Development of Filter Modeling with Polydispersed Fibers

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Outline

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  - Filter generation
  - Flow field calculation
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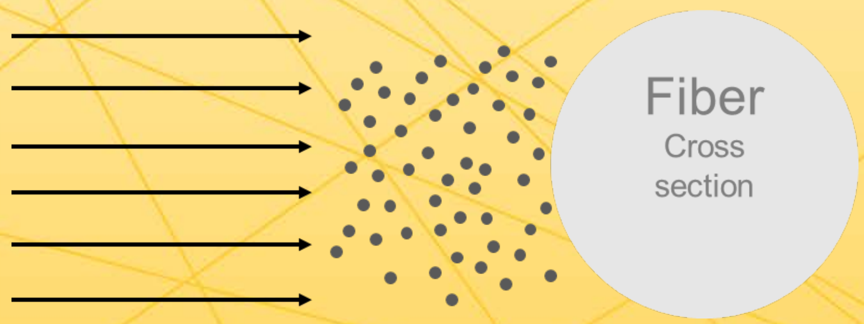
  - Collection efficiency comparison
  - Effect of polydispersity

Single Fiber Efficiency (SFE) theory

- For the estimation of fibrous filter capture efficiency, SFE theory is generally applied



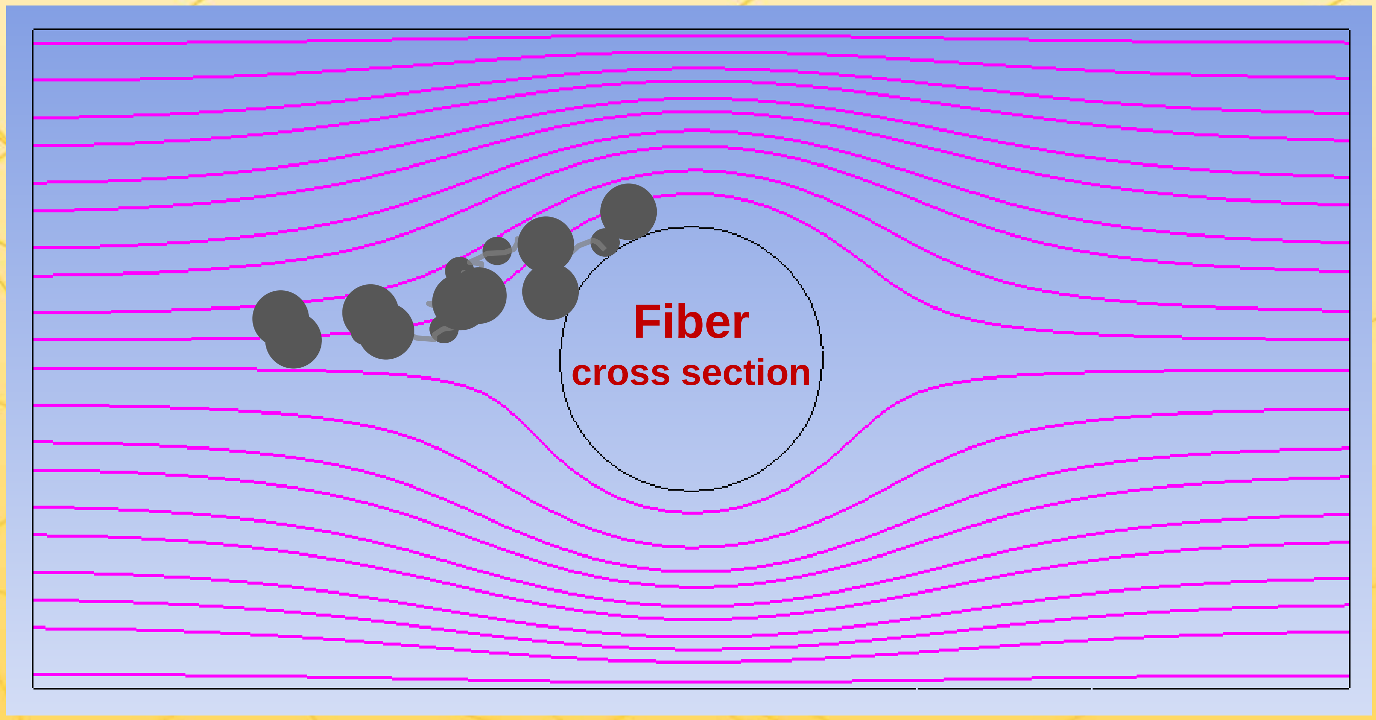
$$P = 1 - E = \exp\left(\frac{-4\alpha E_{\Sigma} t}{\pi d_f (1-\alpha)}\right)$$

t: *filter thickness*, α: *solidity*
d_f: *fiber diameter*, E_{Σ}: *single fiber efficiency*

$$E_{\Sigma} = 1 - (1 - E_R)(1 - E_I)\,(1 - E_D)\,(1 - E_{DR})\,(1 - E_G)$$

E_R: *Efficiency for interception*
E_I: *Efficiency for impaction*
E_D: *Efficiency for diffusion*
E_{DR}: *Efficiency for interception of particles with diffusion*
E_G: *Efficiency for gravitational setting*

Particle deposition mechanism



<u>Deposition mechanism:</u>

- Diffusion
- Interception
- Impaction
- Gravitational settling
- Electrostatic attraction

Analytical expressions for each capture mechanism

SFE Diffusion	E_D
Pich (1965)	$2.27Ku^{-1/3}Pe^{-2/3}(1+0.62Kn_f Pe^{1/3}Ku^{-1/3})$
Stechkina (1966)	$2.9Ku^{-1/3}Pe^{-2/3}+0.624Pe^{-1}$
Lee and Liu (1982)	$1.6\left(\frac{1-\alpha}{Ku}\right)^{1/3}Pe^{-2/3}$
Liu and Rubow (1990)	$1.6\left(\frac{1-\alpha}{Ku}\right)^{1/3}Pe^{-2/3}C_d$
Payet et al. (1992)	$1.6\left(\frac{1-\alpha}{Ku}\right)^{1/3}Pe^{-2/3}C_d C_{d'}$
Kirsch and Fuchs (1968)	$2.7Pe^{-2/3}$

$$Kn_f = \frac{2\lambda}{d_f}$$

$$Ku = -0.15ln\alpha - \frac{3}{4} - \frac{\alpha^2}{4} + \alpha$$

$$C_d = 1 + 0.388Kn_f\left[\frac{(1-\alpha)Pe}{Ku}\right]^{1/3}$$

$$C_{d'} = \left[1 + 1.6\left[\frac{1-\alpha}{Ku}\right]^{1/3}Pe^{-2/3}C_d\right]^{-1}$$

SFE Interception	E_R
Lee and Gieseke (1980)	$\left(\frac{1-\alpha}{Ku}\right)R^2(1+R)^{\frac{-2}{3(1-\alpha)}}$
Pich (1966)	$\frac{(1+R)^{-1}-(1+R)+2(1+1.996Kn_f)(1+R)ln(1+R)}{2(-0.75-0.5ln\alpha)+1.996Kn_f(-0.5-ln\alpha)}$
Lee and Liu (1982)	$0.6\left(\frac{1-\alpha}{Ku}\right)\frac{R^2}{1+R}$
Liu and Rubow (1990)	$0.6\left(\frac{1-\alpha}{Ku}\right)\frac{R^2}{1+R}C_r$

$$R = \frac{d_p}{d_f}$$

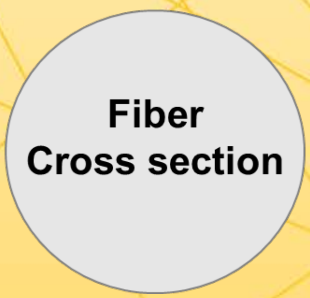
$$C_r = 1 + \frac{1.996Kn_f}{R}$$

SFE Impaction	E_I
Yeh and Liu (1974)	$\left(\frac{stk}{2Ku^2}\right)J$

$$Stk = \frac{\rho_p {d_p}^2 C_c U_0}{18\mu d_f} \qquad J = (29.6 - 28\alpha^{0.62})R^2 - 27.5R^{2.8}$$

Equivalent fiber diameter (for SFE theory)

- An **equivalent fiber diameter** is applied to SFE to obtain collection efficiency of filter media



Equivalent fiber diameter

- **Different concepts of mean:**

*Arithmetic mean: $\sum \frac{D_f}{n}$

*Geometric mean: $\sqrt[n]{D_{f1} D_{f2} \cdots D_{fn}}$

*Volume-surface average fiber diameter: $\frac{\sum n {D_f}^2}{\sum n D_f}$

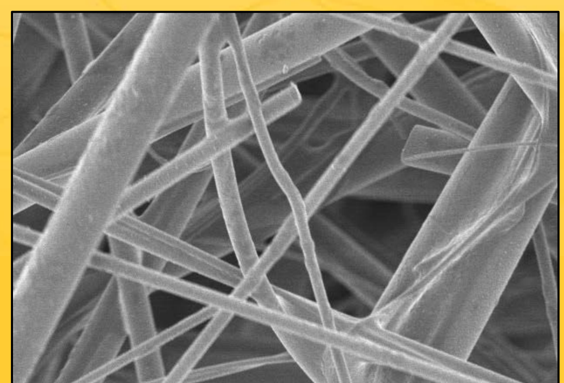
- **Effective fiber diameter:**

*Davies: $D_f = \sqrt{U_\infty \mu t \left(\frac{64\alpha^{\frac{3}{2}}(1+56\alpha^3)}{\Delta P}\right)}$

Direct measurement of fiber size (e.g. SEM)

Empirical expression: Approximation based on the pressure drop measurement (ΔP, t, α are required)

- However, real fibrous filter is composed of a wide range of fibers

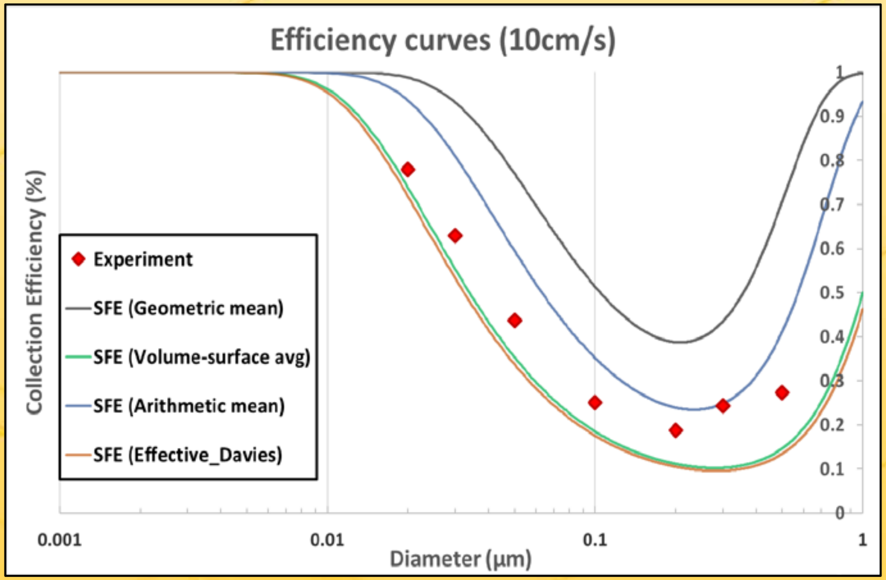


Issues with using an equiv. fiber diameter

- Podgorski (2009) pointed out that

"it is impossible to select any one universal mean fiber diameter to describe penetration of nanoparticles with different sizes."

- Different equivalent fiber diameter definitions affect the efficiency curve



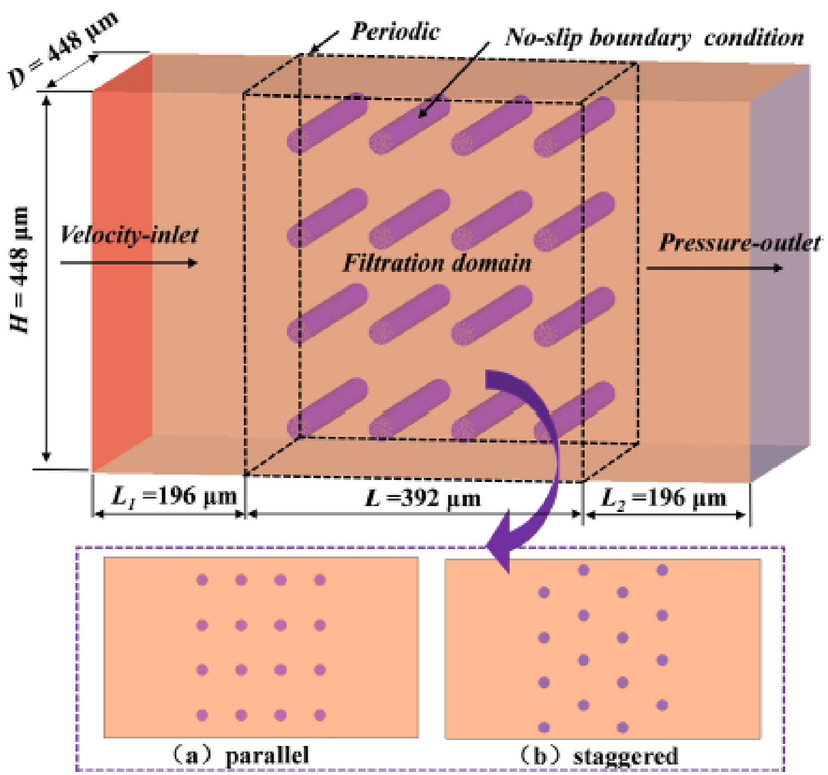
HF-0012 (Hollingsworth & Vose)

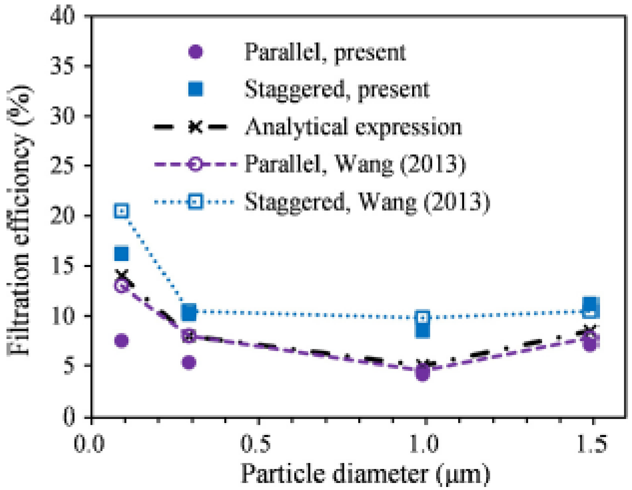
- However, an equivalent fiber diameter is still widely applied to the numerical modeling and SFE theory

- Podgorski (2009). Journal of Nanoparticle Research 11: 197-207.

Recent papers using single fiber diameter

Li et al. (2016). Advanced Powder Technology 27: 638-645.

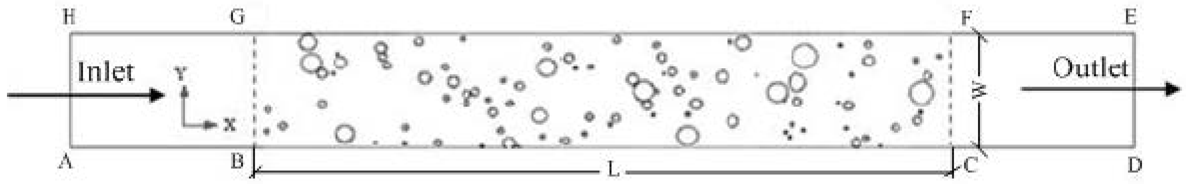


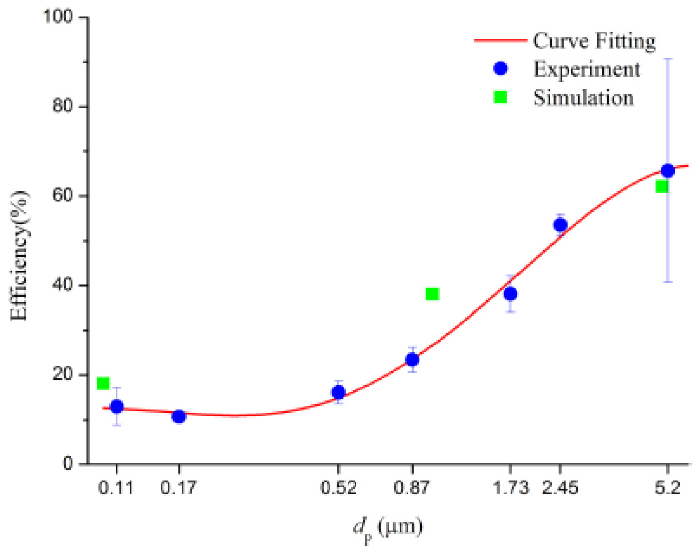


- CFD-DPM (Discrete Phase Modeling)
- Parallel vs staggered
- Collection efficiency of multi-fiber filters is obtained

Papers using polydisperse fibers

Bin et al. (2016). Aerosol and Air Quality Research (Article in press)





- Lattice Boltzmann method
- Randomly located polydisperse fibers

- **Limitations:**
- Smallest particle challenging filter is **100 nm** (Capture by **diffusion** cannot be well understood)
- Only three particle sizes are investigated, and only one of them is submicron

Objectives

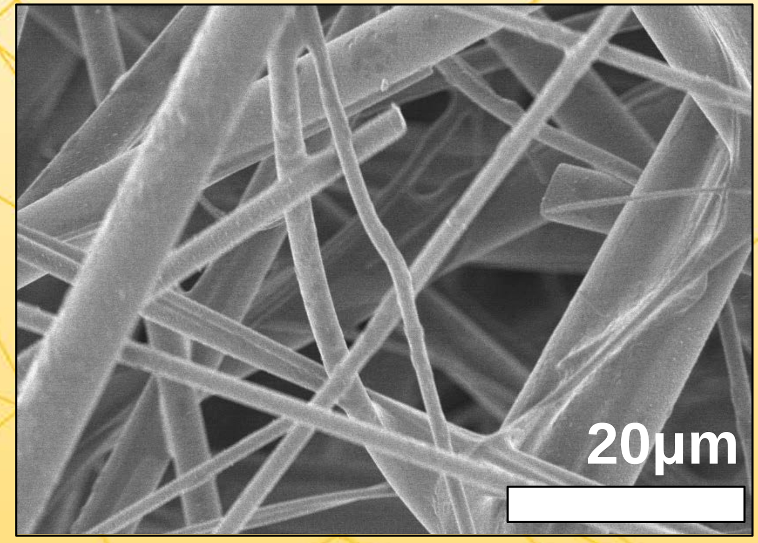
- To develop a method to generate fibrous filter domain composed of polydisperse fibers using commercial filter media (H & V)

- To develop a numerical model of nanoparticle filtration by fibrous filters

- To compare the collection efficiency between numerical model and experimental data with challenging particle diameter from 3nm up to 500 nm

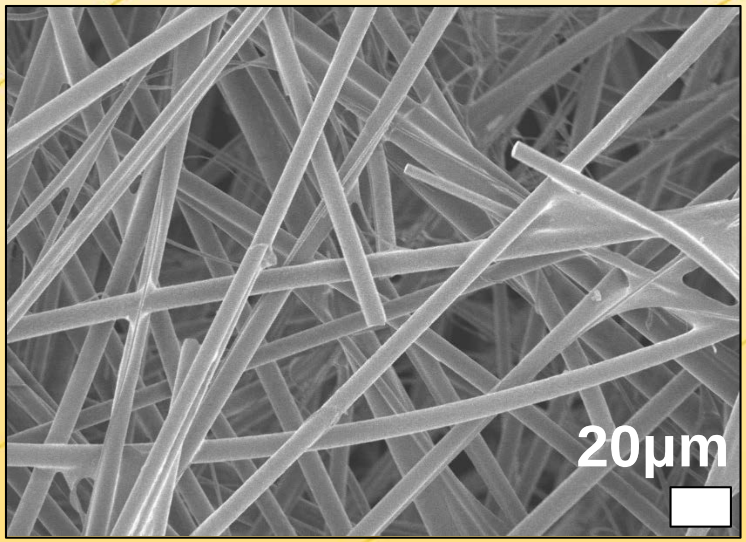
- To investigate the effect of equivalent fiber diameters on predicted collection efficiency

Filter properties (Hollingsworth & Vose)



HF-0012	
Fiber distribution	size (µm)
Arithmetic mean	3.3
Geometric mean	2.5
Volume-surface average	5.1
Effecitve Fiber diameter (Davies)	5.3

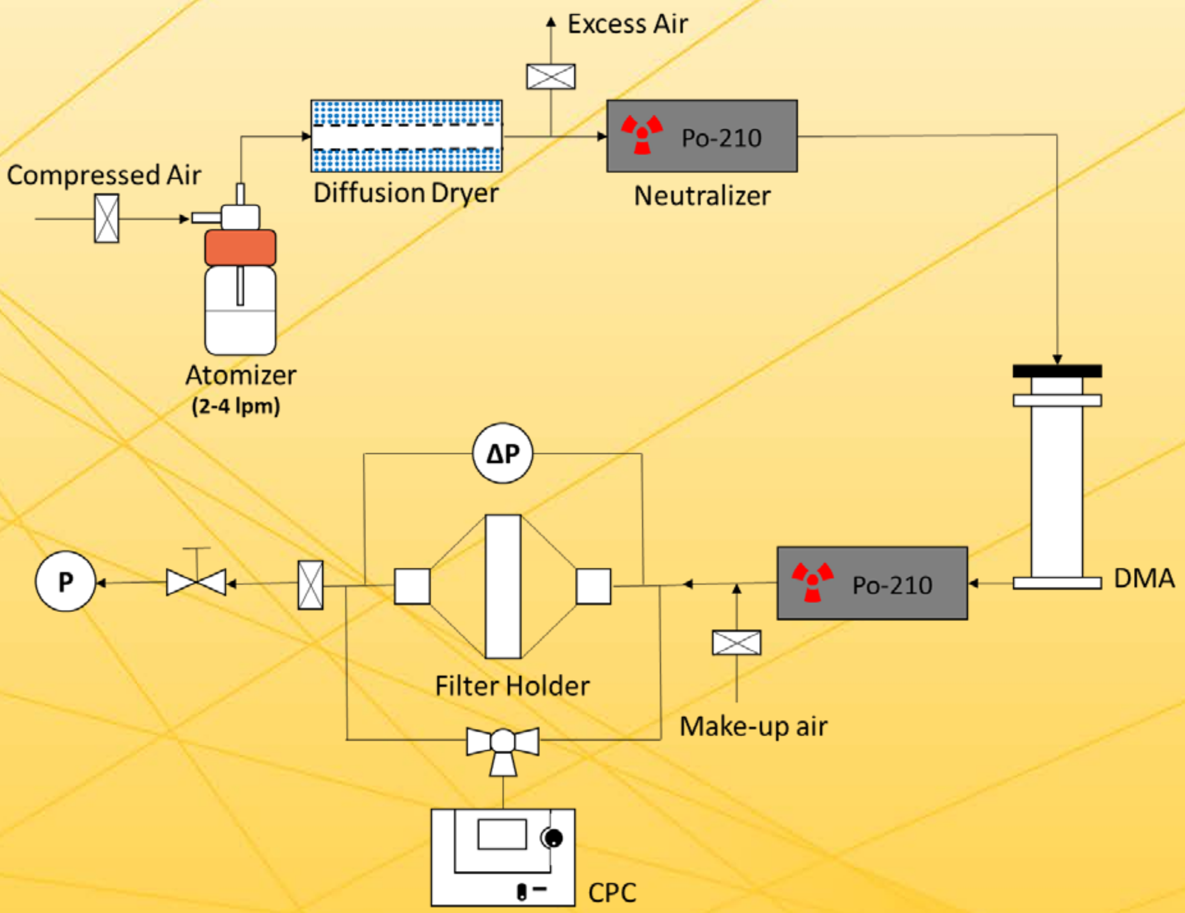
Filter Parameters	
Thickness (mm)	0.74
Solidity	0.039
DOP % Penetration (0.3 µm at 5.3 cm/s)	79.9
Pressure drop (Pa) @ 5.3 cm/s	13



HF-0493	
Fiber distribution	size (µm)
Arithmetic mean	5.7
Geometric mean	4.5
Volume-surface average	5.6
Effecitve Fiber diameter (Davies)	8.3

Filter Parameters	
Thickness (mm)	0.36
Solidity	0.076
DOP % Penetration (0.3 µm at 5.3 cm/s)	88
Pressure drop (Pa) @ 5.3 cm/s	8

Experimental method and setup

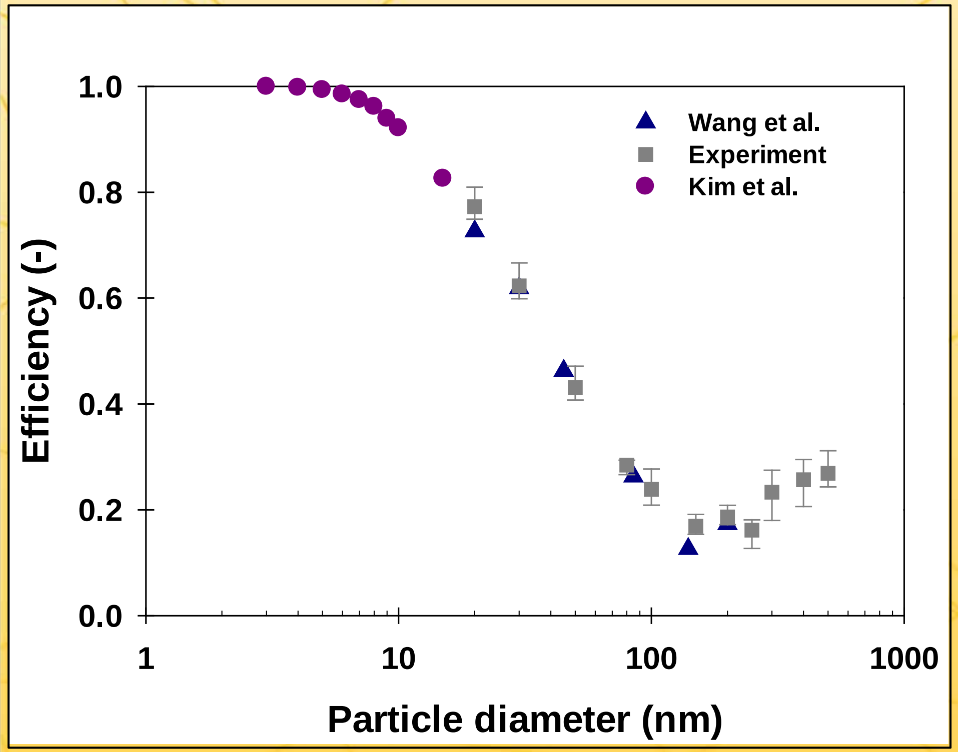


- KCl particles (20, 30, 50, 80, 100, 150, 200, 300, and 500 nm) are used to challenge the filter media (HF-0012 and HF-0493)
- Particle size from 3 to 20nm was obtained from Kim et al. (2008) to be compared with the simulation results

- Kim et al. (2007). Journal of Nanoparticle Research 9: 117-125.
- Wang et al. (2007). Journal of Nanoparticle Research 9: 109-115.

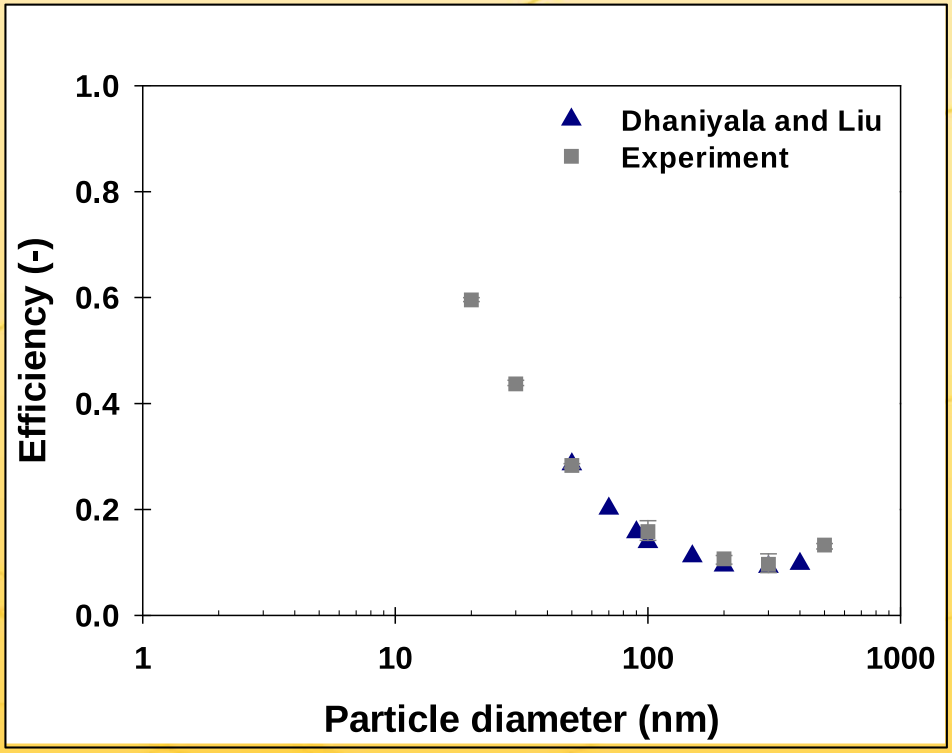
Experimental results comparison

HF-0012 10cm/s



- Kim et al.: Silver particles (3-20nm)
- Wang et al.: NaCl particles (20-200nm)
- Experiment: KCl particles (20 – 500nm)

HF-0493 10cm/s

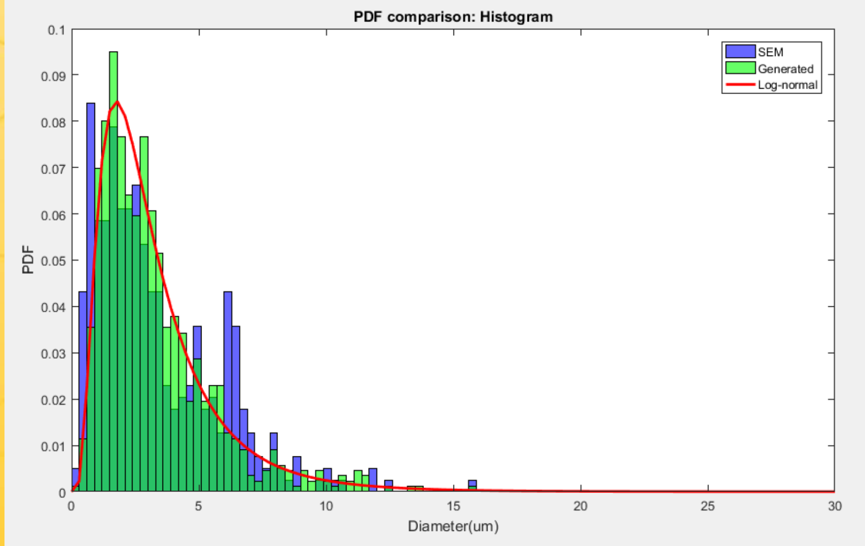


- Dhaniyala and Liu: DOS (50-400nm)
- Experiment: KCl particles (20 – 500nm)

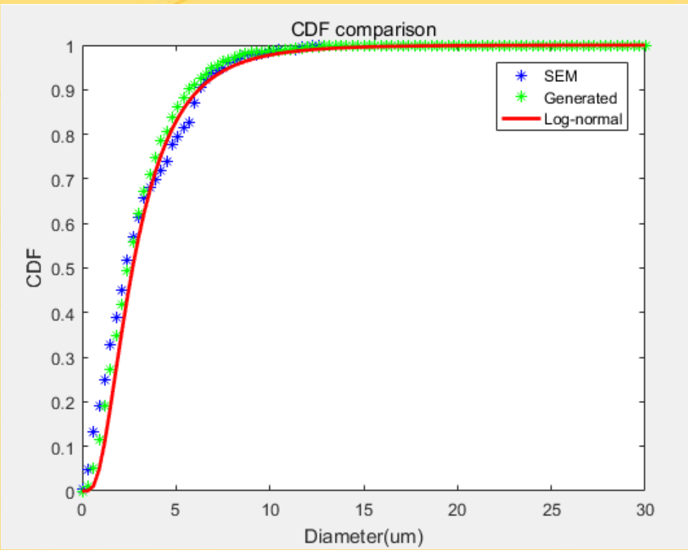
- Dhaniyala and Liu (1999). Journal of the IEST 42(1): 32-40.
- Wang et al. (2007). Journal of Nanoparticle Research 9: 109-115.
- Kim et al. (2007). Journal of Nanoparticle Research 9: 117-125.

Fiber generation

- Fiber size distribution measured by SEM images follows log normal distribution
- Figures shows the fiber size distribution from HF-0012 (Blue color – Measured by SEM) and from randomly generated one (Orange color – Generated by the code developed)
- Their distributions are well agreed as shown in the picture



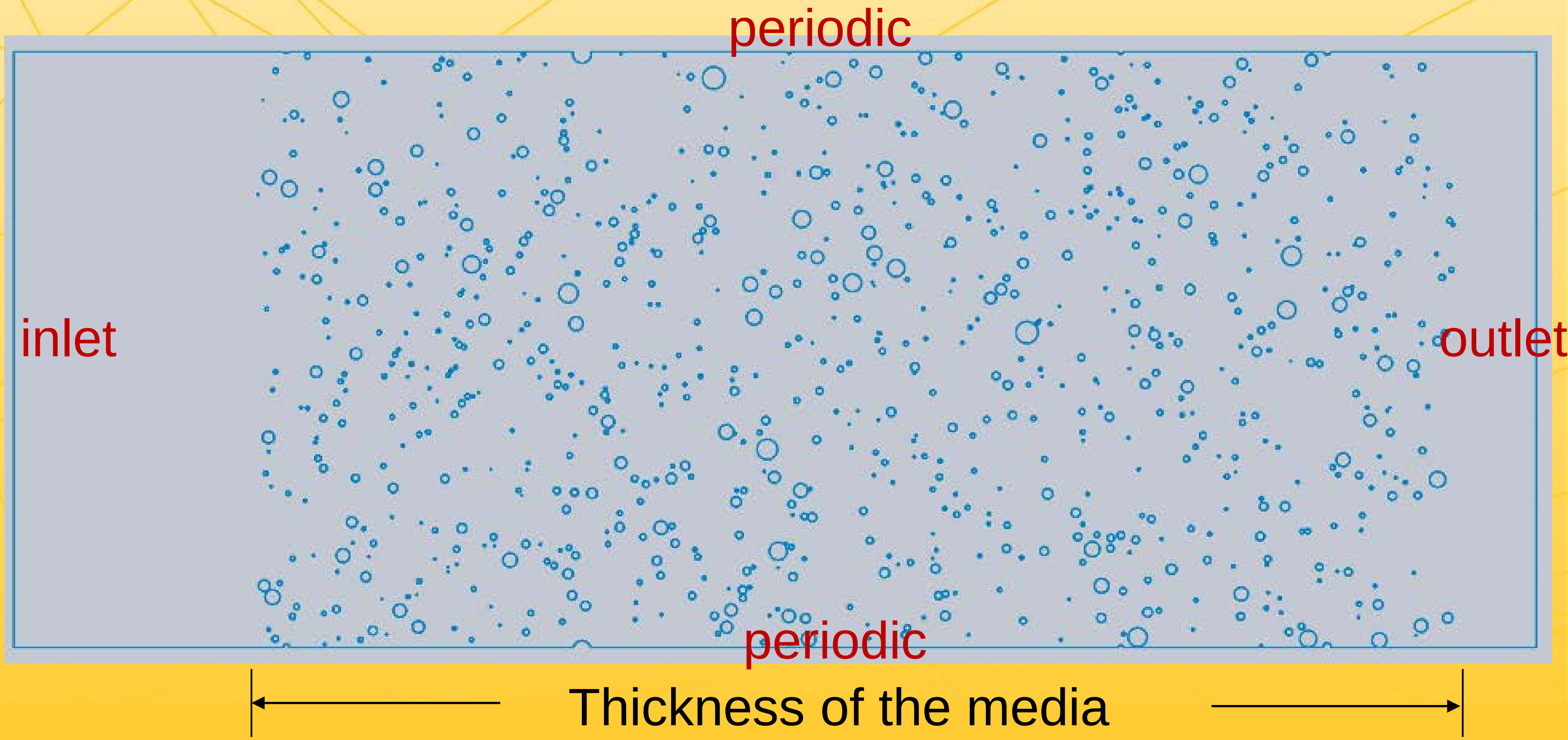
Fiber size distribution
(Probability density function)



Fiber size distribution
(Cumulative size distribution)

Fiber arrangement and boundary condition

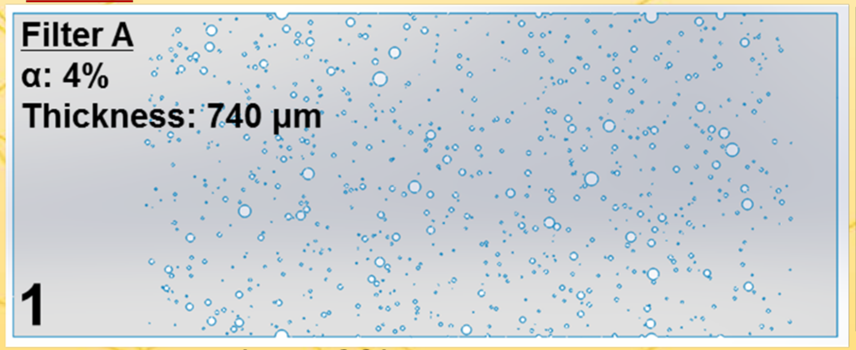
- Fibers are randomly generated and arranged in the real size of the filter domain until the target solidity is achieved

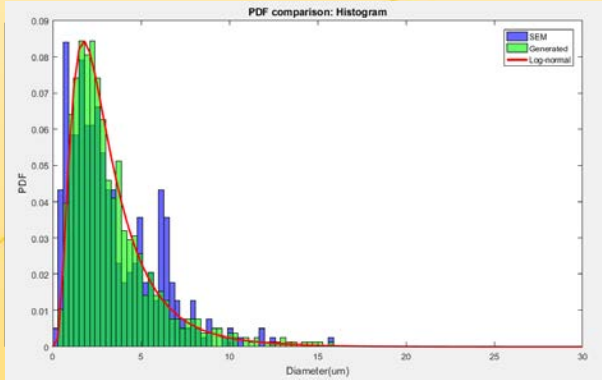


Example of fiber distribution for HF-0012

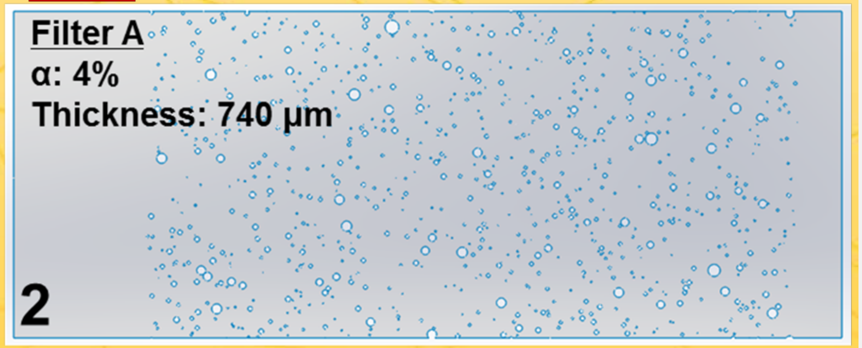
- Three fiber domains below have the same domain size and solidity
- Fibers are randomly generated until target solidity (α =0.04) is achieved

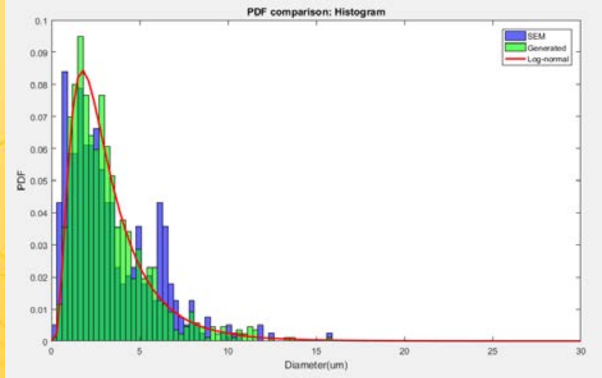
Case1: Number of fibers: **782**



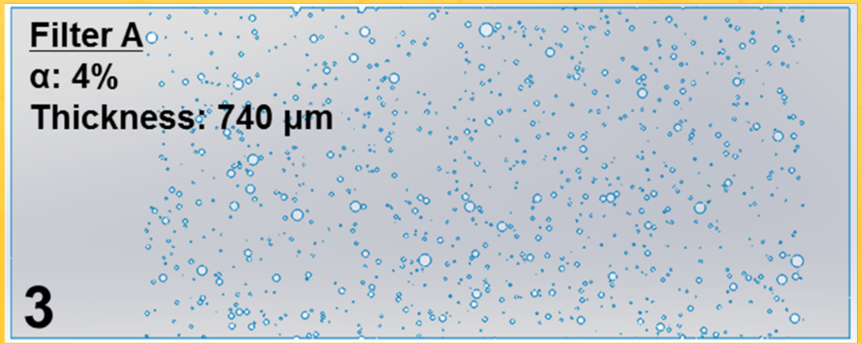


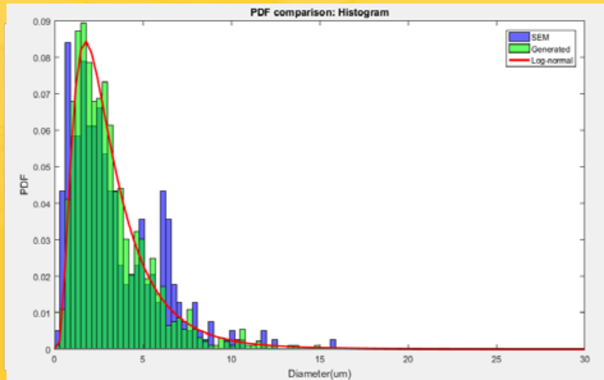
Case2: Number of fibers: **874**





Case3: Number of fibers: **929**





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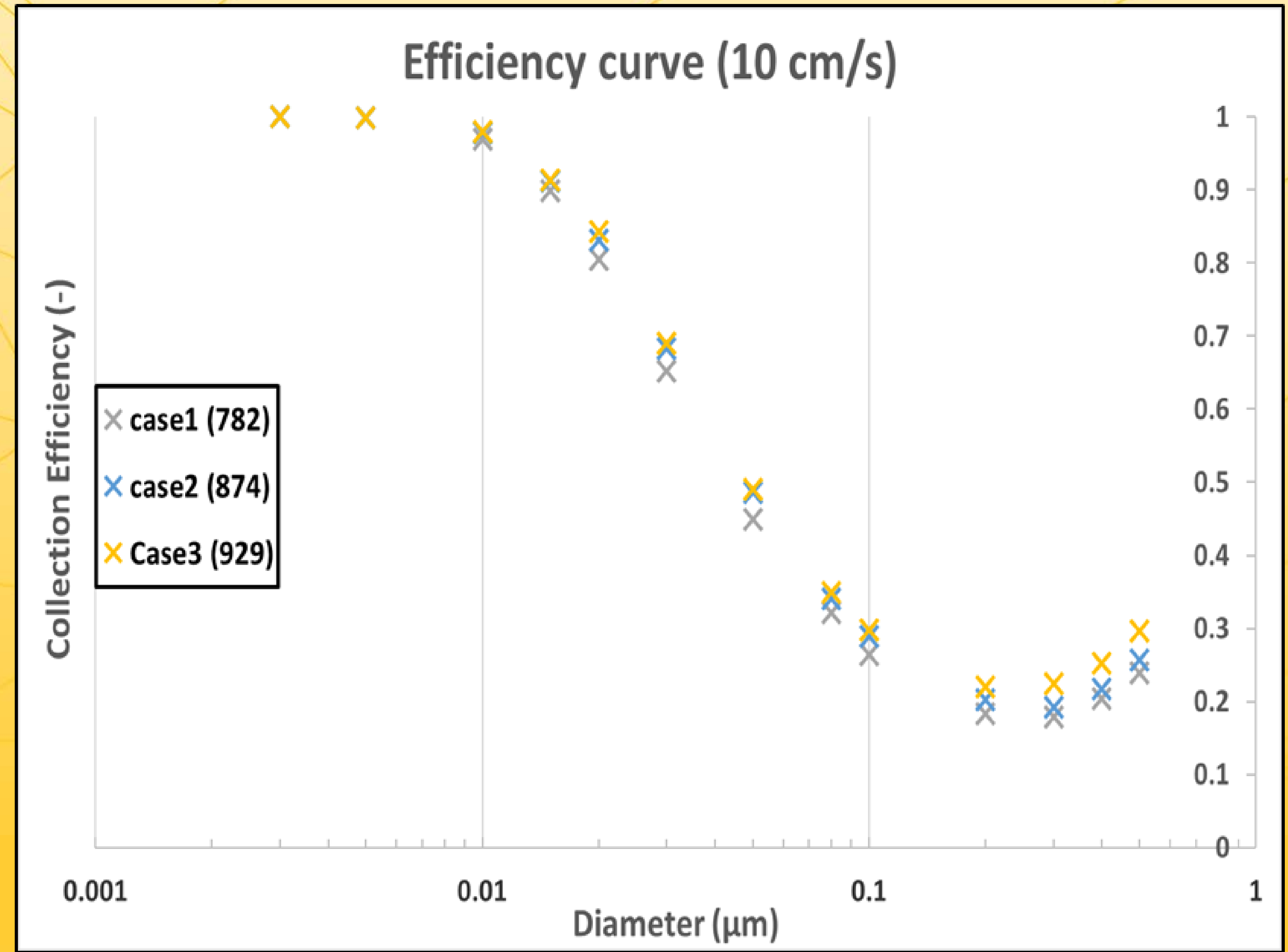
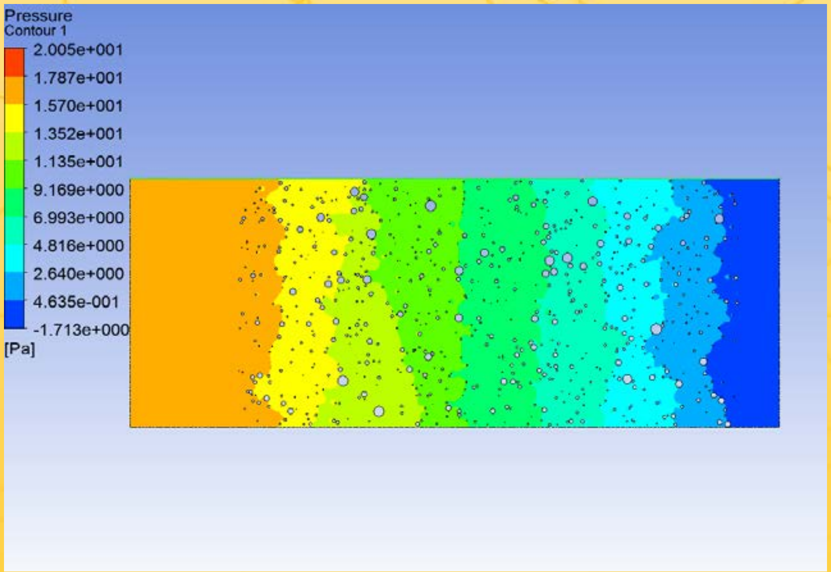


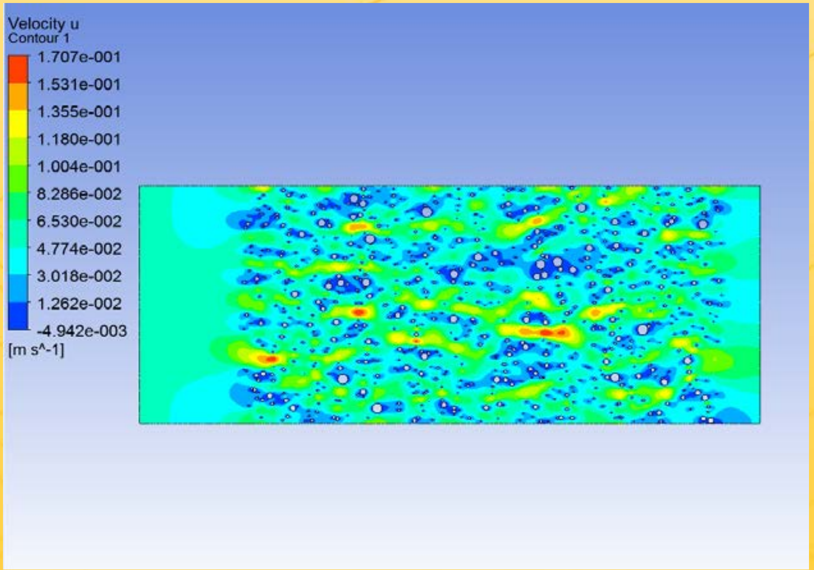
Flow field calculation: CFD

- Continuity and momentum equation in the Stokes regime were numerically solved (Fluent)

$$\nabla \cdot u = 0$$
$$\nabla p - \mu \nabla^2 u = 0$$



Pressure drop

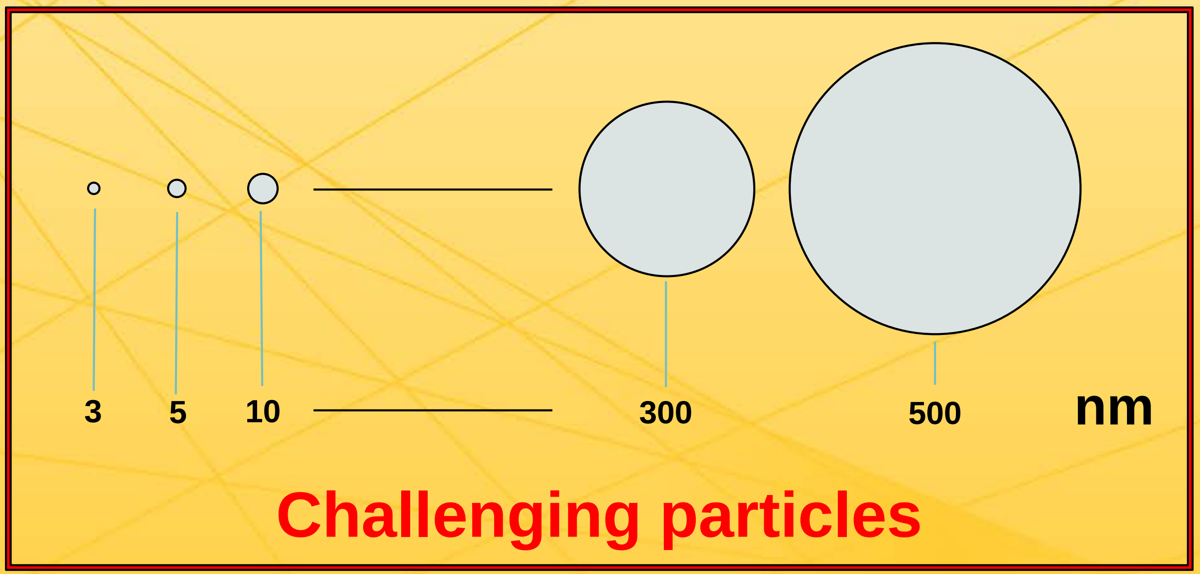


Streamline

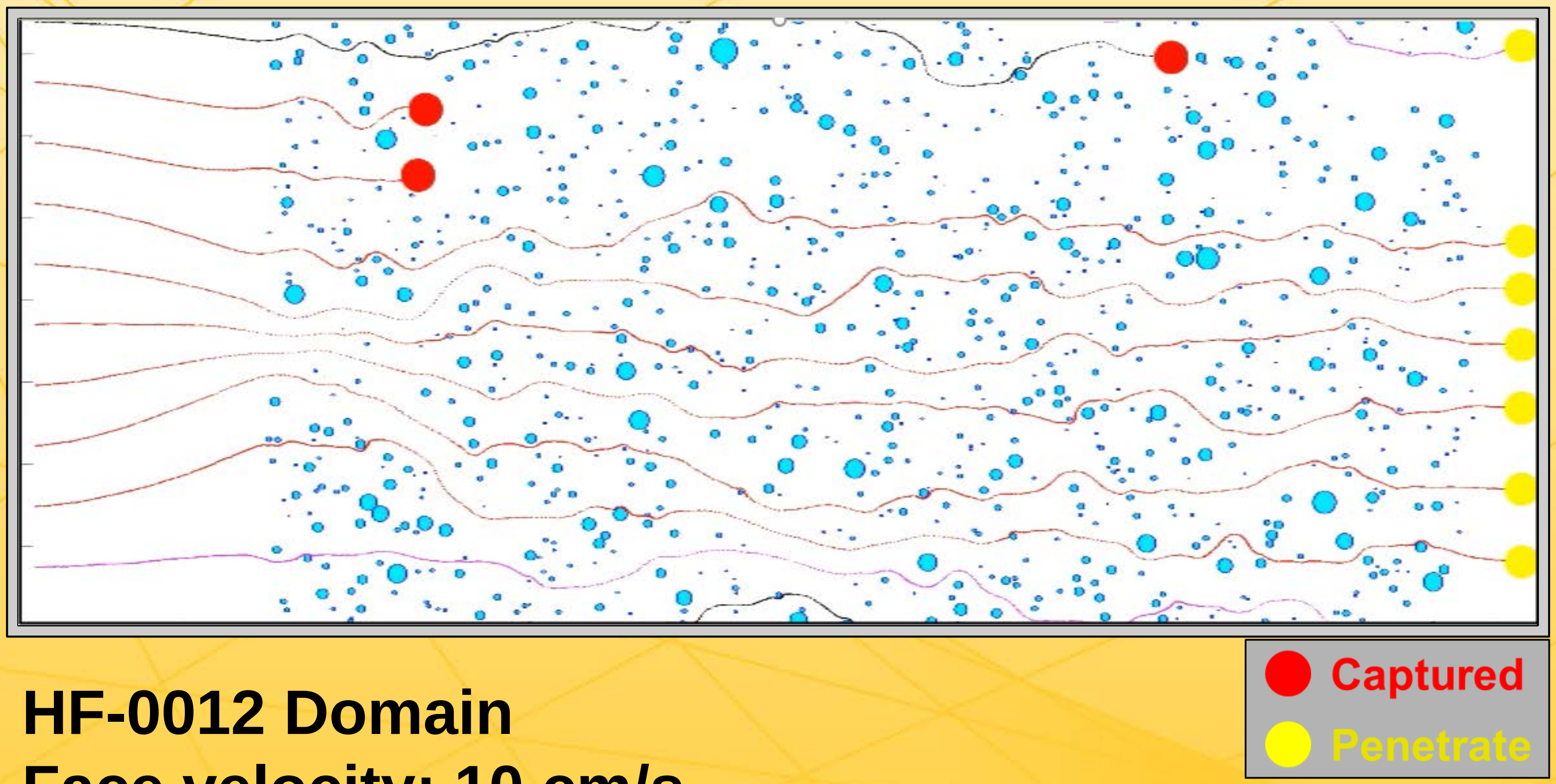
Particle trajectory

- In-house JAVA code is applied to solve the Langevin equation
- Collection efficiency is obtained using the particles from 3 nm up to 500 nm

Size (nm)
3
5
10
15
20
30
50
80
100
200
300
400
500



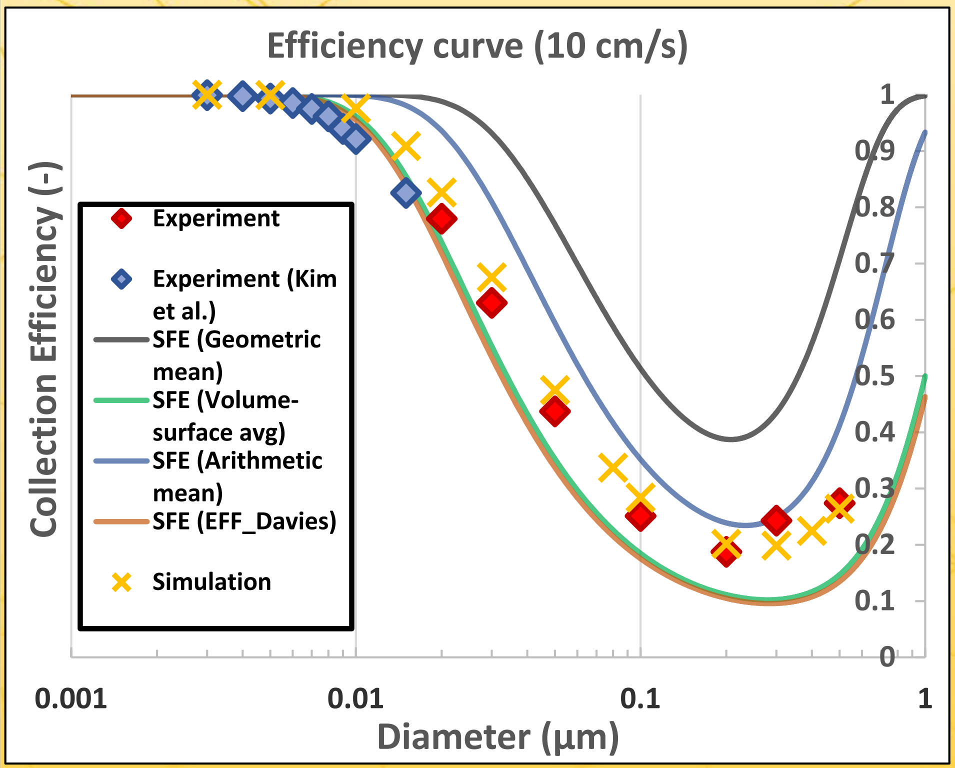
Example particle trajectory



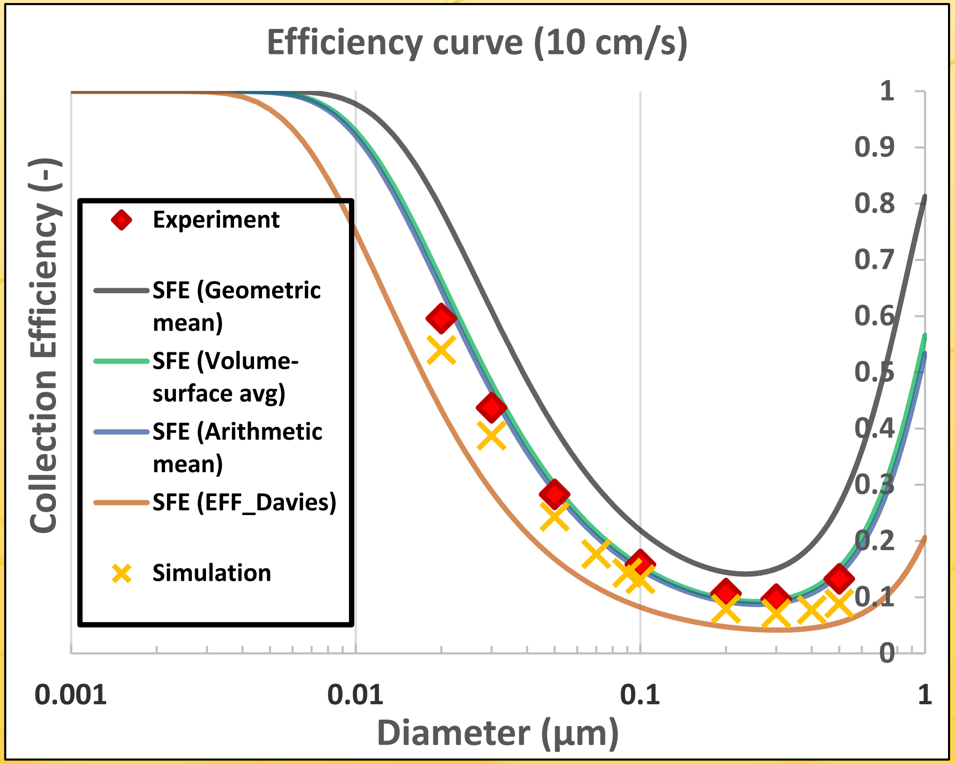
HF-0012 Domain
Face velocity: 10 cm/s
200nm particles

Filtration efficiency comparison

HF-0012 10cm/s



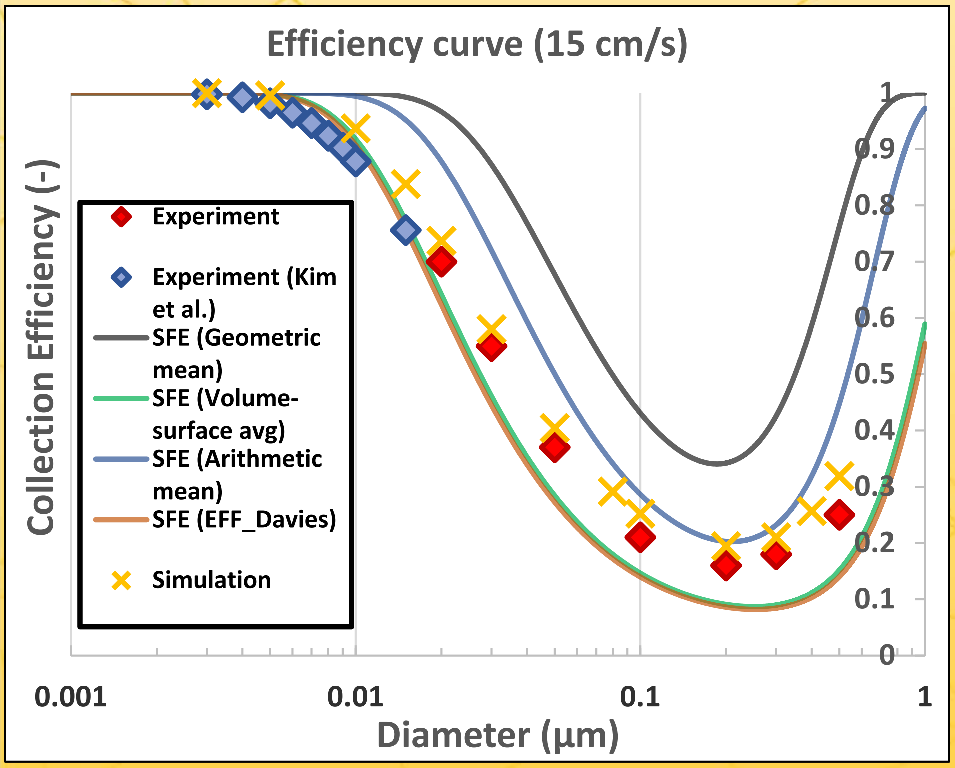
HF-0493 10cm/s



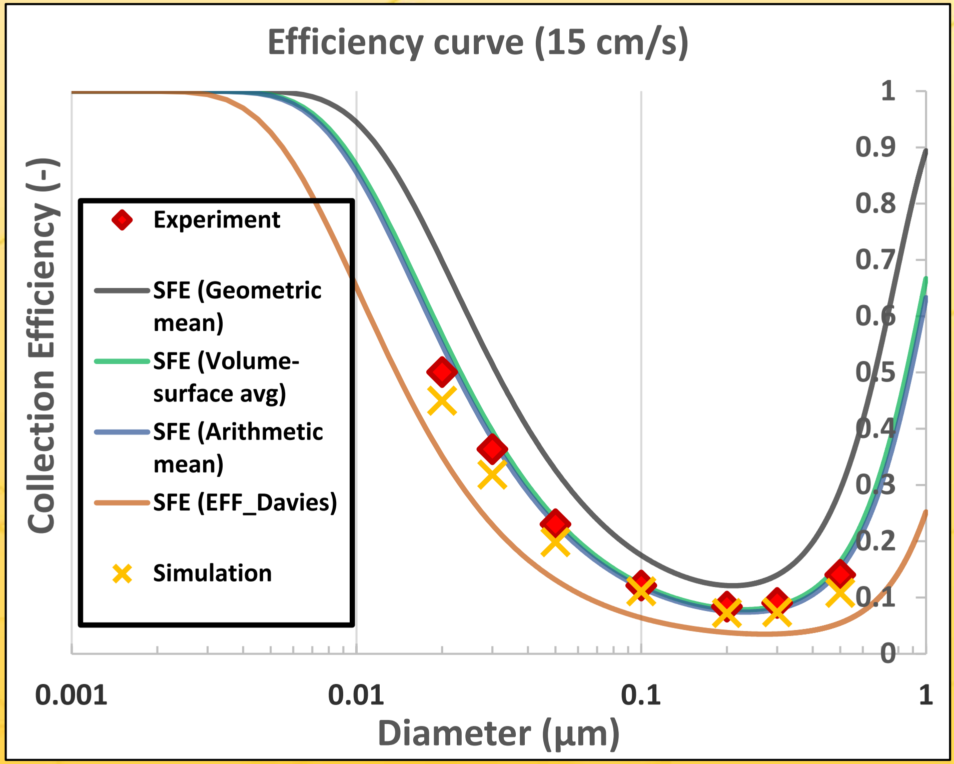
- The relative accuracy of estimated efficiency curve using equivalent fiber diameters varies with the filter media
- Simulation results agree well with experimental data for both filters

Filtration efficiency comparison

HF-0012 15cm/s

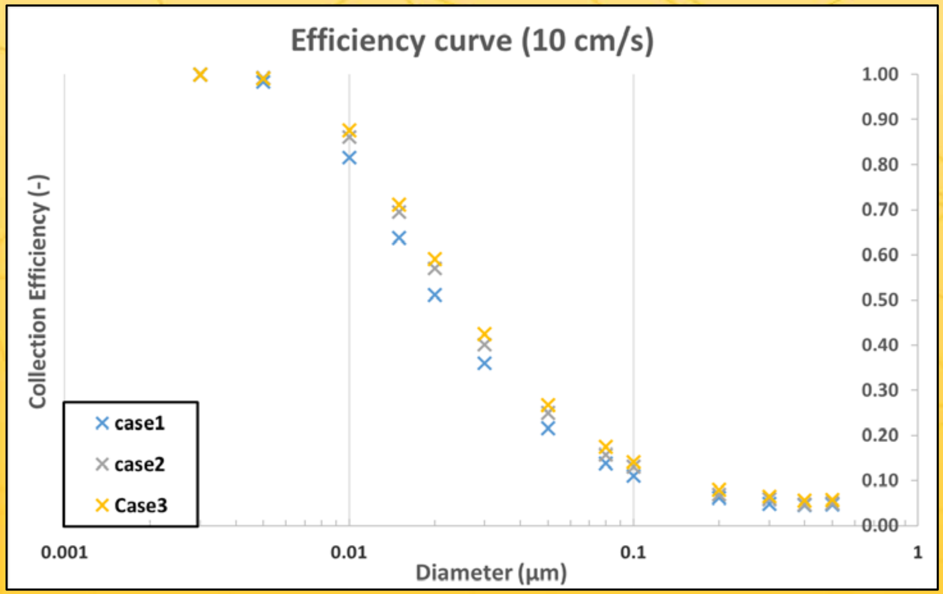


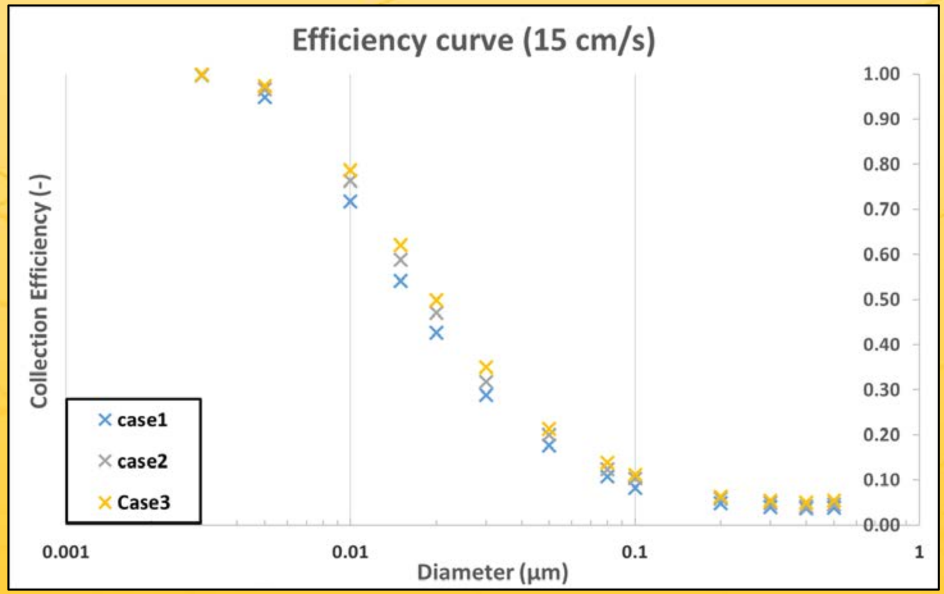
HF-0493 15cm/s



Effect of polydispersity:
same average diameter

case	Thickness (mm)	Solidity (-)	Mean (µm)	Min (µm)	Max (µm)	std (µm)	# fibers	COV (SD/mean)
1	1	0.1	15	3.5	65.0	7	227	0.5
2			15	7.9	30.7	4	269	0.3
3			15	12.5	18.4	1	283	0.1





Applications using the developed method will help us better understand/design filters

- Air/Liquid filtration
- Electret filter
- Particle loading on filter media
- Pleated filter

Summary

- We have developed a numerical simulation of nanoparticle filtration by fibrous filter media
- Collection efficiencies for two different filters were measured experimentally with challenging particles from 3nm up to 500nm, and the efficiencies agree well with those from simulation
- SFE theory is a good method for estimating the trends of collection efficiency for fibrous filters, but the estimated efficiency can deviate depending on the fiber diameter definitions and SFE equations for each capture mechanism
- The relative accuracy of predicted collection efficiency, using an equivalent fiber diameter can be altered for the filter media
- The degrees of polydispersity affect the collection efficiency