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A presentation on:

PMM-DPM SIMULATION OF AEROSOL DROPLET FILTRATION USING COALESCING FILTER

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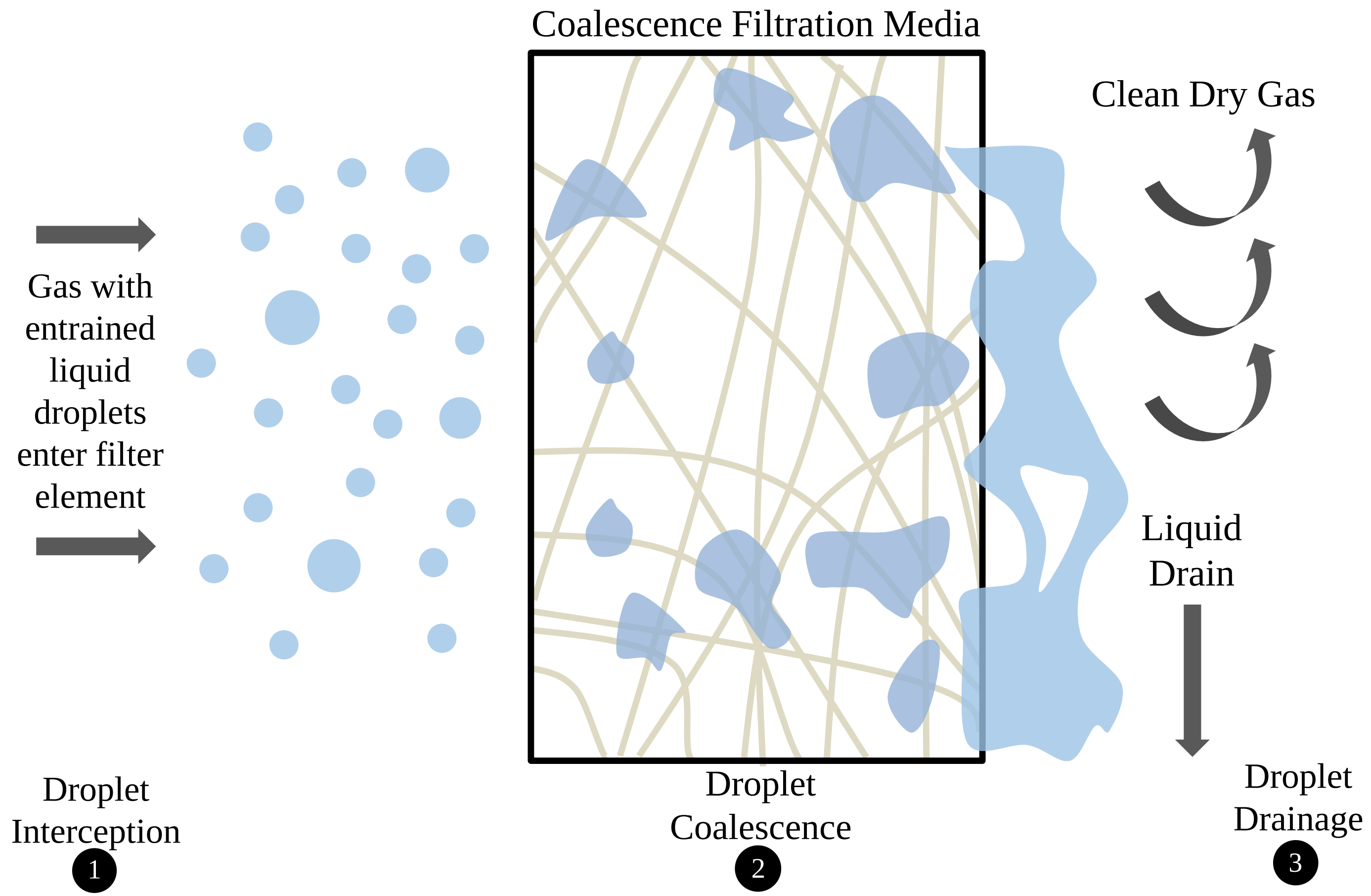
Coalescence Filtration



Applications: Removal of oil droplets from engine exhaust or water droplets from fog, separation of dispersed water droplets from diesel fuel.

- Removal of dispersed droplets from a gas or an immiscible fluid.
- Ratio of the volume of liquid trapped in a filter to the filter's pore volume is saturation.
- Saturation depends on the interplay between drag force on liquid, gravitational force, and capillary force.

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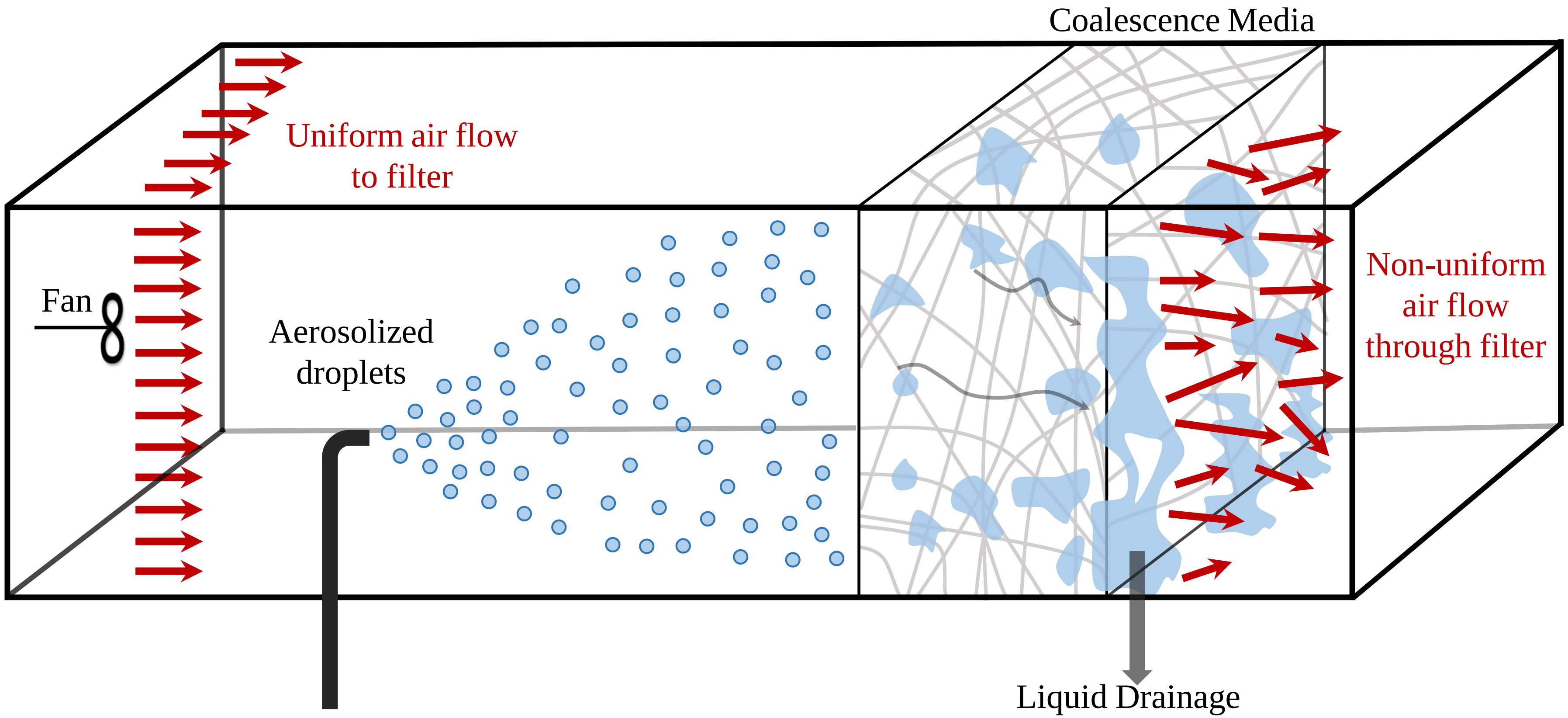
Motivation



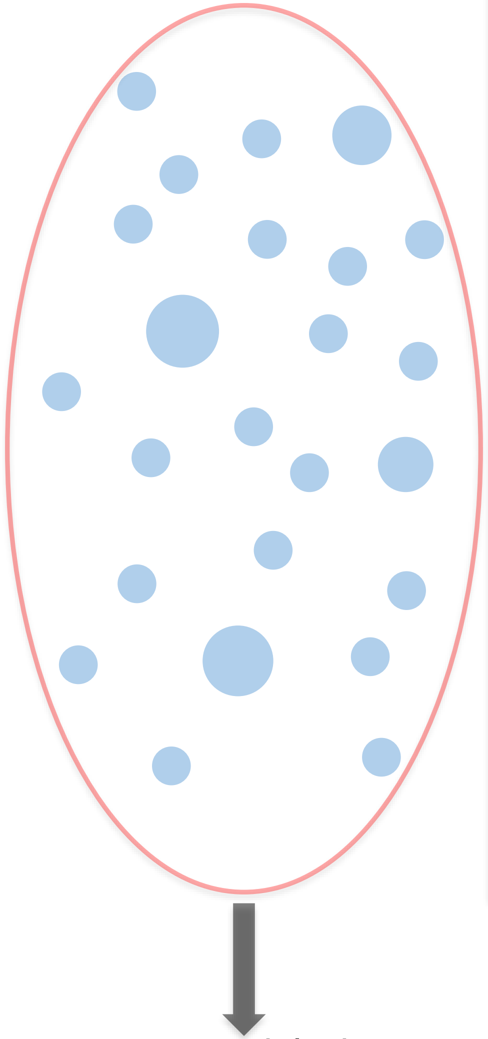
Problem:

- Steady state saturation levels happens after few hours in a coalescence filtration experiment.
- Computational time-step needed for similar CFD simulation (VOF method): 1 μs
- Computationally impractical to run through the experimental timescale
- Inherent boundary conditions problems simulating coalescing filter with representative element volume (REV)

Proposed Simulation Strategy

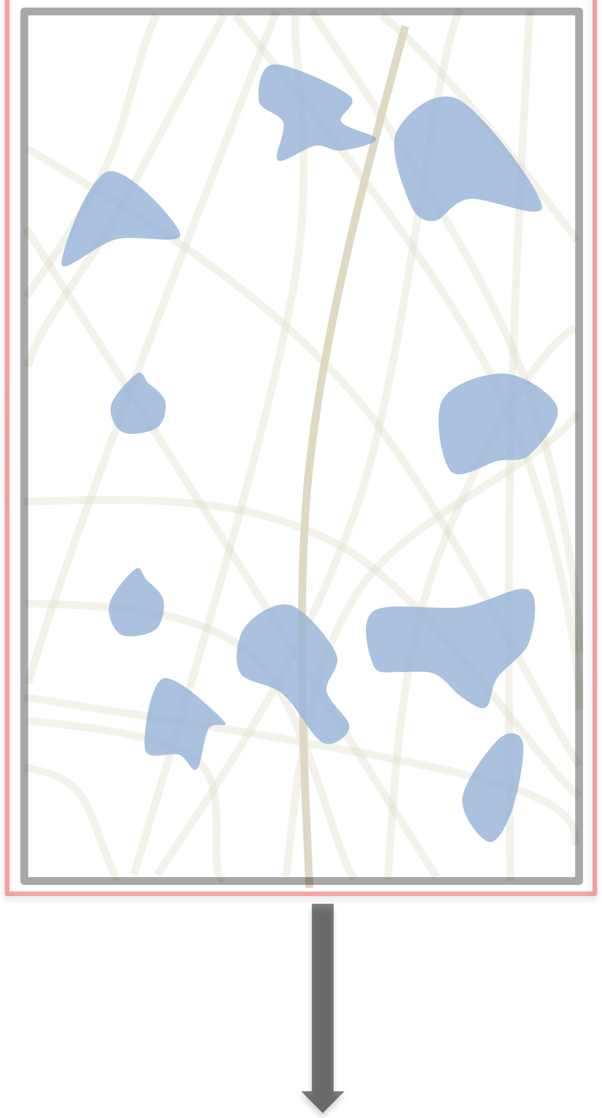
- Use a computationally friendly pore morphology method (PMM) based desaturation to create a partially saturated media
- Use the Lagrangian discrete phase model (DPM) to inject aerosolized droplets into the media at equilibrium partial saturation

The proposed approach allows one to predict collection efficiency and pressure drop as a function of wetting saturation in a virtual filter.



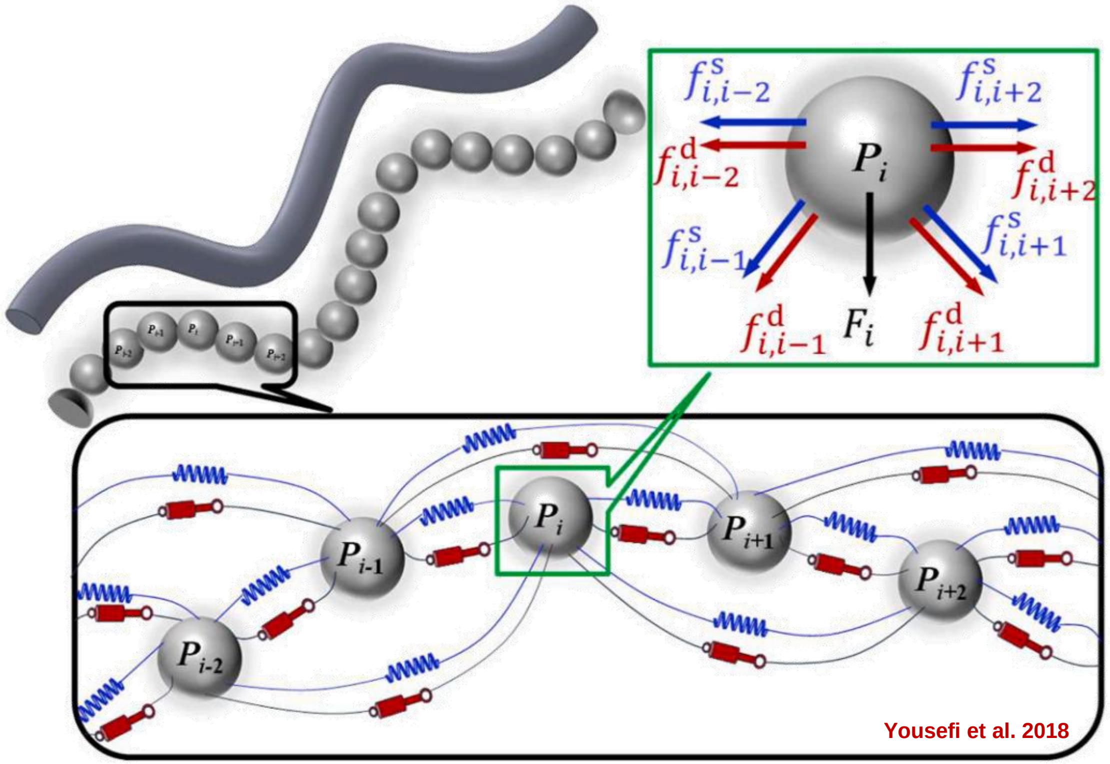
DPM models the trajectories of droplet particles

Coalescence Filtration Media



PMM models the saturation field in the filter

Mass-Spring-Damper (MSD) model



$$\frac{d}{dt}\begin{bmatrix}\vec{v}_i\\ \vec{p}_i\end{bmatrix} = \begin{bmatrix}\frac{\vec{f}_i^{net}}{m_i}\\ \vec{v}_i\end{bmatrix}$$

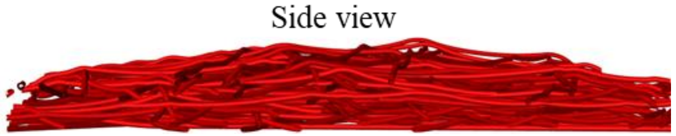
$$\vec{f}_i^{net} = \vec{f}_{i,i-2}^{s} + \vec{f}_{i,i-1}^{s} + \vec{f}_{i,i+1}^{s} + \vec{f}_{i,i+2}^{s} + \vec{f}_{i,i-2}^{d} + \vec{f}_{i,i-1}^{d} + \vec{f}_{i,i+1}^{d} + \vec{f}_{i,i+2}^{d}$$

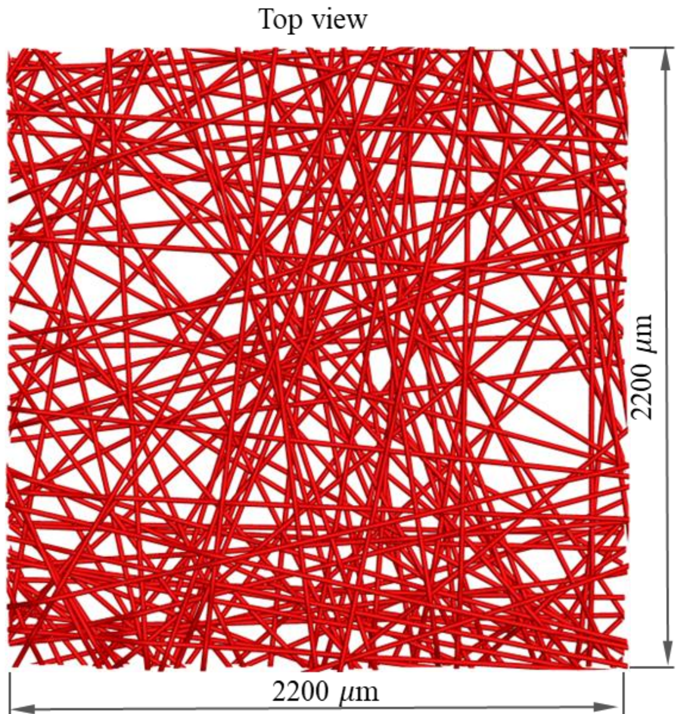
$$\vec{f}_{i,i+1}^{d} = -k_d(\vec{v}_i - \vec{v}_{i+1})$$

$$\vec{f}_{i,i+1}^{s} = -k_s(\|\vec{p}_i - \vec{p}_{i+1}\| - l_r)\frac{\vec{p}_i - \vec{p}_{i+1}}{\|\vec{p}_i - \vec{p}_{i+1}\|}$$

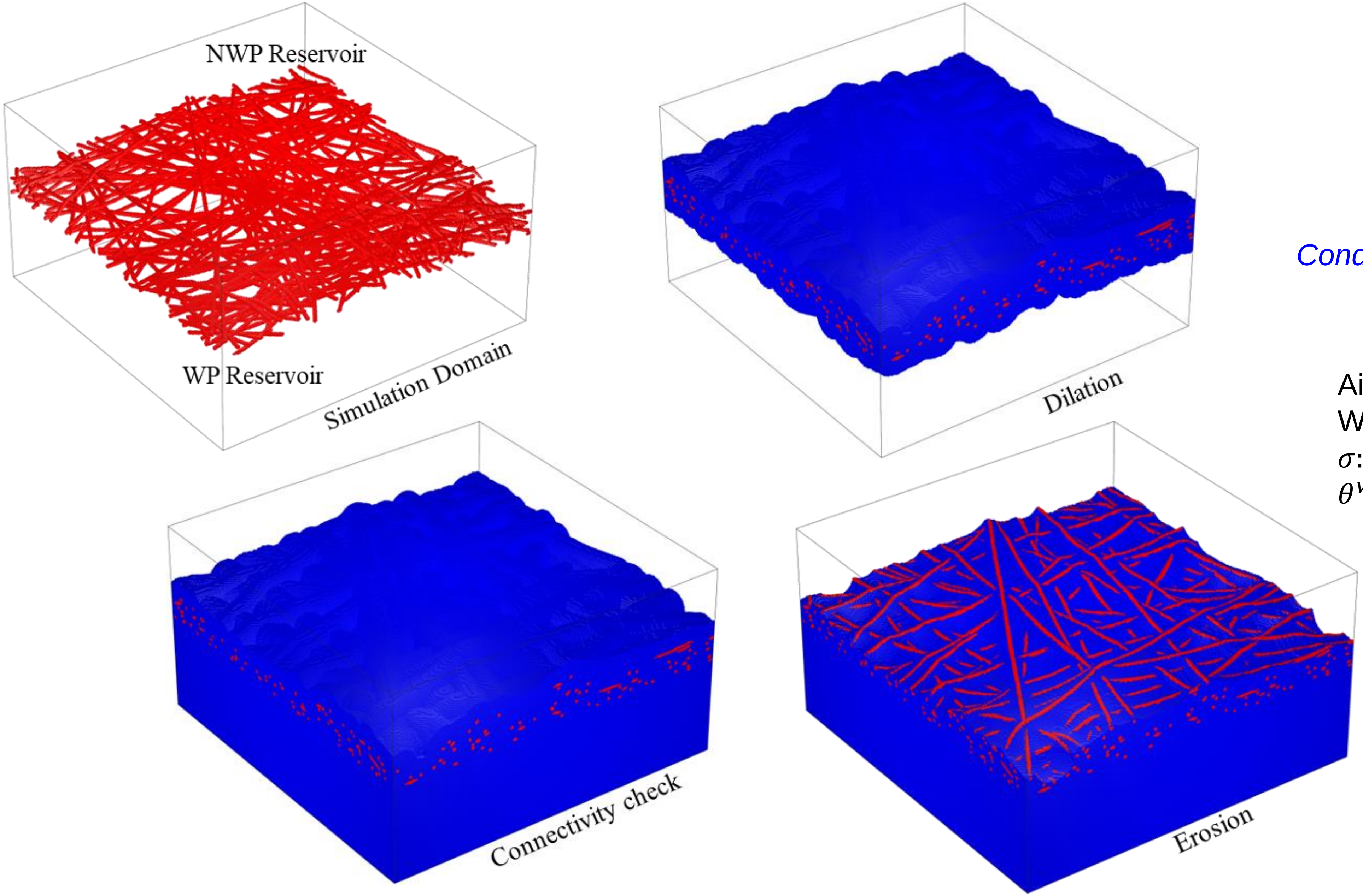
- Represent fibers as flexible arrays composed of interconnected beads.
- Bead diameter = fiber diameter
- Fibers do not overlap or interpenetrate
- Yields fibers with curvature

$d_f = 20\ \mu m$
$t = 300\ \mu m$
$\varepsilon = 5.71\ \%$





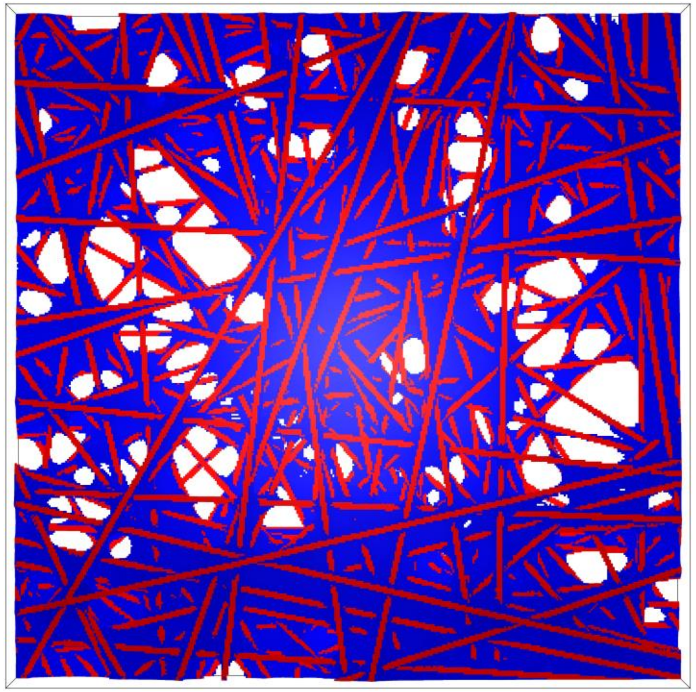
PMM in 3D



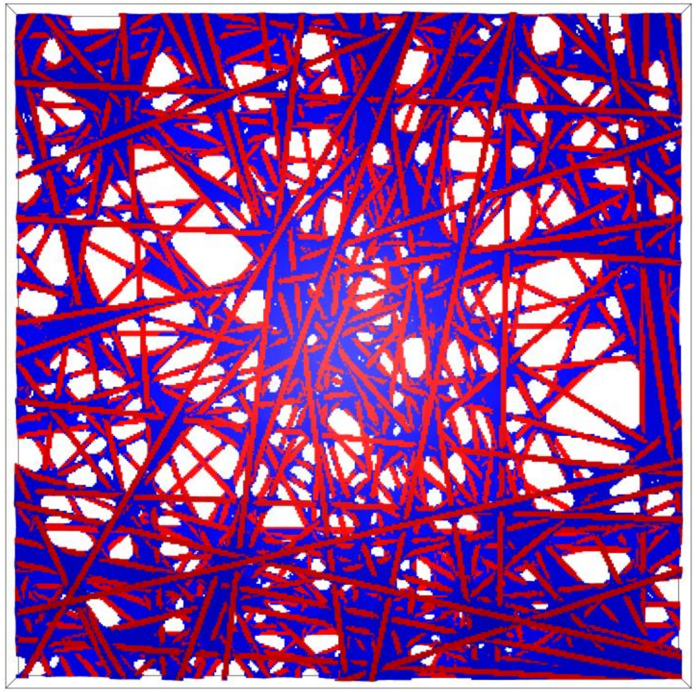
Conducted to create a partially saturated media

Air: NWP
Water: WP
σ: 0.07275 N/m
$\theta^w = 10°$ (arbitrarily chosen)

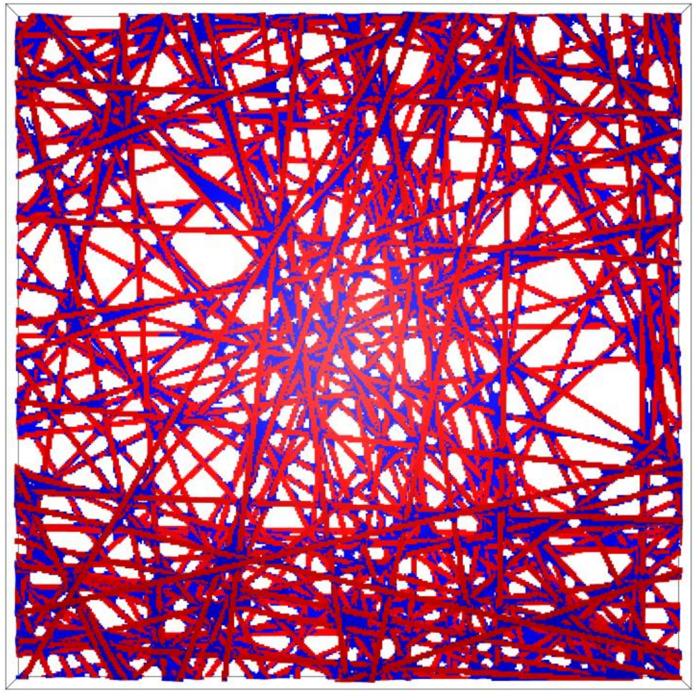
PMM-based desaturation simulation



$P = 2.7$ kPa, $S_w = 31.47$ %



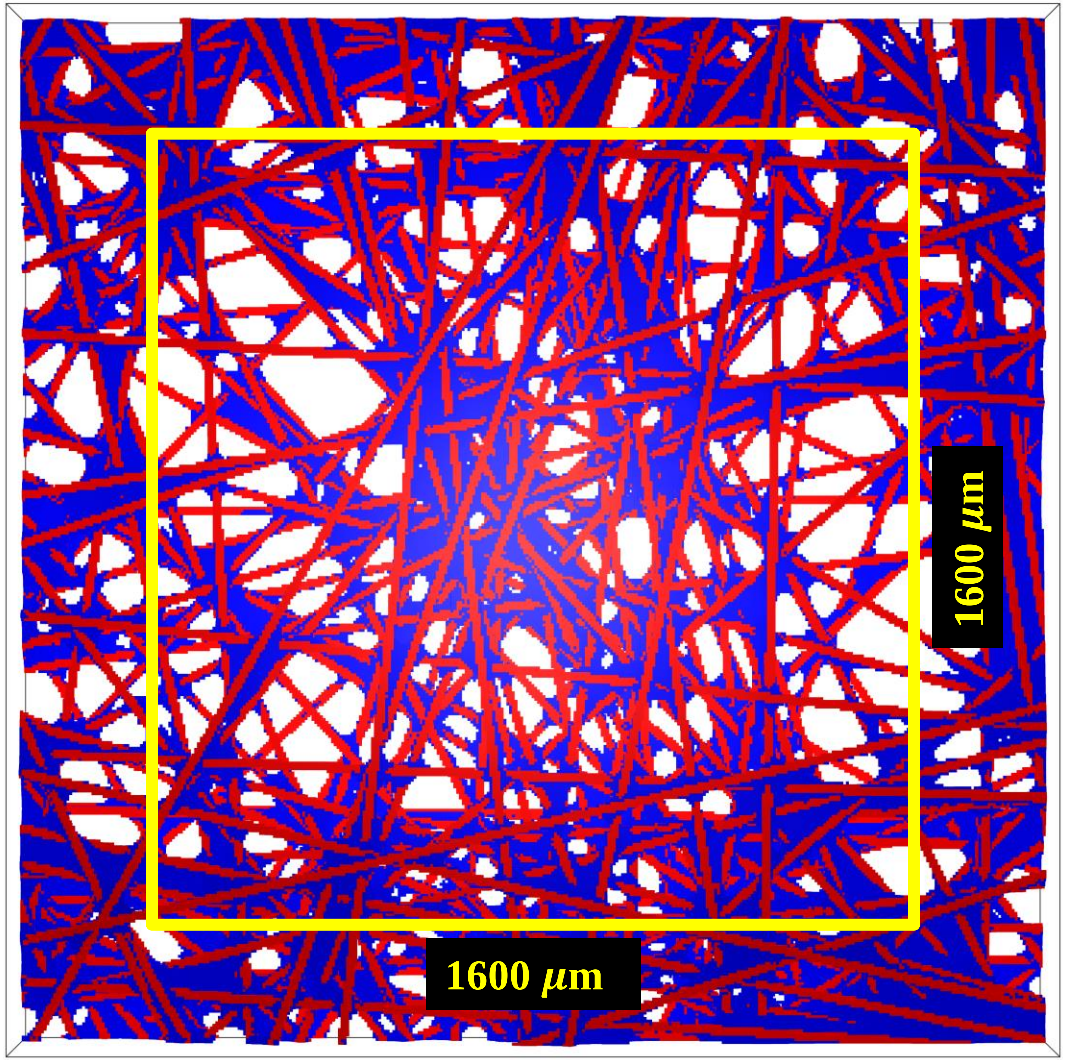
$P = 3.5$ kPa, $S_w = 11.69$ %



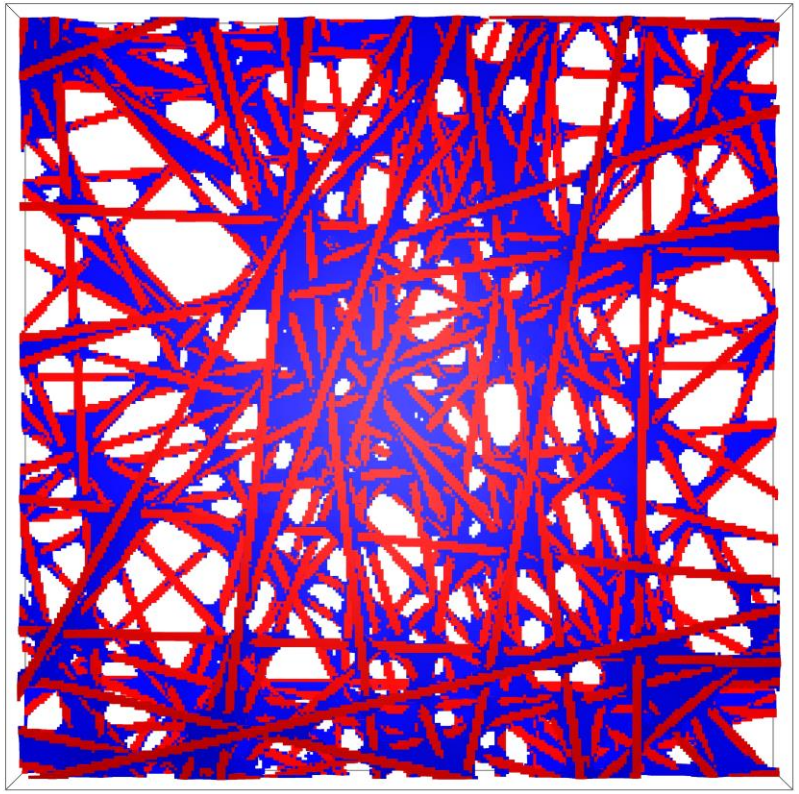
$P = 4.9$ kPa, $S_w = 3.59$ %

Partially saturated medium with different wetting saturation values were obtained

Boundary treatment for PMM simulation



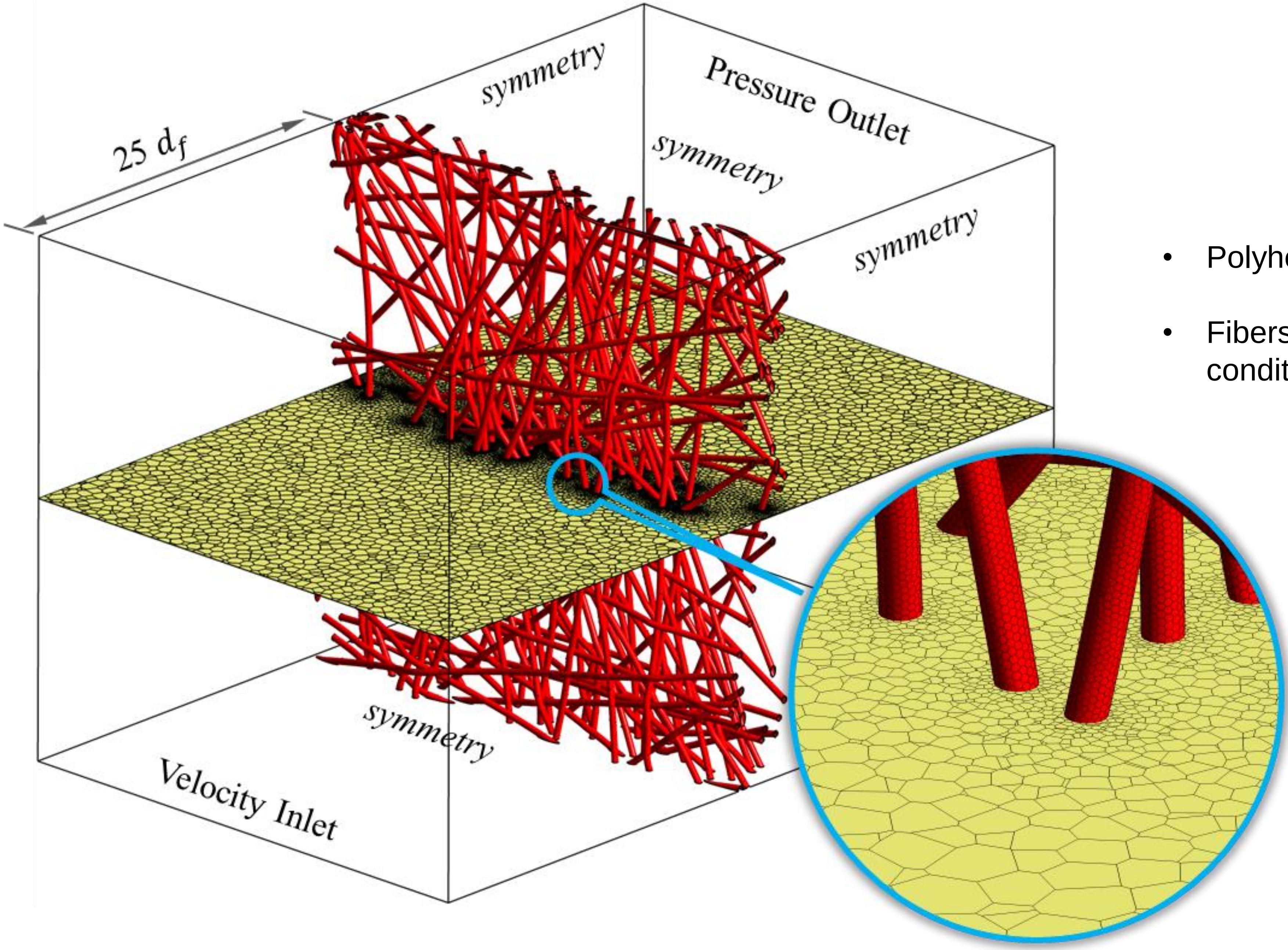
Original domain



Cropped domain

Removes the edge-effect problem associated with symmetric boundaries

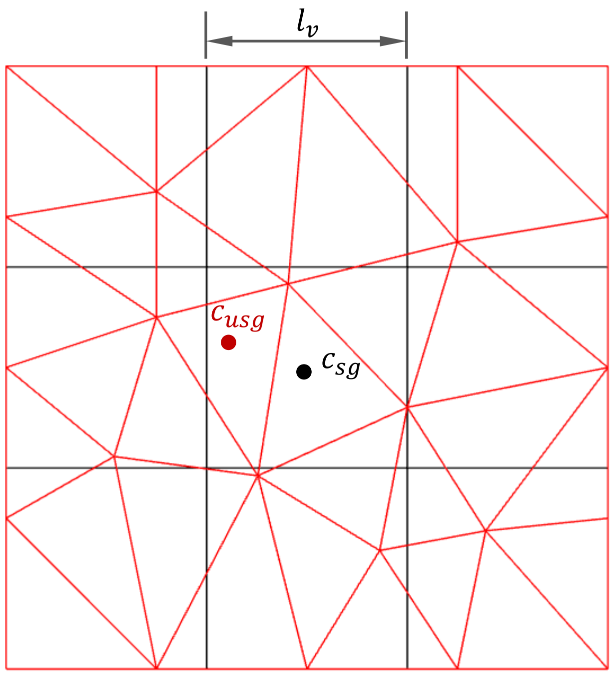
Computational Domain



- Polyhedral mesh (3.55 million elements)
- Fibers: wall with no-slip boundary condition

Cell Marking

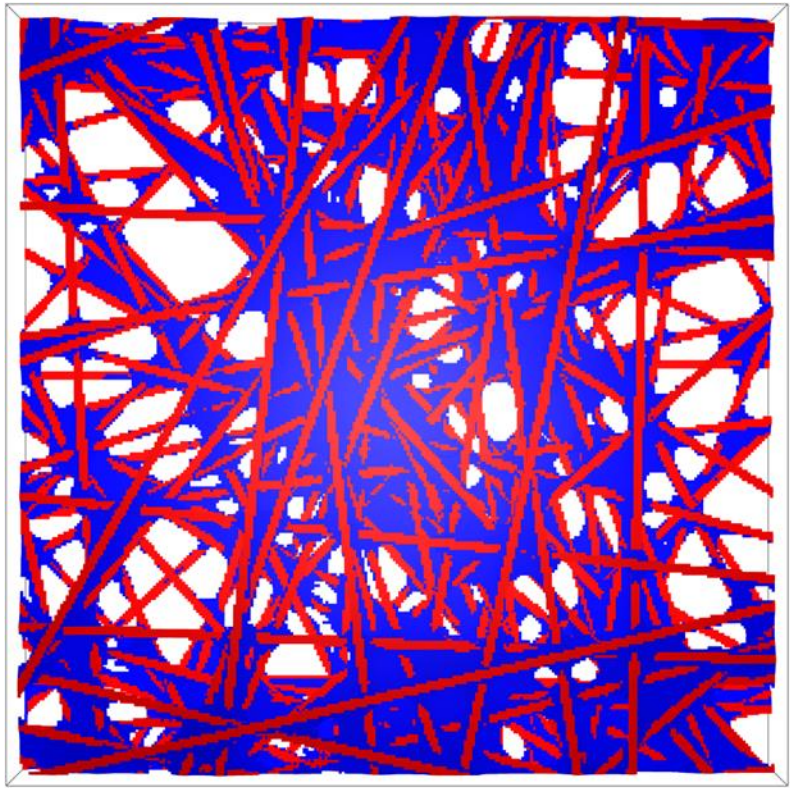
PMM: Structured Mesh
DPM: Unstructured Mesh



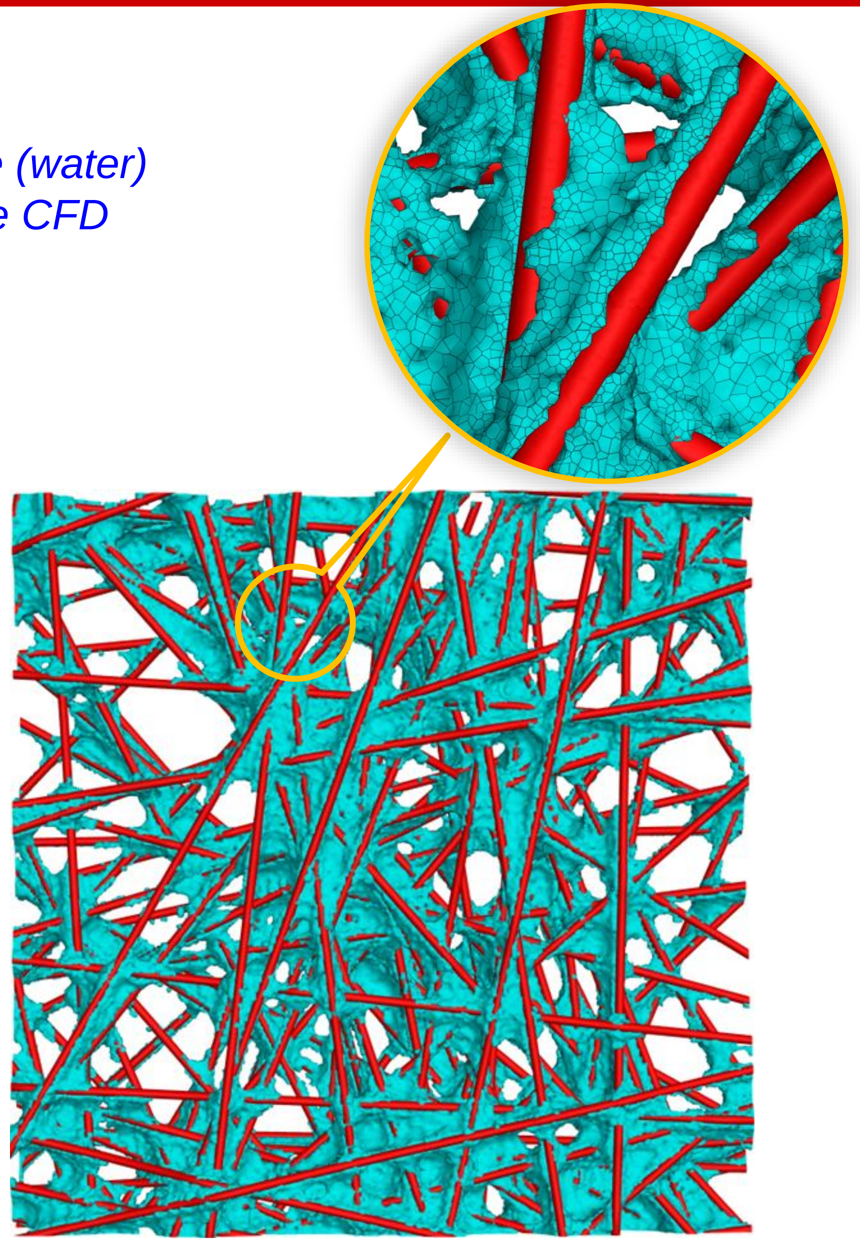
$$c_{usg} - c_{sg} \leq \xi$$

$$\xi = \frac{l_v}{2}$$

Mapped the wetting phase (water) from PMM domain to the CFD domain



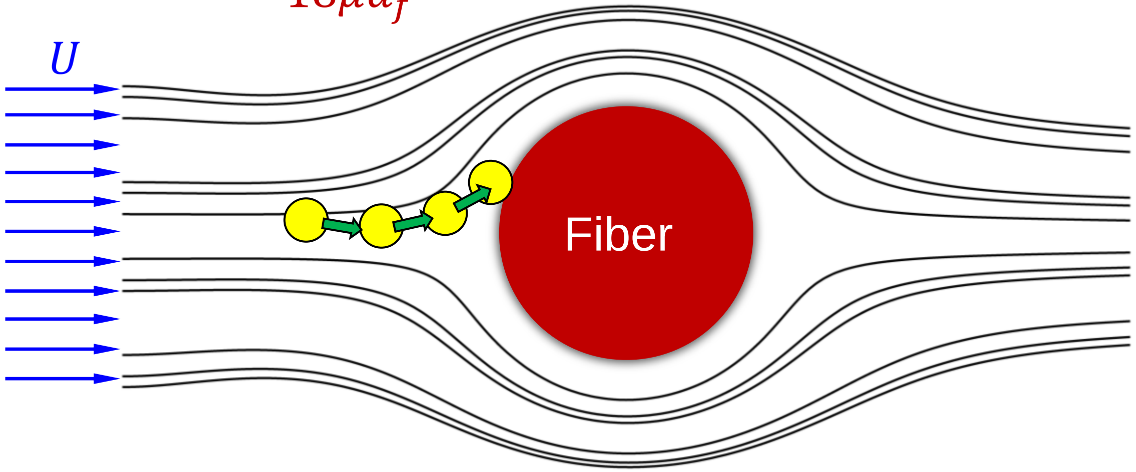
PMM domain



CFD domain

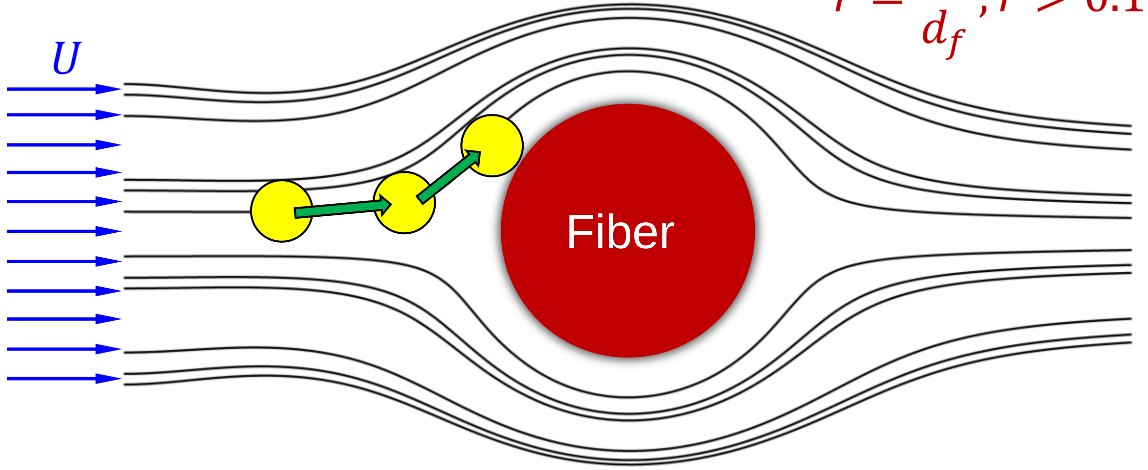
Single Fiber Efficiency (SFE)

$$Stk = \frac{\rho d_p^2 C^c U}{18 \mu d_f}$$



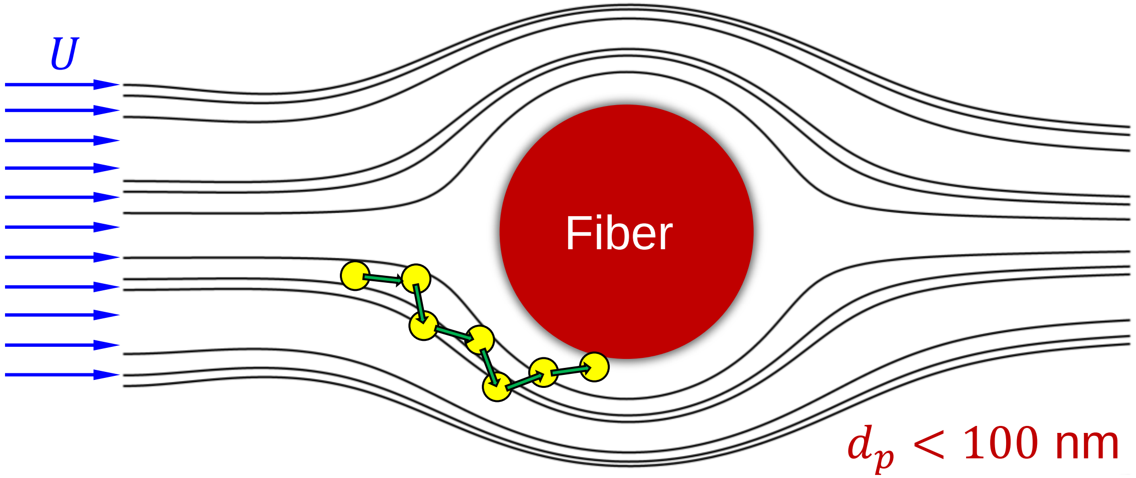
Inertial Impaction

$$r = \frac{d_p}{d_f}, r > 0.1$$



Interception

particle range:
$1 \leq d_p \leq 10$ (in μm)



$d_p < 100$ nm

Brownian Diffusion

Not considered for our particle range

Example of our particle tracking simulation

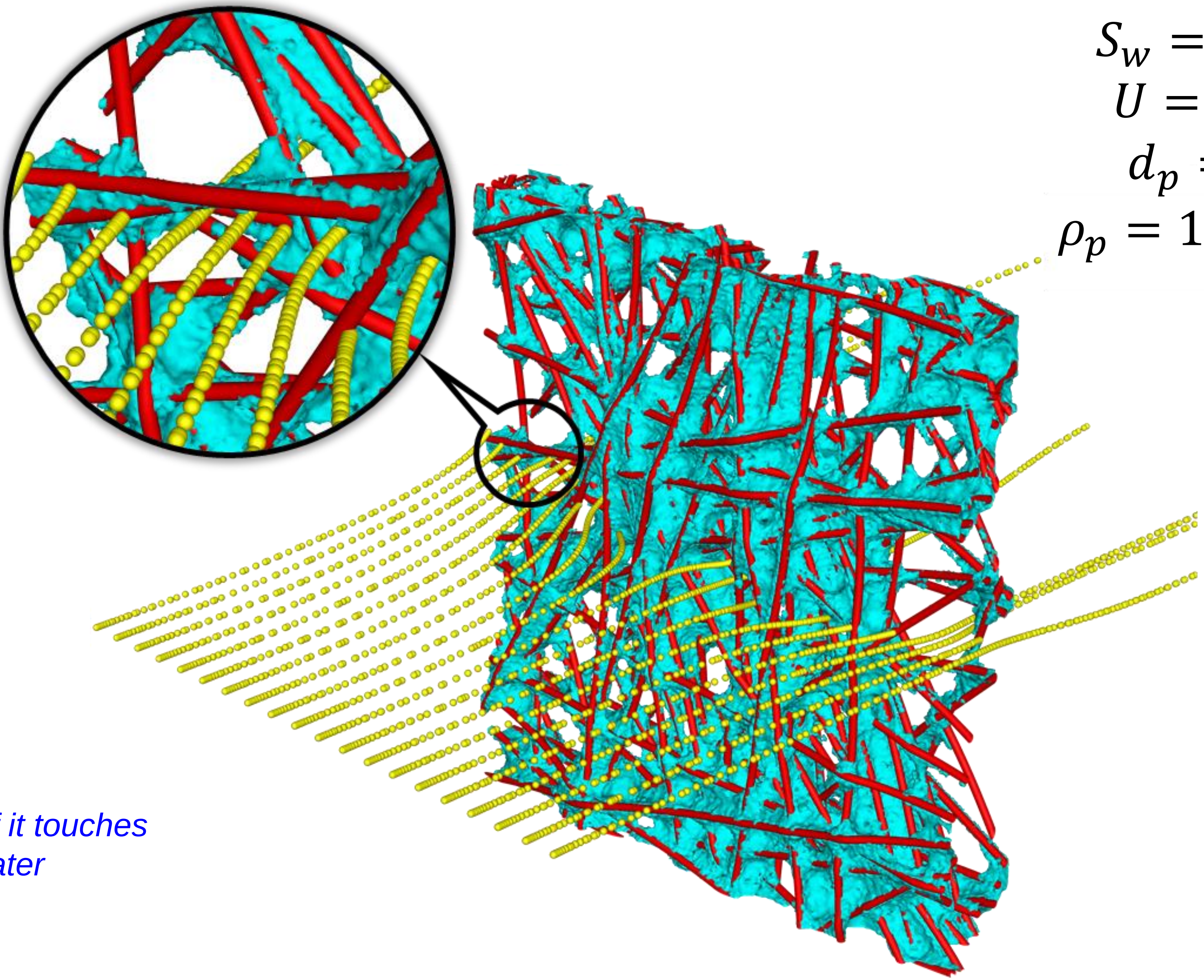
Total number of injected particles (T_n): 1955

Collection efficiency:

$$\frac{T_n - T_e}{T_n} \times 100\ (\%)$$

where,
T_e is total number of escaped particles

Droplets are captured if it touches either fiber or water



$S_w = 14.59\%$
$U = 0.5$ m/s
$d_p = 8\ \mu m$
$\rho_p = 1000$ kg/m^3

Clean filter efficiency using empirical equations

Interception:

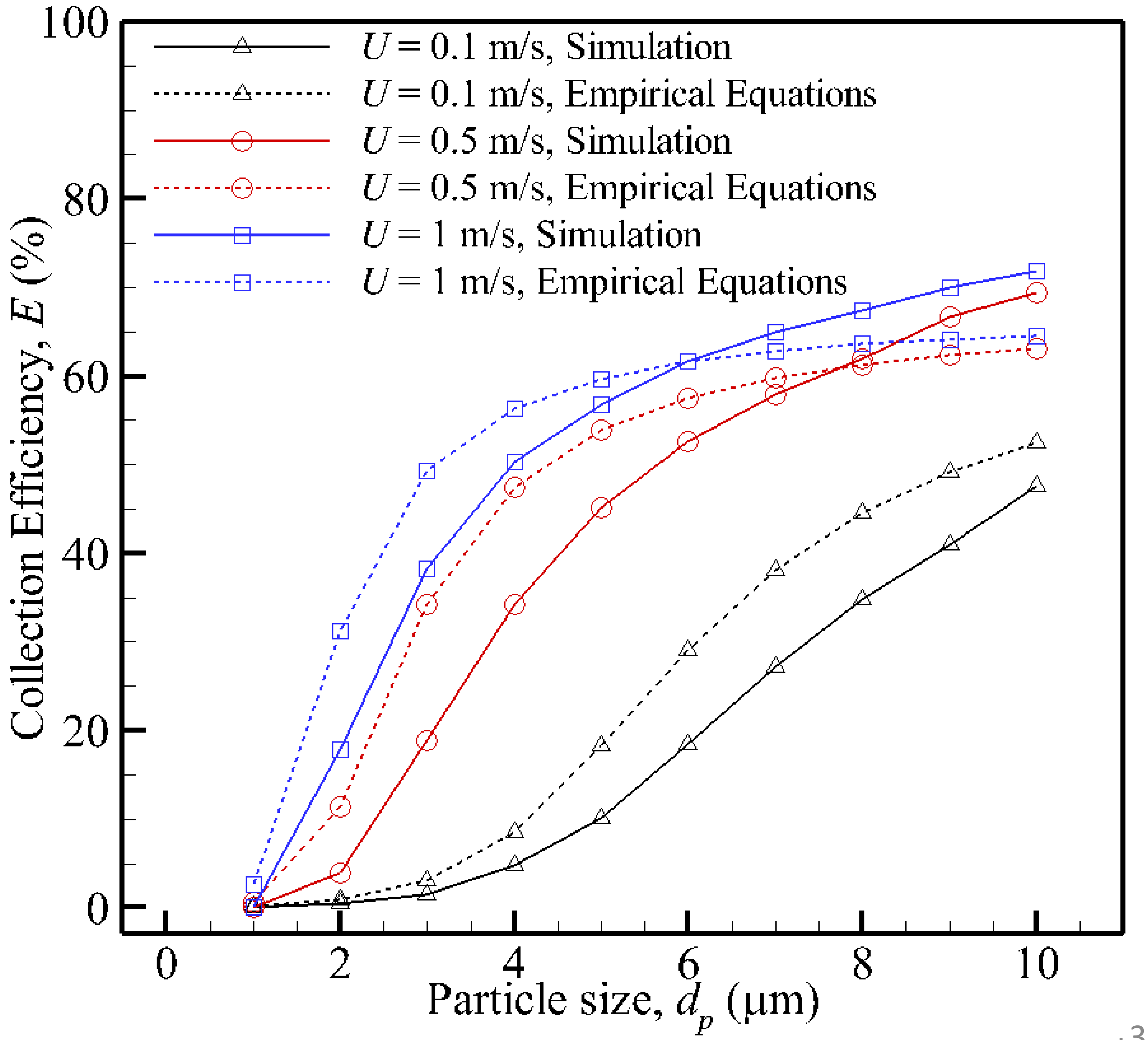
$$E_R = 0.6\left(\frac{1-\varepsilon}{Ku}\right)\left(\frac{R^2}{1+R}\right)\left(1+1.996\,\frac{kn_f}{R}\right)$$

Impaction:

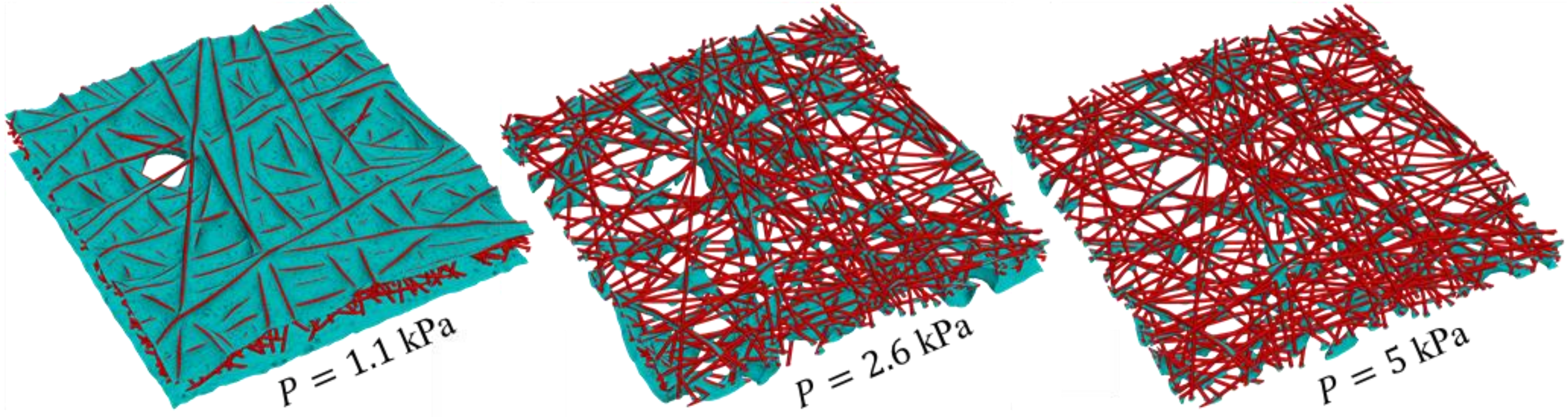
$$E_I = \frac{Stk^3}{Stk^3 + 0.77\,Stk^2 + 0.22}$$

$$E_{tot} = 1 - (1-E_R)(1-E_I)$$

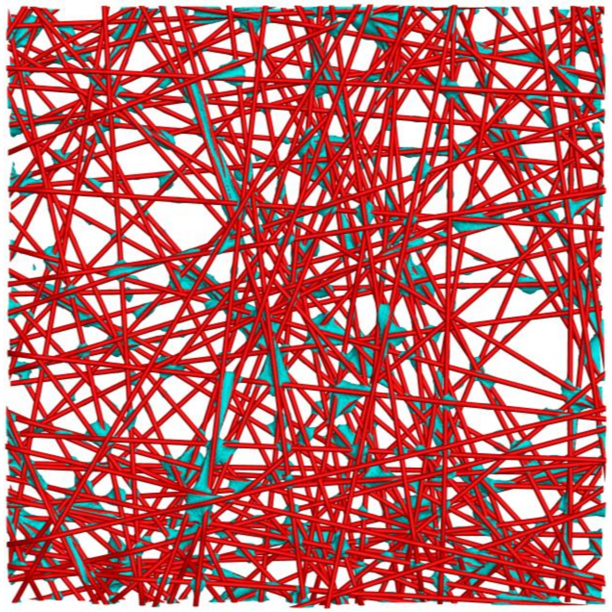
$$E = 1 - \exp\left(\frac{-4\varepsilon E_{tot} t}{\pi d_f}\right)$$



VOF-DPM simulation



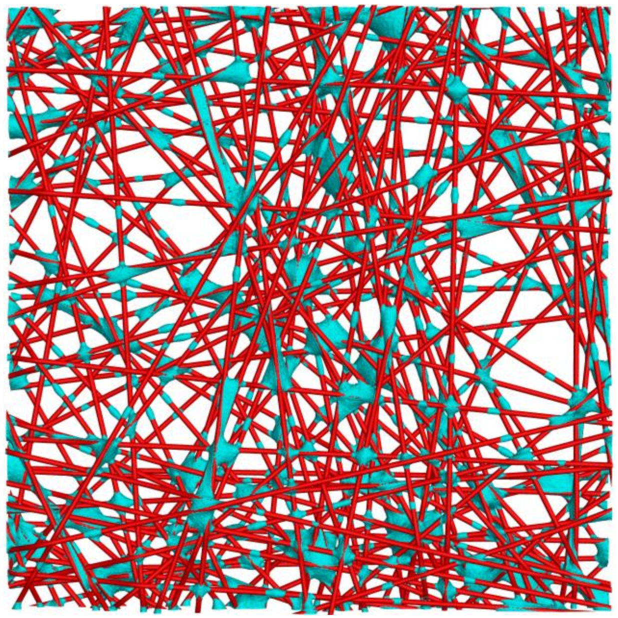
VOF desaturation



Fluid hanging below the media

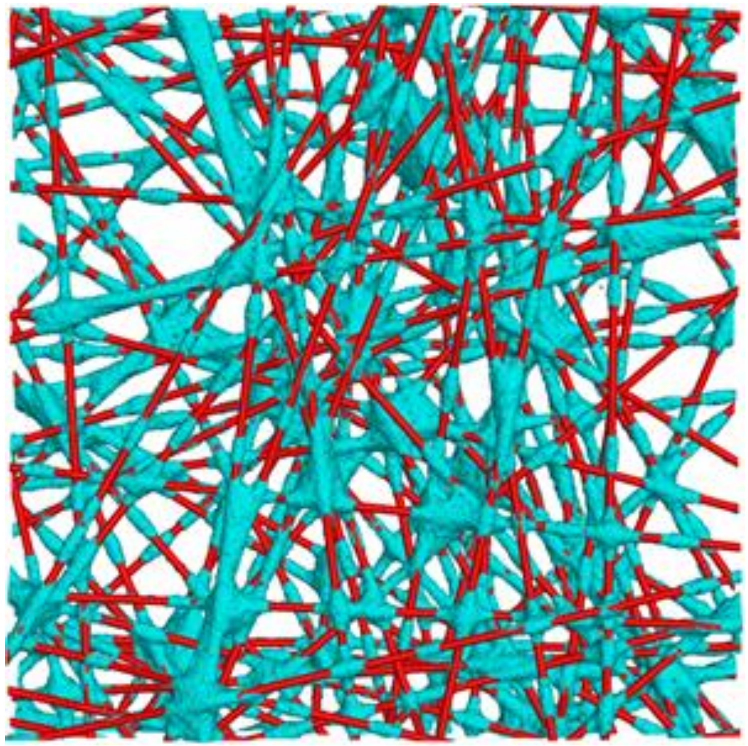
Changing boundary conditions

$U = 0.1$ m/s

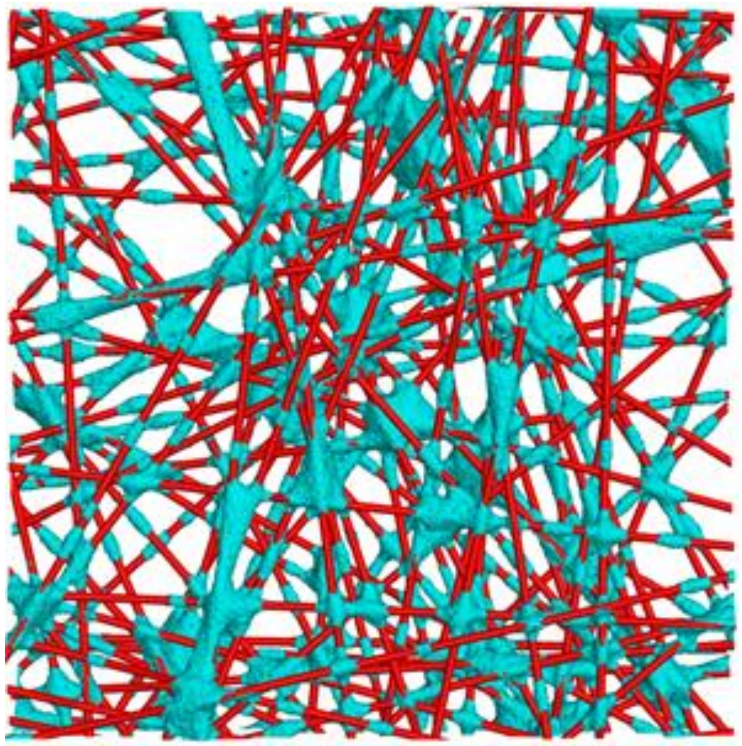


Fluid rising to the top of the media

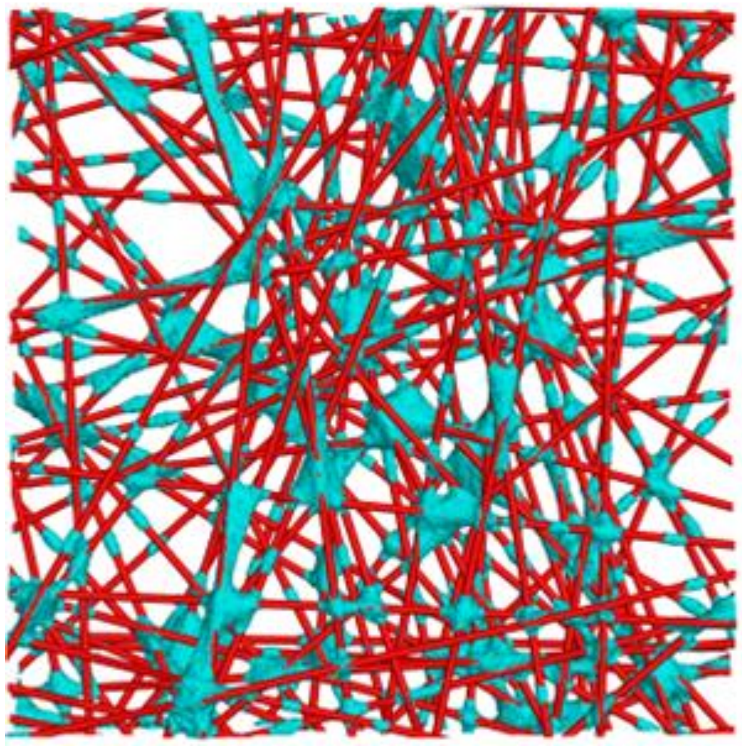
Cell Marking (VOF-DPM)



$\rho > 50\ \mathrm{kg/m^3}$



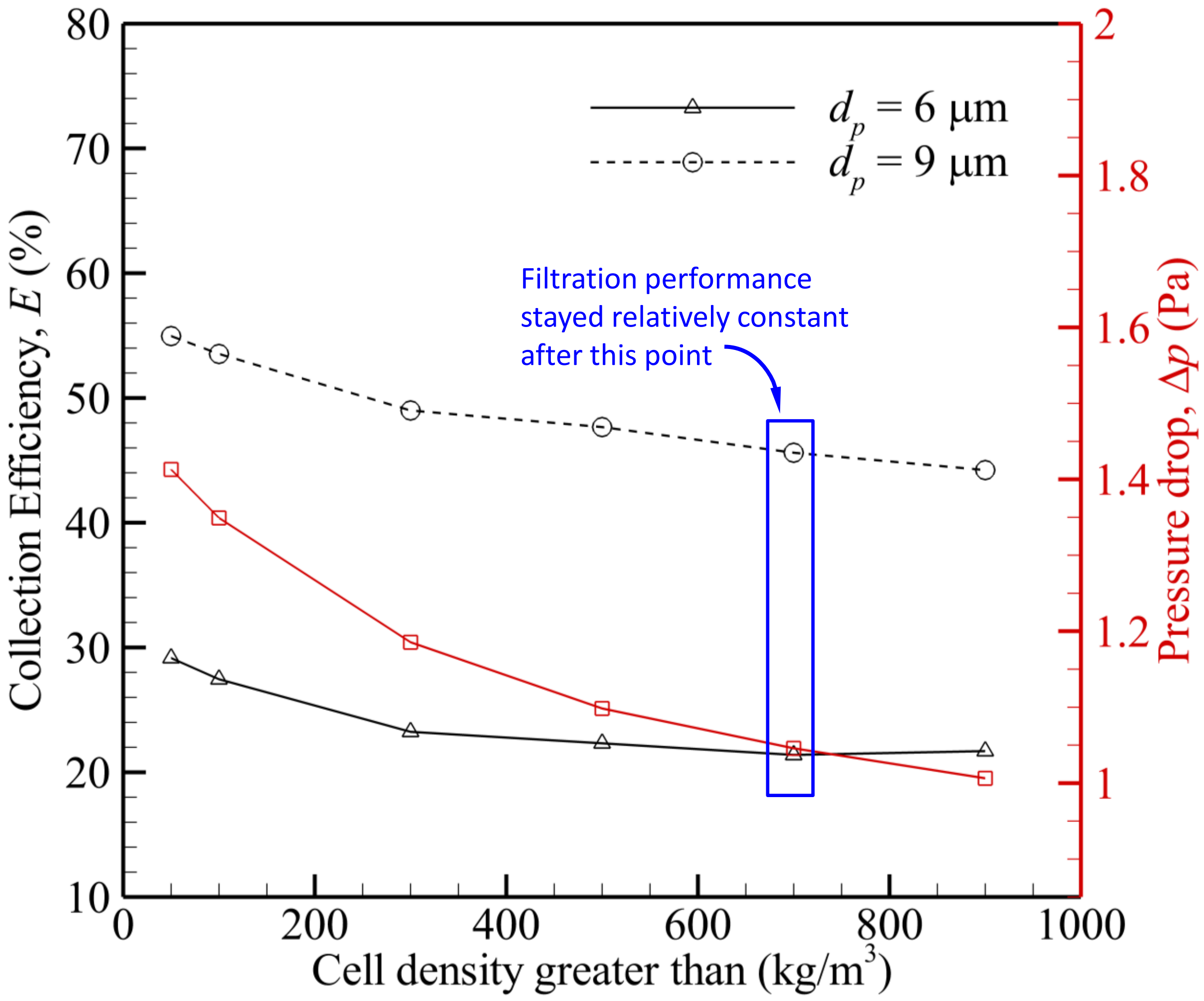
$\rho > 300\ \mathrm{kg/m^3}$

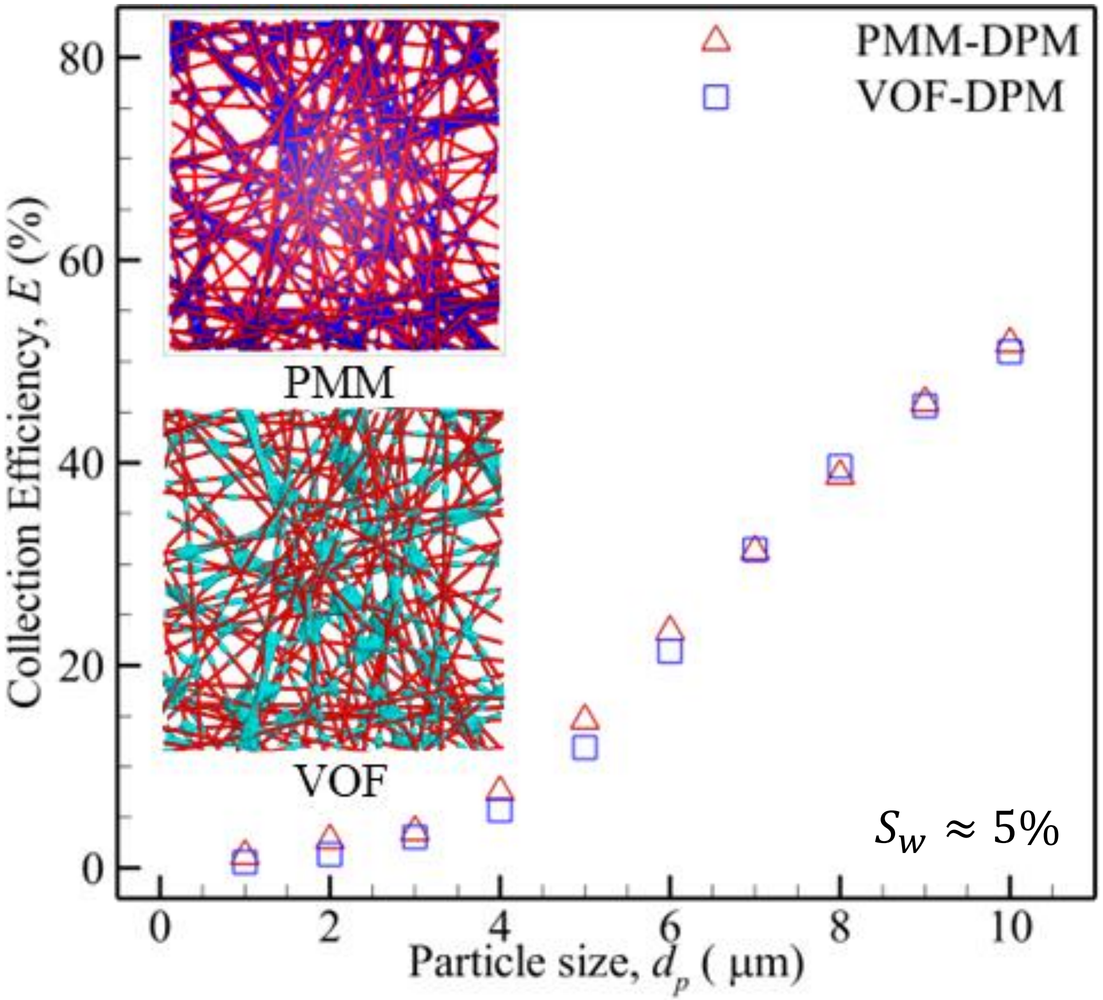


$\rho > 700\ \mathrm{kg/m^3}$

If cell density is chosen near the air density, the filtration performance is over-estimated as saturation increases.

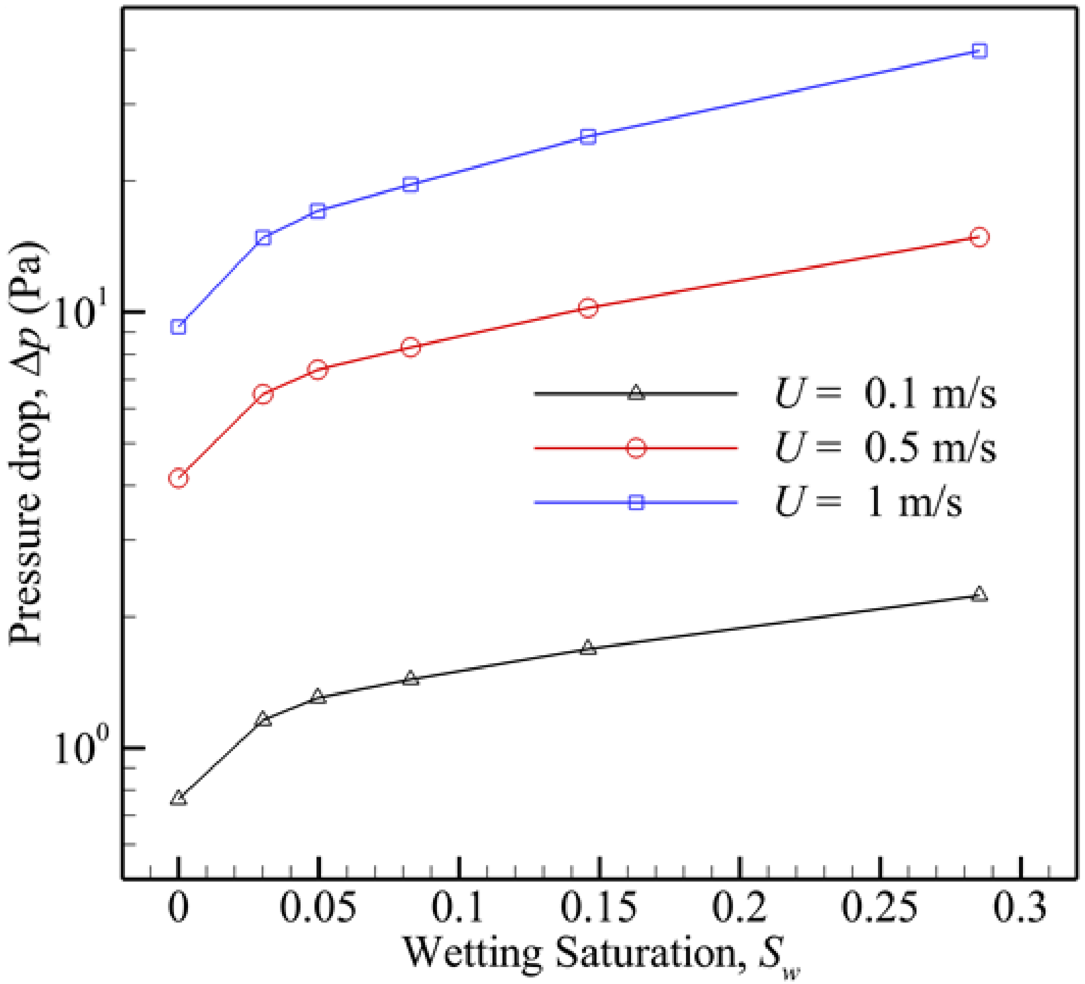
Comparison with VOF-DPM

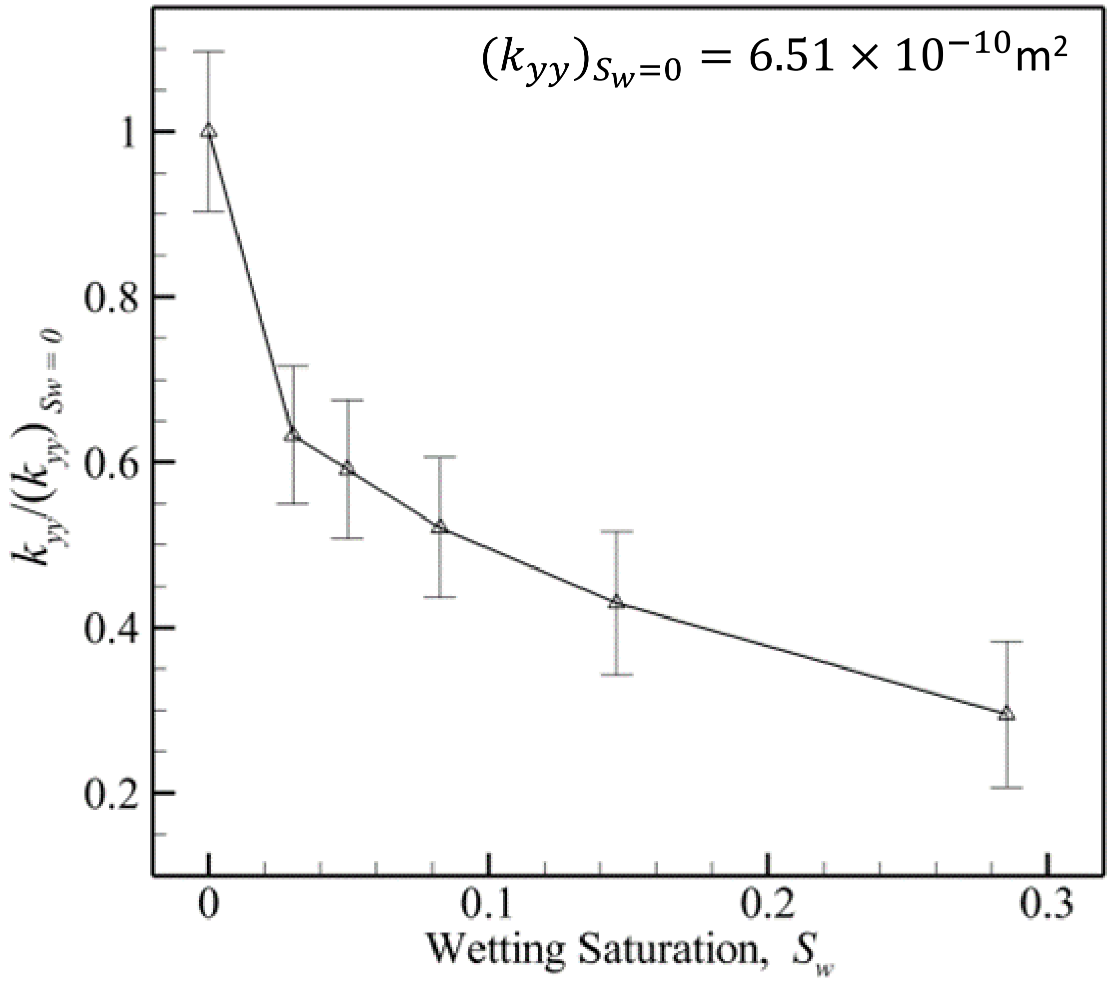




Excellent agreement was observed between the PMM-DPM and VOF-DPM simulation

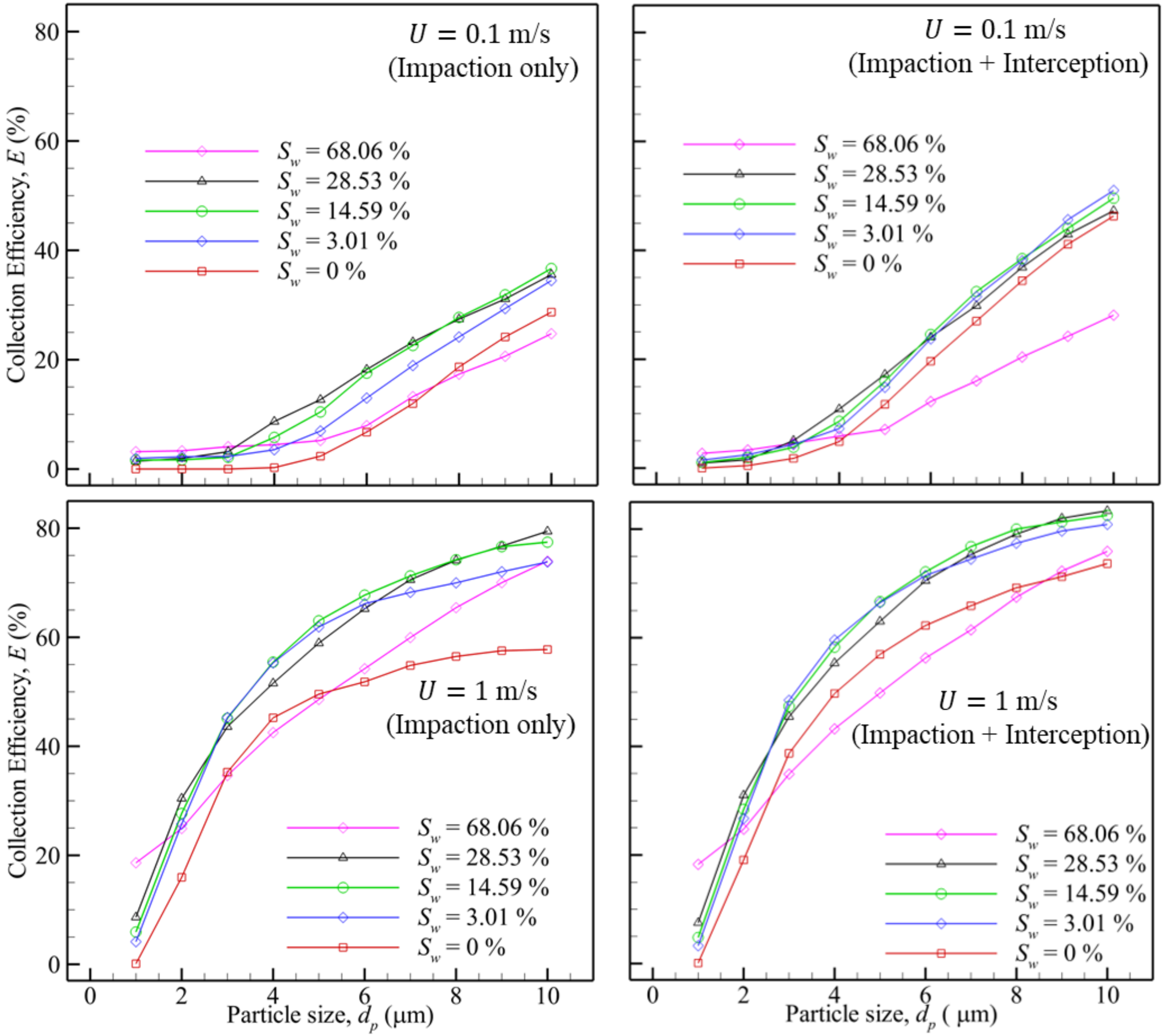
Pressure drop and Permeability





As expected, pressure drop increased with wetting saturation and air permeability decreased with wetting saturation.

Collection Efficiency



Collection efficiency stayed relatively same for low-medium saturation levels but reduced significantly for high-saturation level.

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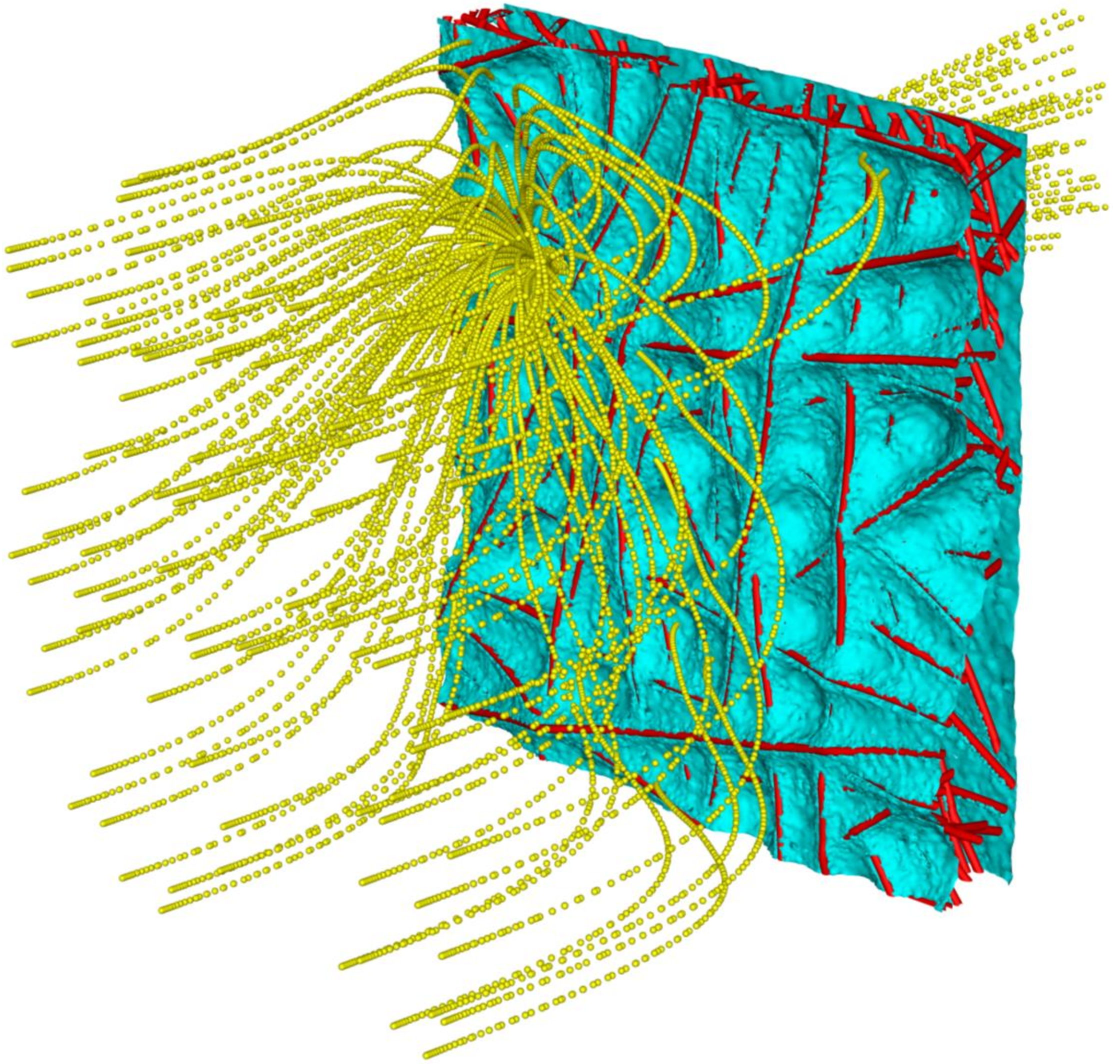
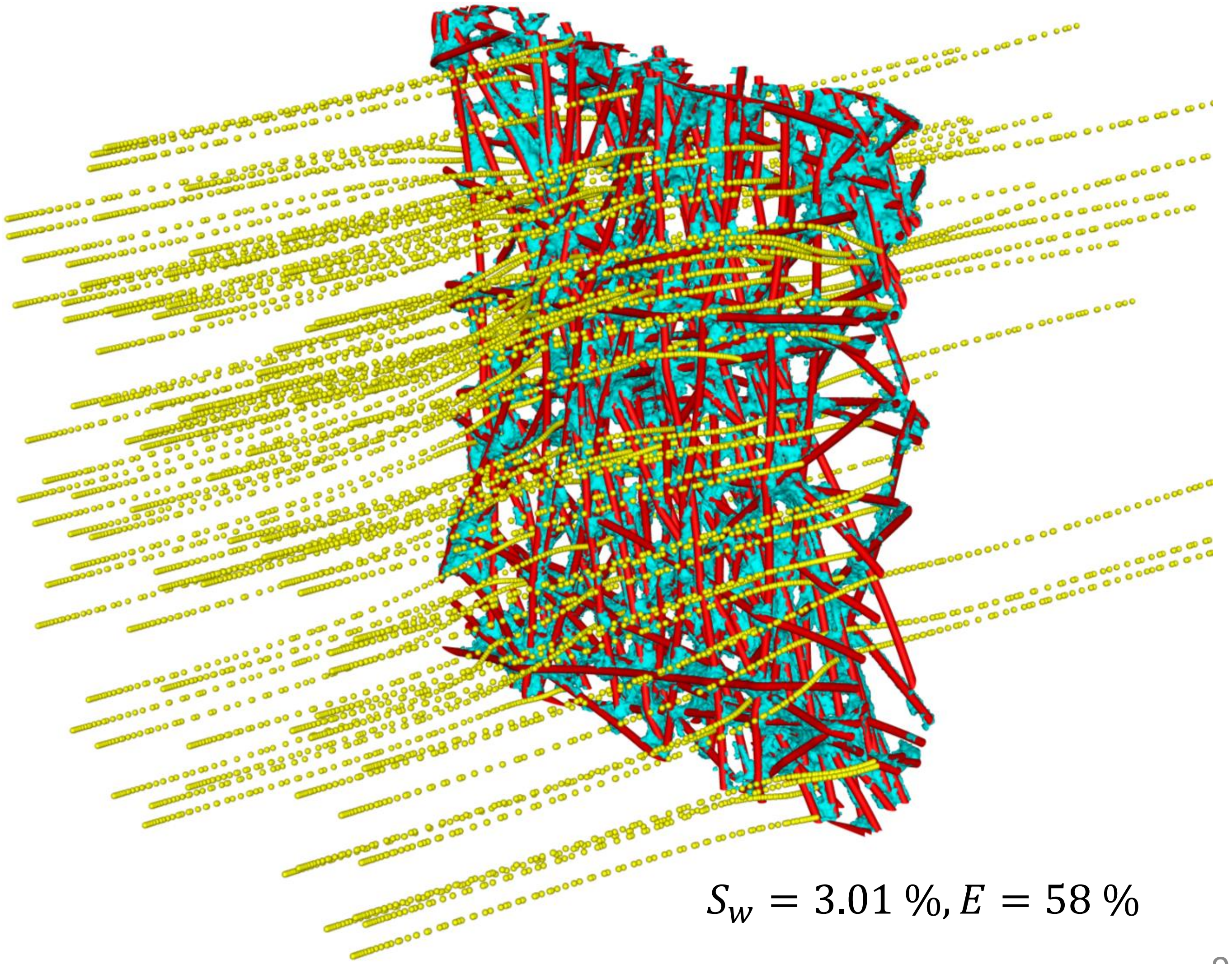
Comparison of particle trajectories

$d_p = 7\ \mu$m
$U = 0.5$ m/s



$S_w = 68.06\ \%, E = 43\ \%$



$S_w = 3.01\ \%, E = 58\ \%$

Conclusions

- A novel PMM-DPM simulation strategy was developed to conduct aerosol droplet filtration simulation using a coalescing filter.
- The PMM models fluid distribution in the fibrous media in a computationally cheap manner while the DPM was used to calculate particle trajectories.
- The collection efficiency of the filter depends primarily on the interaction of air with the fibers section and trapped fluid.
- At higher saturation, the trapped liquid avoids fluid interaction around its vicinity, and concurrently renders some fiber sections unavailable for droplet collection.

Acknowledgements

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