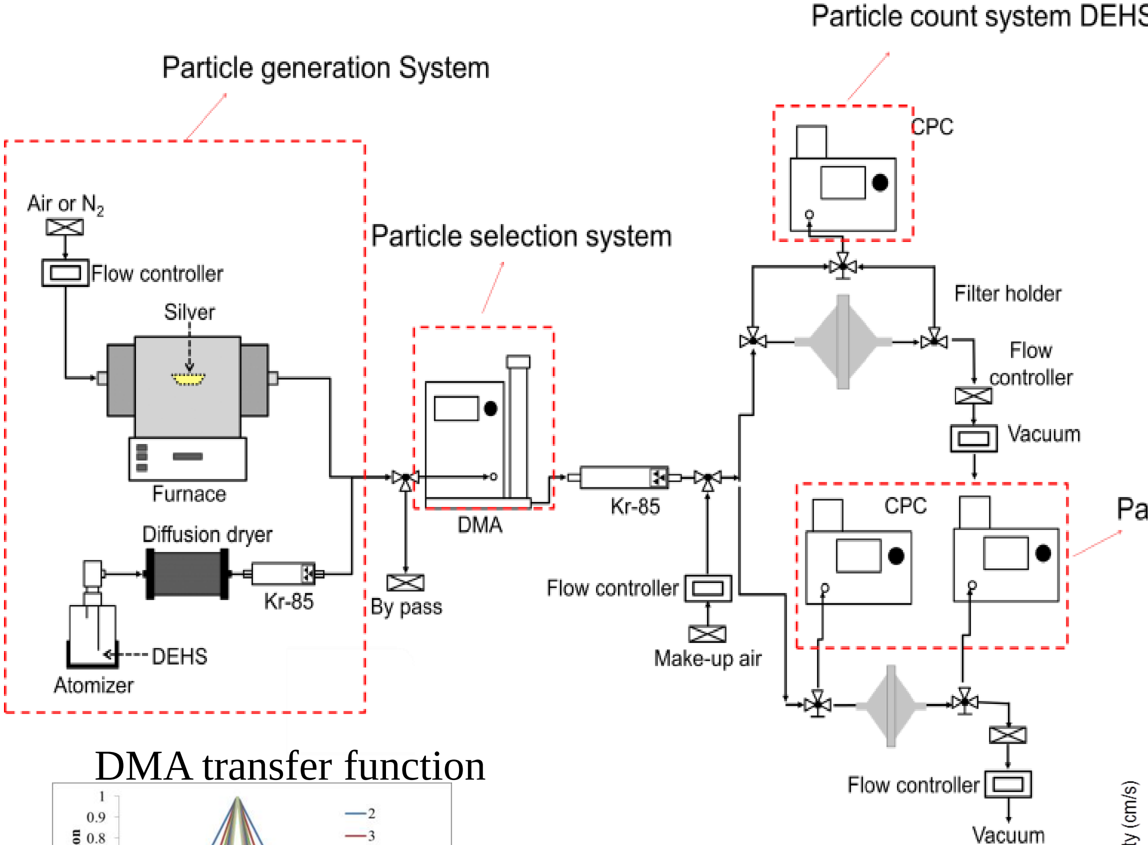
Qualification

Interlaboratory Tests

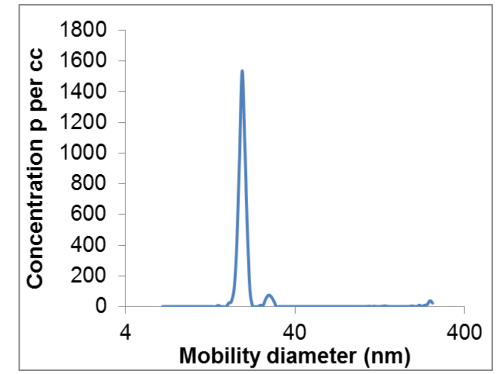
Designation	Title	Test particle	Remark
ANSI/ASHRAE Standard 52.2 (2012)	Method of testing general ventilation air-cleaning devices for removal efficiency by particle size	KCl particles in the range of 0.3–10 µm	Wind tunnel test using optical or aerodynamic particle sizers
EN 779 (2012)	Particulate air filters for general ventilation—determination of the filtration performance	DEHS particles in the range of 0.2–3.0 µm	Wind tunnel test using optical particle sizers
ISO 29463 series (2011a, b, c, d, e)	High-efficiency filter and filter media for removing particles in air	DEHS, PAO, and Paraffin Oil in the range 0.04 µm to 1.0 µm (0.1–2.0 µm with OPS)	Focus on the minimum efficiency at the MPPS and local efficiencies
NIOSH 42 CFR 84.181 (1995)	Non-powered air-purifying particulate filter efficiency level determination	A mass median aerodynamic diameter of ~0.3 µm, NaCl or DOP polydisperse particles	For respirator certification
EN 1822 series (2009a, b, c, d, e)	High-efficiency air filters (EPA, HEPA and ULPA)	DEHS, PAO, and Paraffin Oil in the range 0.05 µm to 0.8 µm (0.1–2.0 with OPS)	Focus on the minimum efficiency at the MPPS and local efficiencies
EN 143:2000	Respiratory protective devices—Particle filters—requirements, testing, marking	Various aerosol allowed including sodium chloride and paraffin oil	For respirator air filter certification
ISO 29461-1:2013	Air intake filter systems for rotary machinery—test methods—part 1: static filter elements	DEHS particles in the range of 0.3–3.0 µm	Wind tunnel test using optical particle sizers

Jing Wang & Paolo Tronville (2014), Toward standardized test methods to determine the effectiveness of filtration media against airborne nanoparticles, J Nanopart Res 16:2417

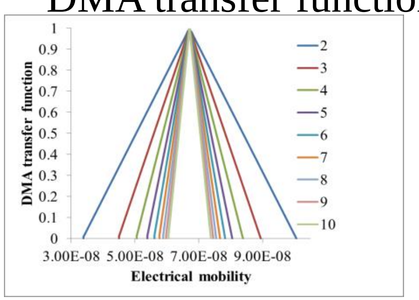
Filtration tests



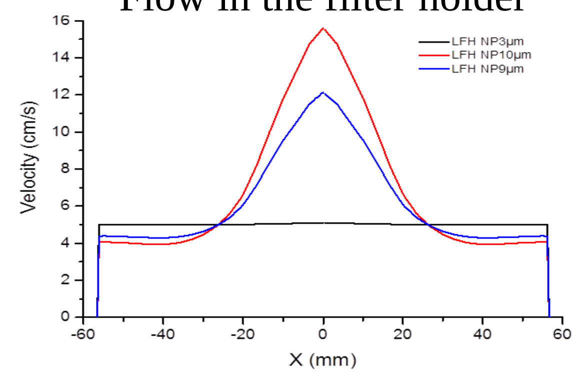
Particle size



DMA transfer function

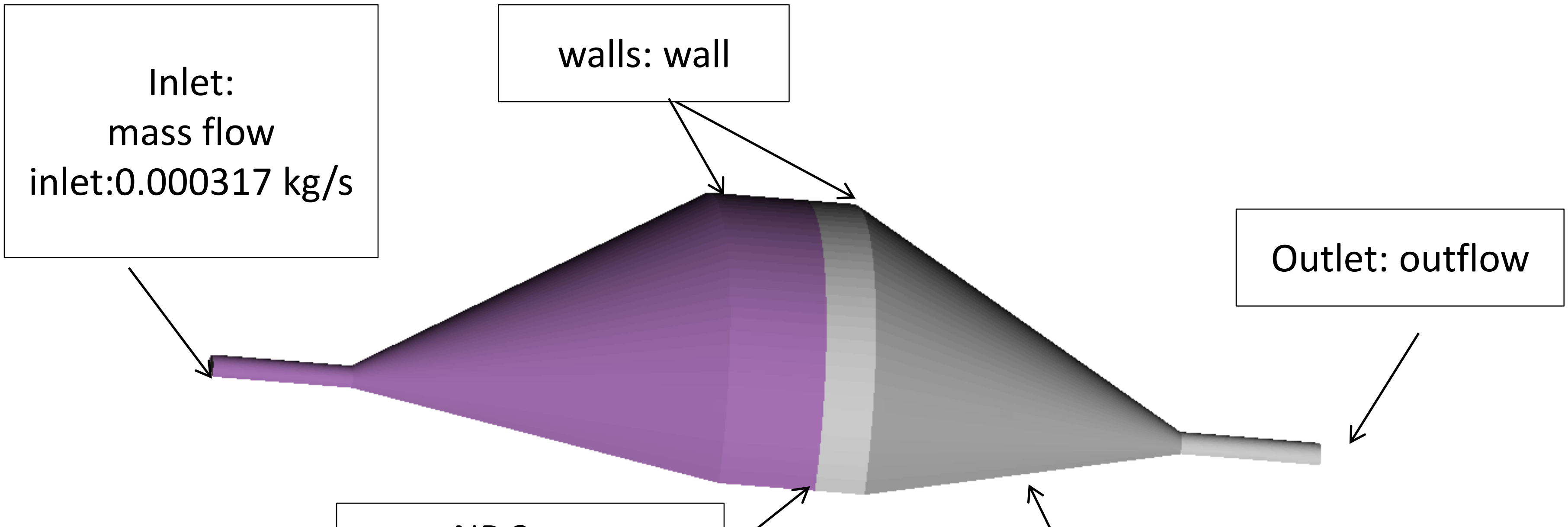


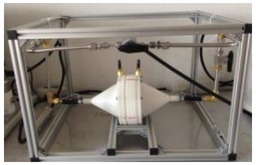
Flow in the filter holder



Sachinidou, P., Bank, Y.K., & Wang, J, Aerosol Sci & Tech, 2017

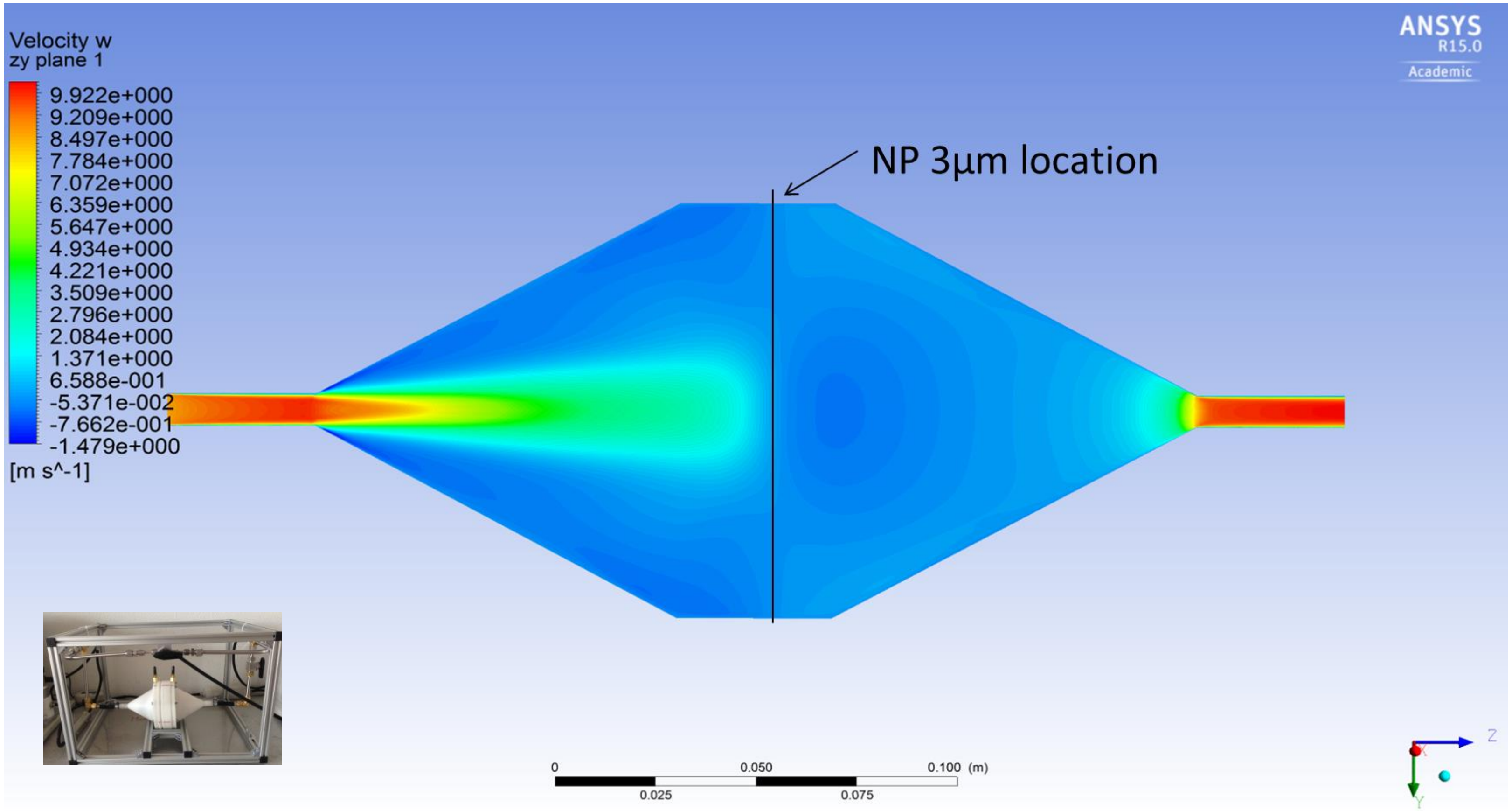
Flow distribution-CFD analysis





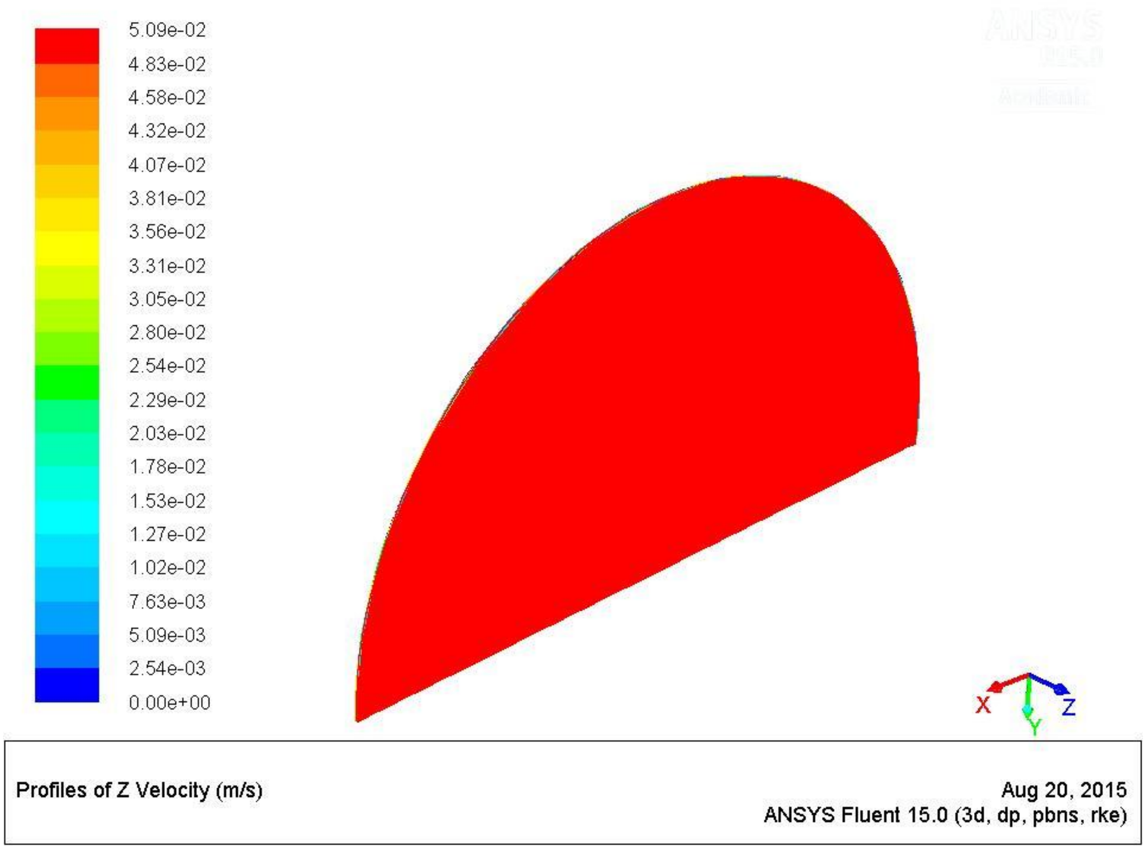
- Flow distribution in the large filter holder was simulated using ANSYS FLUENT.
- K-ε realizable model was applied and mesh independency study was performed.
- NP 3µm filter which is homogeneous was chosen for the investigation and simulated with porous jump boundary conditions.

Flow distribution- velocity distribution

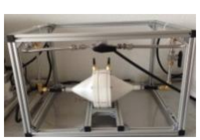


Face velocity has a jet profile which is distributed homogeneously before the filter.

Flow distribution-face velocity distribution immediately upstream the filter

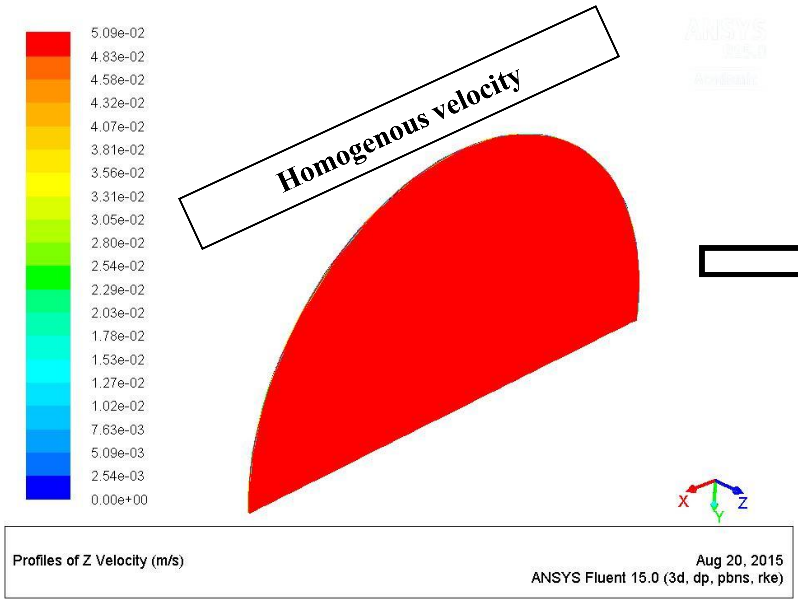


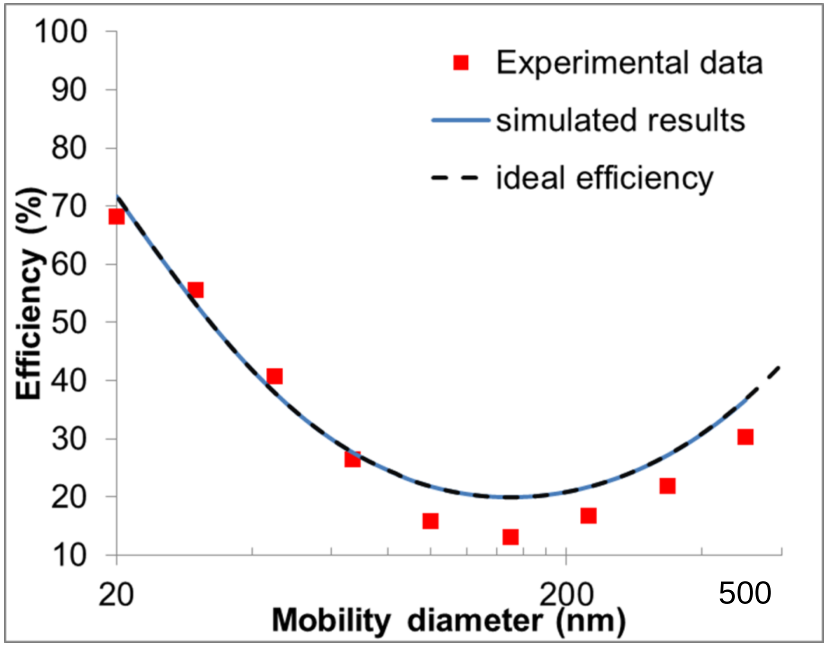
Face velocity is homogeneously distributed upstream the filter



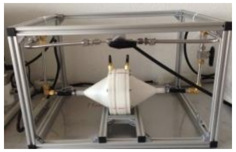
Monodispersity investigation

- Flow distribution incorporated in the filtration model





- Flow distribution does not affect the calculated filtration efficiency.



Qualification procedure

Background

Pre-norm Research

Qualification

Interlaboratory Tests

- **Zero count test**
- **Counting accuracy calibration**
- **DMA test**
- **Neutralization efficiency test**
- **Zero efficiency test**
- **Preparatory checks**

Qualification of the test rig -Neutralization efficiency

Neutralization Test

The neutralization effectiveness of the neutralizer was checked using two DMA connected in series. The first one was used to pre-select the desired particle diameter and the second one was used to select the particle diameter corresponding to singly, doubly and triply charged particles. This set up allows checking the efficiency of the neutralizer that is located inside the second DMA. The experimental particle charge ratio was compared with the theoretical one (Wiedensohler (1988) and Kim et al. (2005)) The same experiments were carried, using an additional neutralizer in between the two DMA in order to study if the residence time does not affect the neutralization efficiency.

Qualification of the test rig -Neutralization efficiency

			1charges/icharge	
	Mobility diameter (nm)	Raw counts	Experimental Ratio	Theoretical Ratio
1 charge	**51.4**	706.53		
2 charges	35.66	26.97	26.19	24.2

			1charges/icharge	
	Mobility diameter (nm)	Raw counts	Experimental Ratio	Theoretical Ratio
1 charge	**95.6**	190.07		
2 charges	64.99	22.87	8.31	7.23

			1charge/icharge	
	Mobility diameter (nm)	Raw counts	Experimental Ratio	Theoretical Ratio
1 charge	**193.3**	84.31	1	
2 charges	125.7	26.42	3.19	2.94
3 charges	99.22	4.855	17.36	14.49

ETH (Kr-85)

			1charges/icharge	
	Mobility diameter (nm)	Raw counts	Experimental Ratio	Theoretical Ratio
1 charge	**33.98**	22389.4		
2 charges	23.73	277.8	80.68	78.06

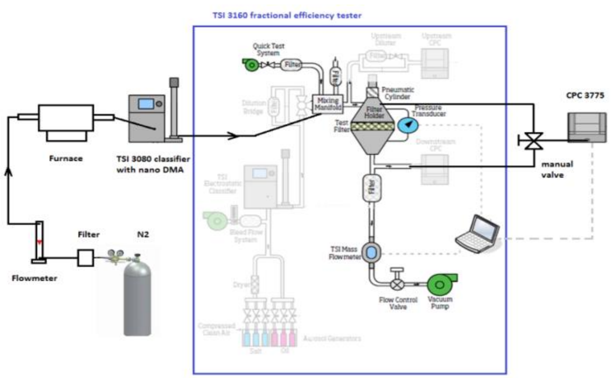
			1charges/icharge	
	Mobility diameter (nm)	Raw counts	Experimental Ratio	Theoretical Ratio
1 charge	**80.58**	7246		
2 charges	55.28	784	9.24	9.62

			1charge/icharge	
	Mobility diameter (nm)	Raw counts	Experimental Ratio	Theoretical Ratio
1 charge	**191.1**	4690.8		
2 charges	124.9	1455	3.22	2.98
3 charges	98.6	342.8	13.66	14.86

UMN (Po-210)

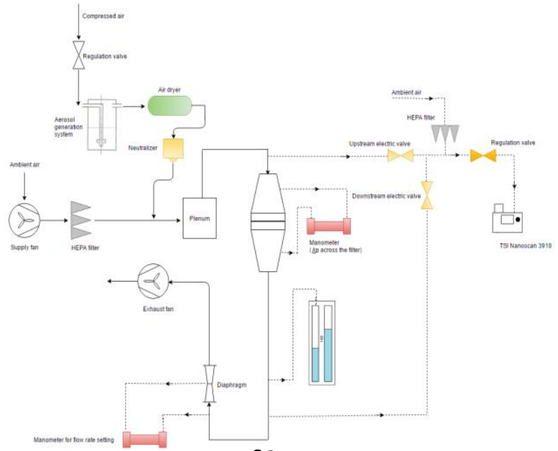
- Results show the experimental ratio is in good agreement with the theoretical one.

Test setup

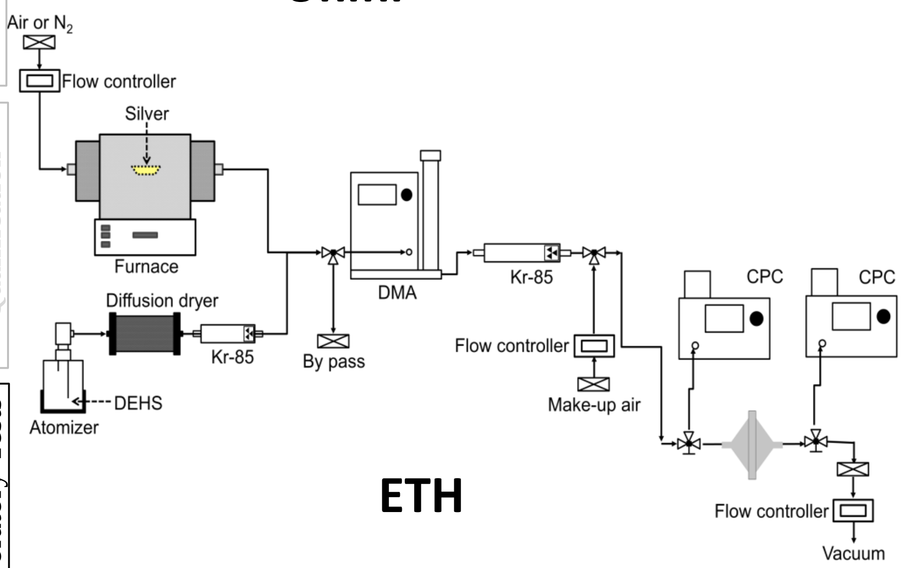


Unifil

Camfil



Polito



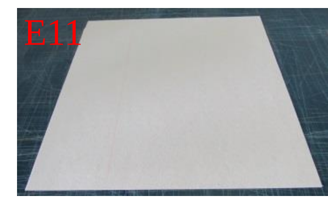
ETH

UMN

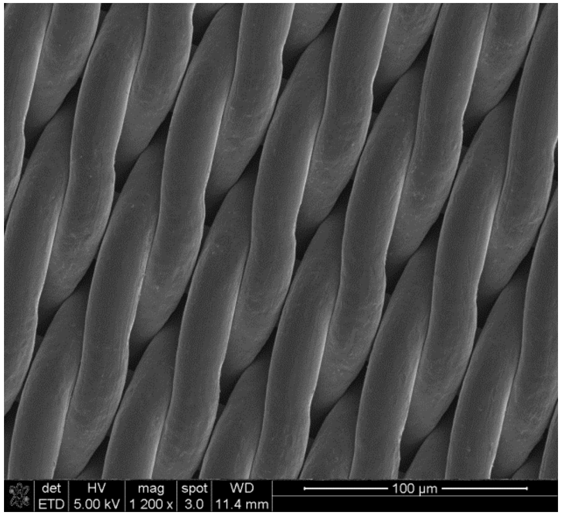
Sachinidou, P., Bahk, Y.K., Tang, M., Chen, S.C., Pui, D.Y.H., Lima, B. A., Bosco, G., Tronville, P., Mosimann, T., Eriksson, M., Wang, J. (2017) *Aerosol and Air Quality Research*.

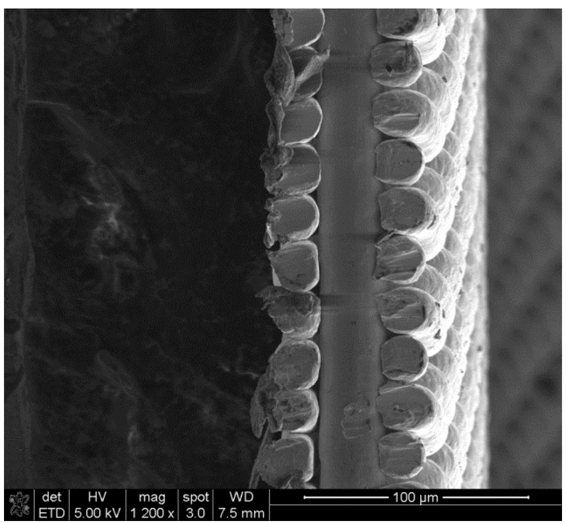
Filters tested

filter class:	**filter type:**		media type:				
	bag filter	pleatable	synthetic			glass fiber	PET Synthetic
			non-charged	charged	discharged/ non charged		
Mesh			X				
M5	X			X			
NP 3µm			X				
F7	X			X	X		X
F7	X		X			X	
F9		X	X			X	
E11		X	X				X
H13		X	X			X	

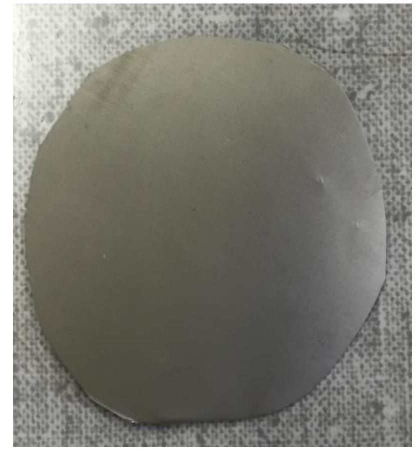


Interlaboratory Tests: Twilled Dutch weave mesh 350x2600



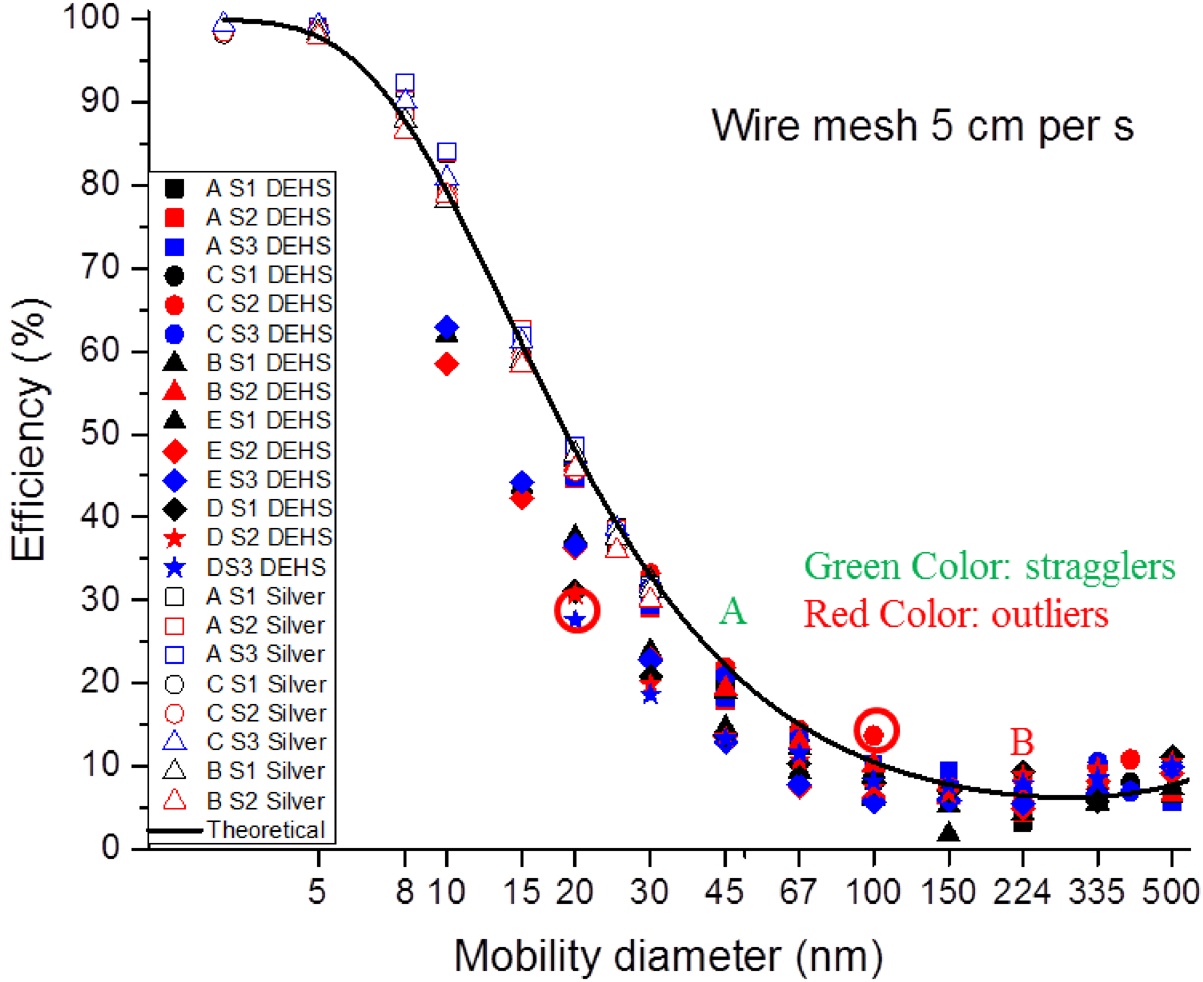


SEM image



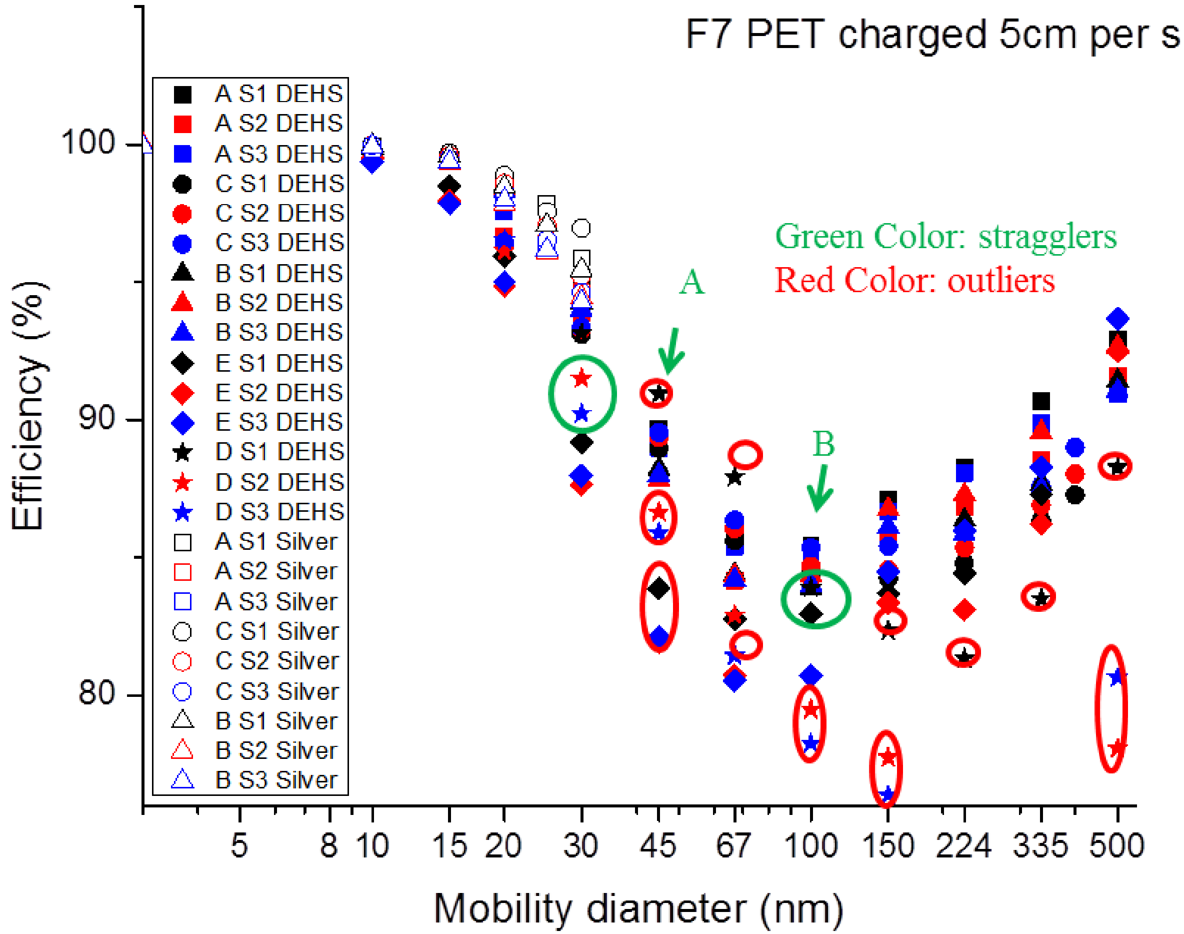
Twilled Dutch weave 350x2600		
Solidity	0.62	**-**
Fiber Size (wrap)	32	**µm**
Fiber Size (weft)	22	**µm**
Filter thickness	0.08	**mm**
Material	Stainless Steel	

Wire mesh



- There are not many straggles or outliers in the whole particle size range.

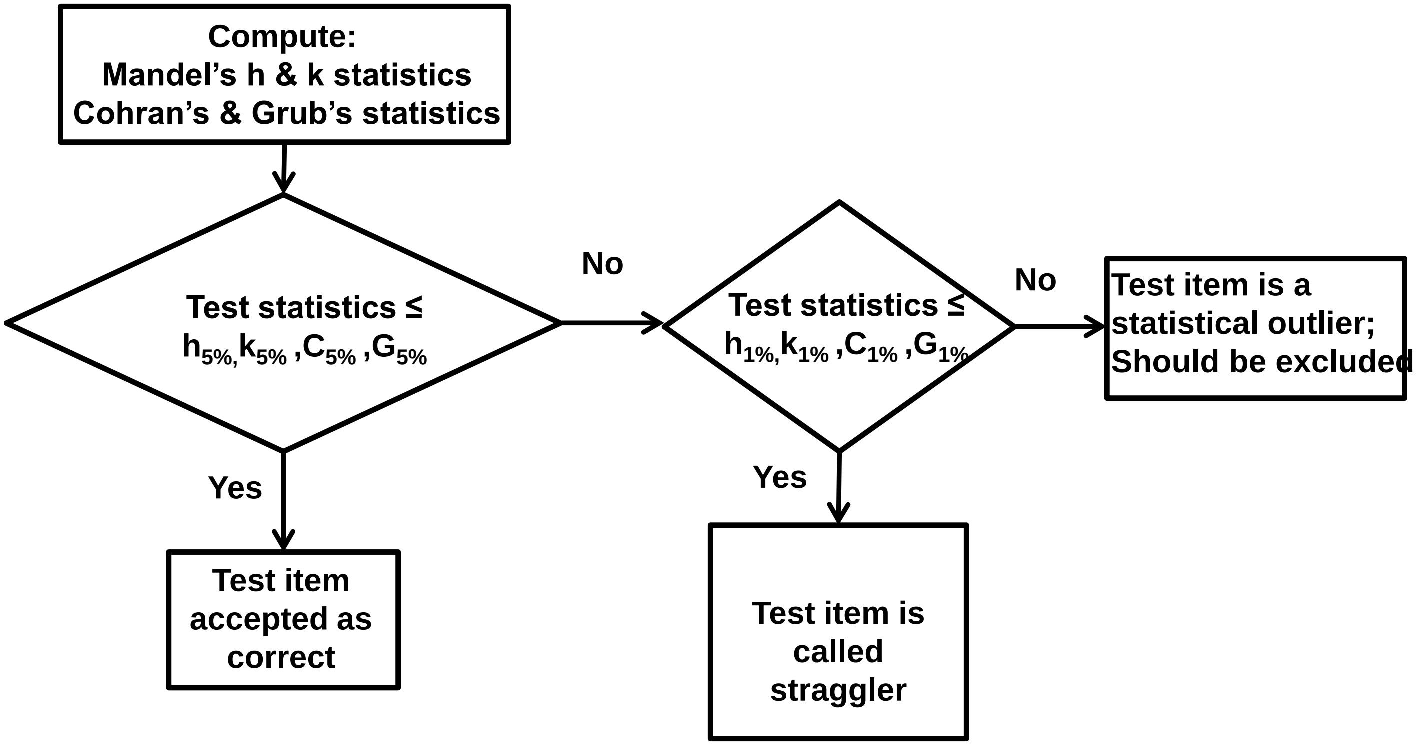
F7 PET charged (5cm/s)



- Statistical analysis reveals many stragglers or outliers due to high variance of charged filters.

Statistical analysis-Results analysis

Statistical analysis is performed based on ISO 5725-2. In the beginning, statistical tests, to note the stragglers and/or outliers, are implicated. Into more details, three different tests are used; Mandel's h & k statistics, Cohran's and Grubb's test.



General mean and variance

- $\hat{m} = \frac{\sum_1^p n_{ij} \overline{y_{ij}}}{\sum_1^p n_{ij}}$, **General mean**

- $s^2{}_r = \frac{\sum_1^p (n_{ij}-1) s^2{}_{ij}}{\sum_1^p (n_{ij}-1)}$, **Repeatability variance within lab and averaged between all participated labs**

- $s^2{}_l = \frac{s^2{}_d - s^2{}_r}{\overline{\overline{n_j}}}$, **Between laboratory variance**

  $s^2{}_d = \frac{\sum_1^p n_{ij} (\overline{y_{ij}} - \overline{\overline{y_j}})^2}{p-1}$,

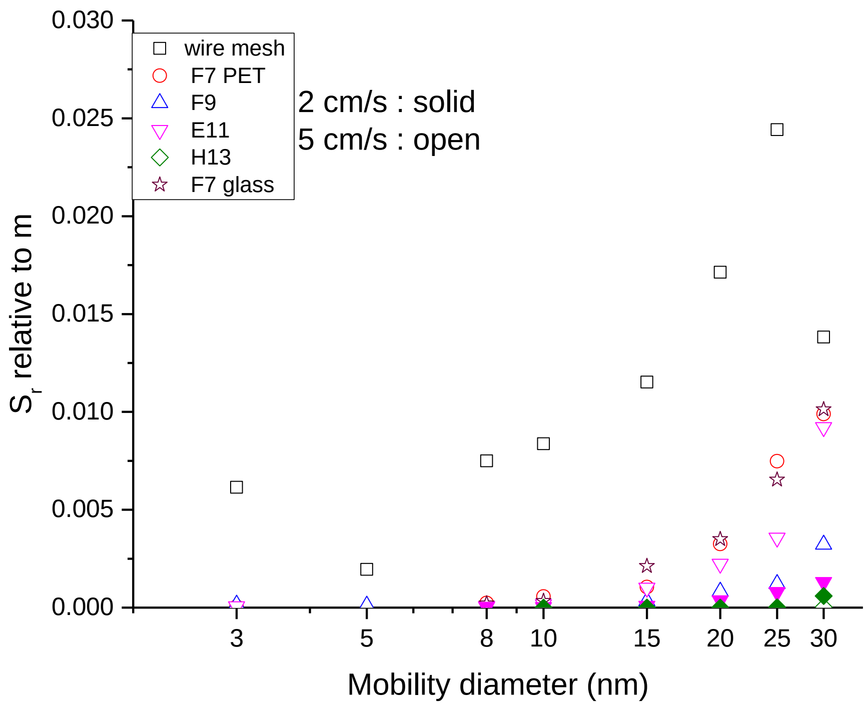
  $\overline{\overline{n_j}} = \frac{\sum_1^p n_{ij} - \frac{\sum_1^p n_{ij}{}^2}{\sum_1^p n_{ij}}}{p-1}$,

- $s^2{}_R = s^2{}_r + s^2{}_L$. **Reproducibility variance**

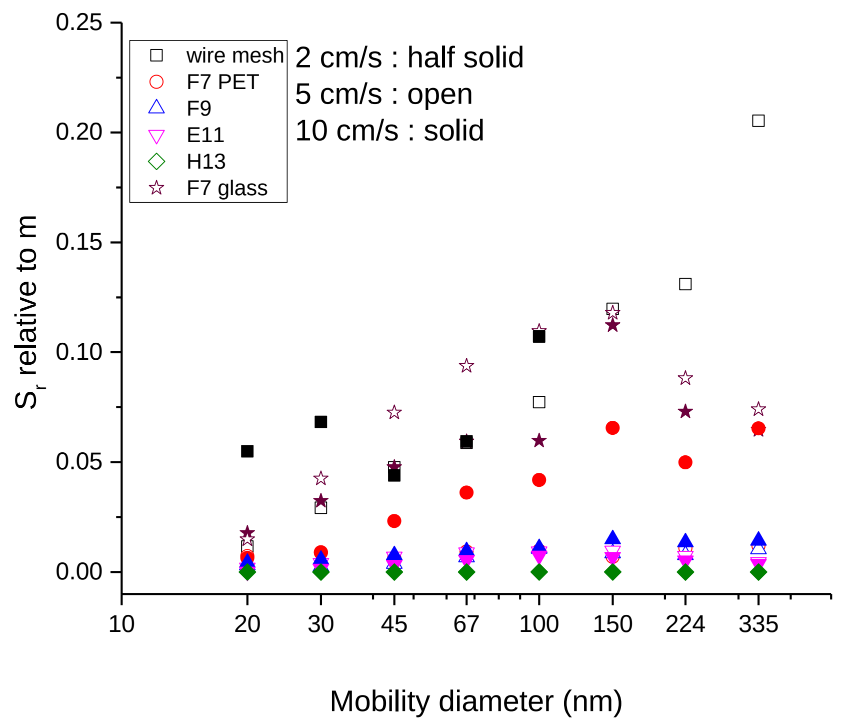
- Repeatability and reproducibility variance determine the accuracy of the test method; Low variances indicate that the method should be reliable

Repeatability variance

Repeatability variance within lab and averaged between all participated labs



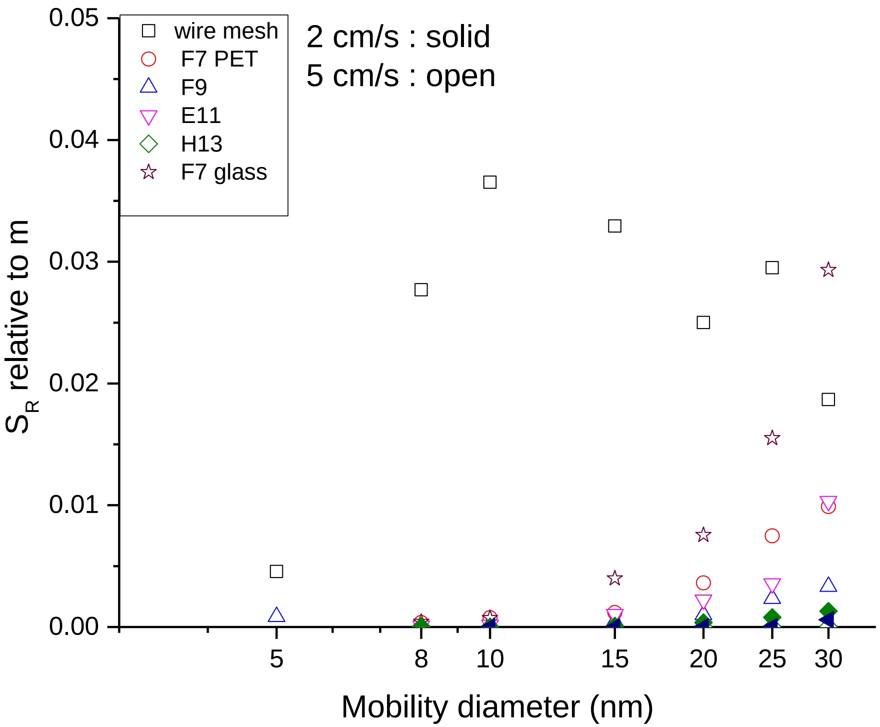
Silver



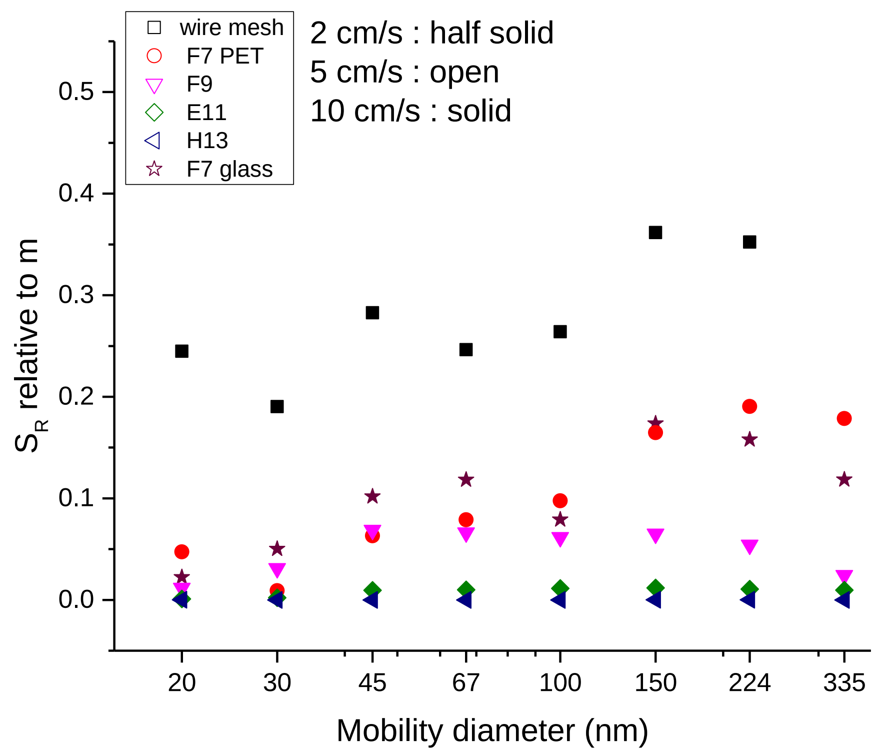
DEHS

Reproducibility variance

Sum of the repeatability variance within lab and Between laboratory variance



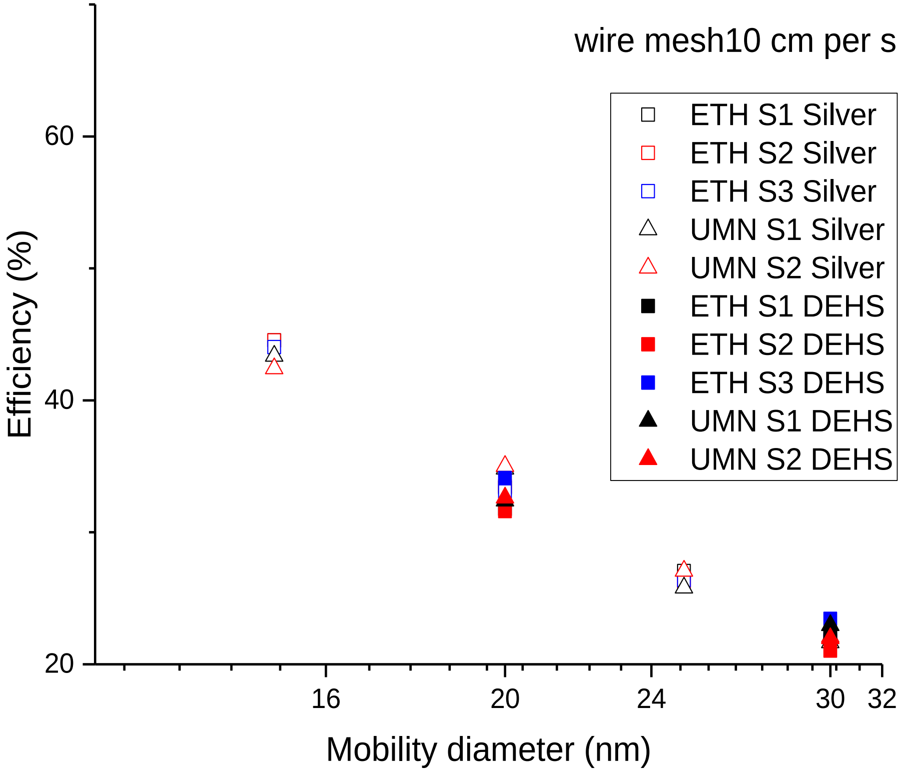
Silver



DEHS

Sensitivity test examples

The particle density has little effect in the nanometer range.



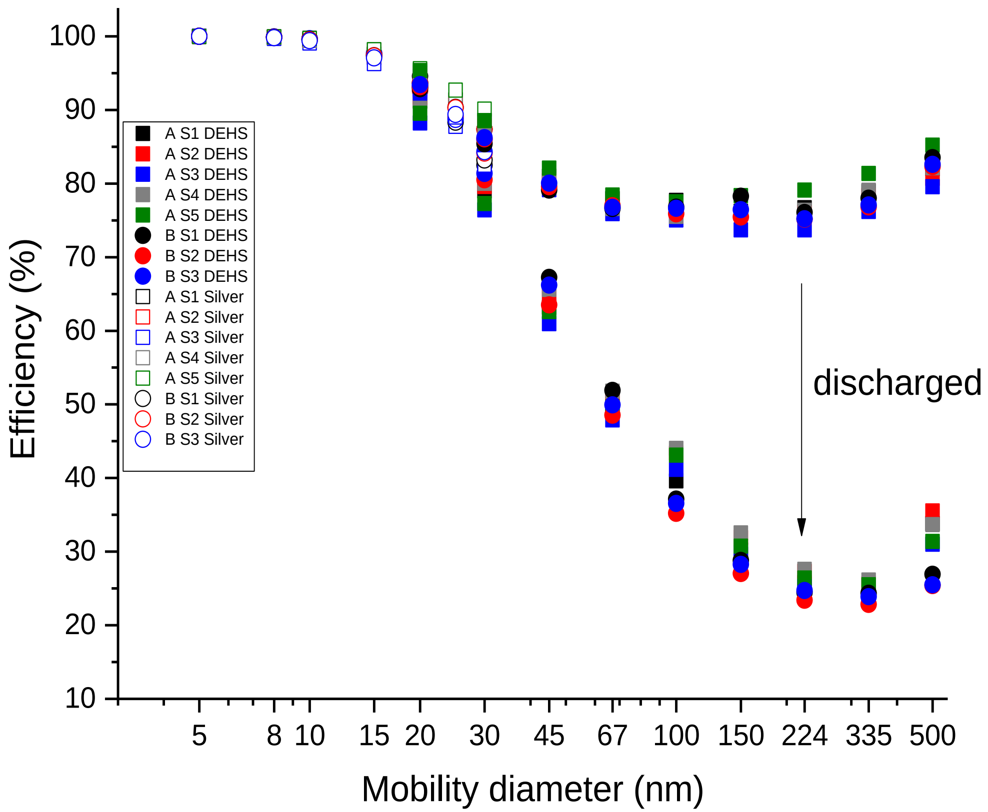
Regression analysis found no significant effects of the temperature, relative humidity or upstream concentration.

	P-value		
Particle size (nm)	T [°C]	RH [%]	C_{up} (p/cm^3)
20	0.73	0.91	0.74
30	0.43	0.52	0.05
45	0.15	0.02	0.01
67	0.81	0.15	0.20
100	0.43	0.27	0.33
150	0.10	0.10	0.14
224	0.67	0.95	0.97
335	0.82	0.56	0.54
500	0.54	0.28	0.49

Regression analysis results for F9 at 10cm/s. Threshold P-value 0.05.

Sensitivity test: filter charge

The filter charge has significant effect.



Summary

❖ There were limited outliers for all the tested cases.

❖ The repeatability deviation was mostly less than 0.1 of the absolute efficiency.

❖ The reproducibility deviation was more significant.

❖ Relative humidity, temperature, upstream challenging particle concentration and density did not show significant effects on the filtration efficiency in the ranges in the tests.

❖ The filter charge status exhibited a crucial effect on the filtration efficiency.

❖ The process of standardization is in the final phase.

Thank you