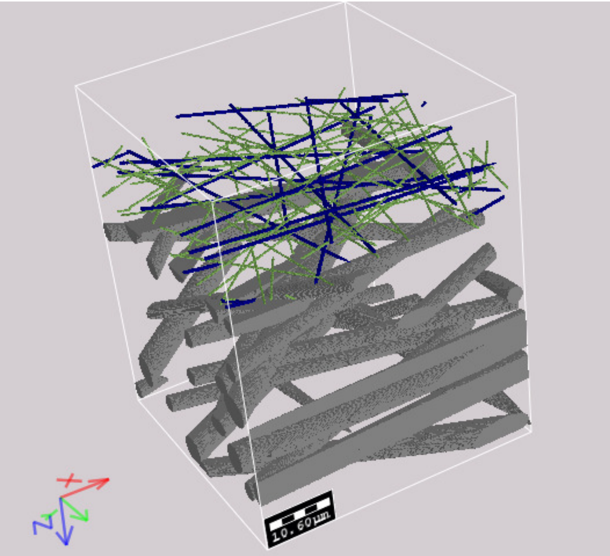
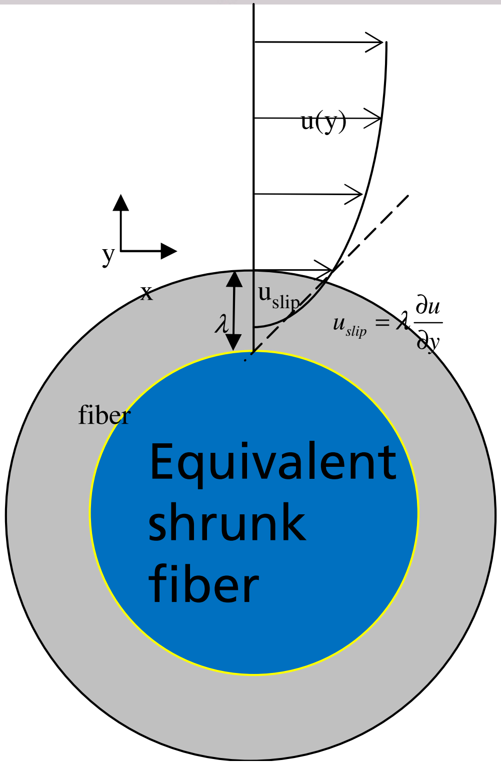




Simulation of nano fibers and filter efficiency

Andreas Wiegmann, Liping Cheng & Stefan Rief

Fraunhofer ITWM

Sponsored by the German ministry for education and research (BMBF)

Introduction

- Nanofiber filter media simulation: what and why?

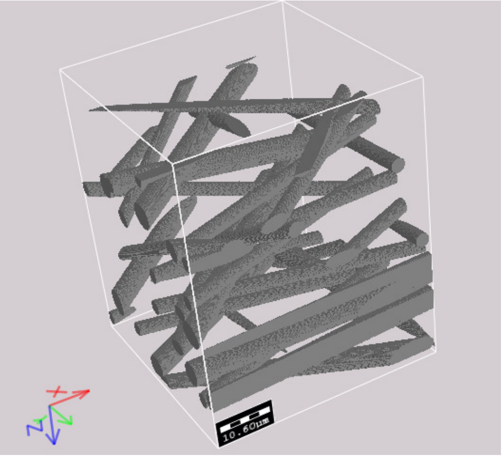
  - Industry: nanofibers have a diameter < 1 μm
  - Marked increase in filter efficiency; small increase of pressure drop
  - Longer life and more dust holding capacity than conventional media
  - Balance between advantages and cost

  - Physics: Fluid flow
  - Physics: Particle adhesion
  - Physics: Particle deposition
  - Simulation challenge: Resolution demands run-time & memory
  - Modeling challenge: Slip instead of no-slip boundary condition

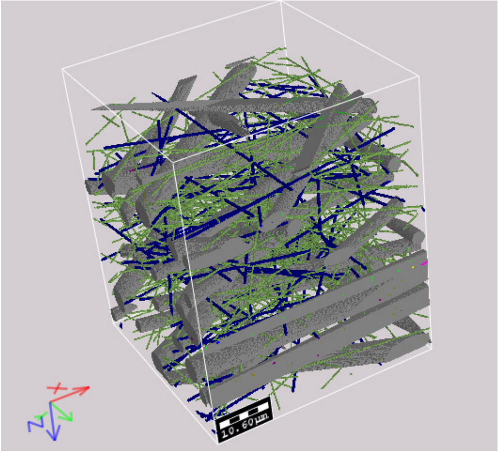
Micro fibers vs. embedded nano fibers vs nano fiber layers

Medium 1: 3 and 5 µm fibers ; SVF10%
Medium 2: + 0.3 µm,0.5µm fibers (SVF +1%)
Medium 3: with 5 µm nano fiber layer
Medium 4: with 10 µm nano fiber layer

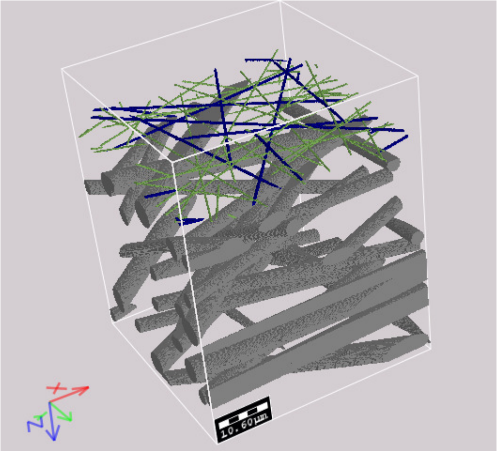
Voxel length: 100nm
Medium size: 512 x 512 x 512



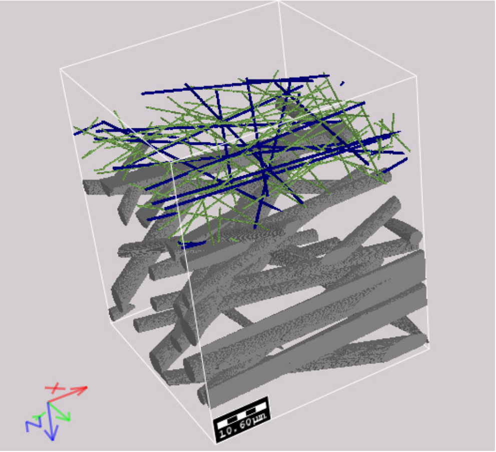
Medium 1



Medium 2



Medium 3

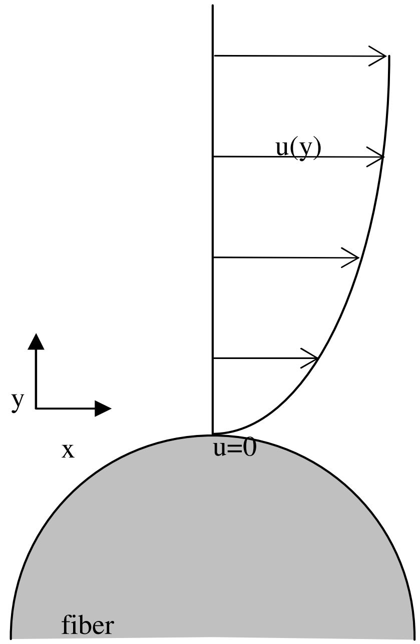


Medium 4

Method

- **Eulerian Description of Stationary Stokes Flow**
  No-Slip boundary condition

$$
\begin{aligned}
-\mu\Delta\vec{u} + \nabla p &= 0 \text{ (momentum balance)} \\
\nabla\cdot\vec{u} &= 0 \text{ (mass conservation)} \\
\vec{u} &= 0 \text{ on } \Gamma \text{ (no-slip on fiber surfaces)} \\
P_{in} &= P_{out} + c \text{ (pressure drop is given)}
\end{aligned}
$$

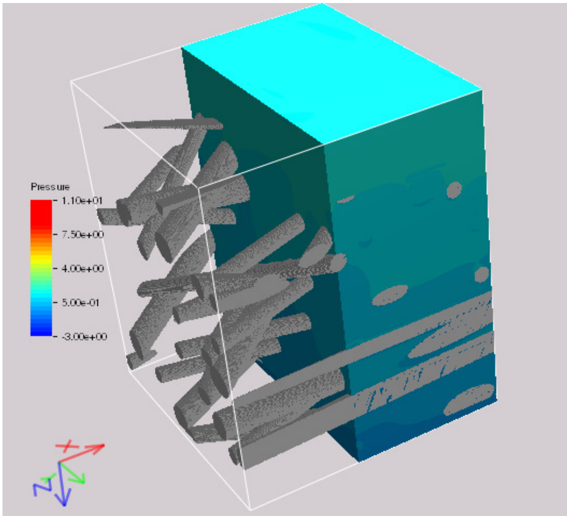


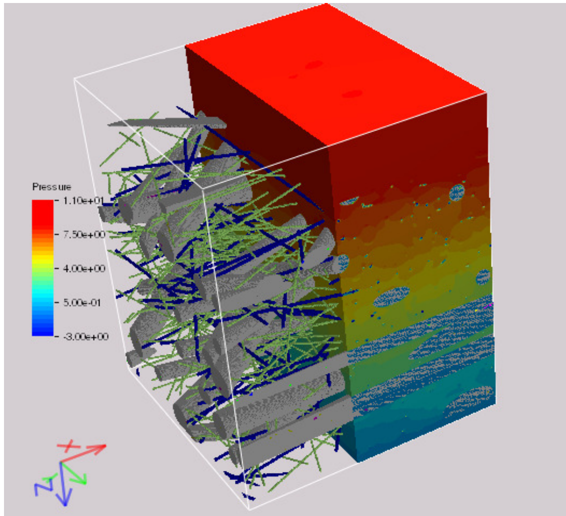
μ : fluid viscosity,
$\vec{u}$: velocity, periodic,
p : pressure, periodic up to pressure drop in flow direction.

Micro fibers vs. Micro+Nano fibers
(no-slip boundary condition)

Medium 1 | Medium 2

Pressure



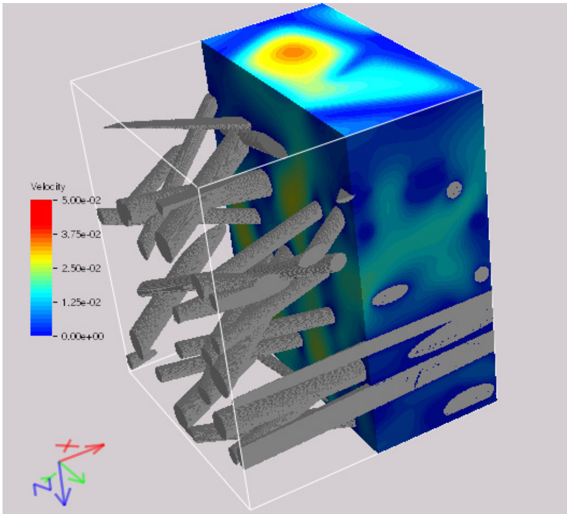


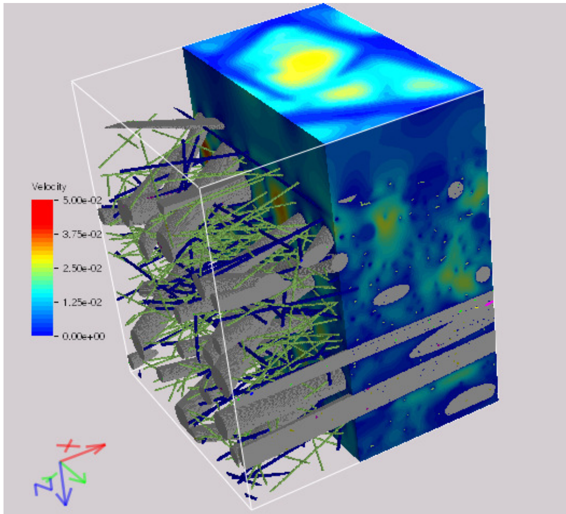
at mean velocity 0.01m/s

ΔP= 1.45 Pa

ΔP= 8.25Pa

Velocity





Method: Particle Motion

$$d\vec{v} = -\gamma \times \left(\vec{v}(\vec{x}(t)) - \vec{u}(\vec{x}(t))\right) dt + \sigma \times d\vec{W}(t),$$

$$d\vec{x} = \vec{v}(\vec{x}(t))dt,$$

$$\sigma^2 = \frac{2k_B T\gamma}{m},$$

$$\gamma = 6\pi\rho\mu\frac{R}{m},$$

$$\langle dW_i(t), dW_j(t)\rangle = \delta_{ij}dt.$$

- $\vec{u}$: fluid velocity
- $\vec{v}$: particle velocity
- t : time
- T : temperature
- γ : friction coefficient
- R : particle radius
- ρ : fluid density
- μ : fluid viscosity
- $\vec{W}$: Wiener Measure (3d)
- k_b : Boltzmann constant
- m : particle mass
- Kn : Knudsen number

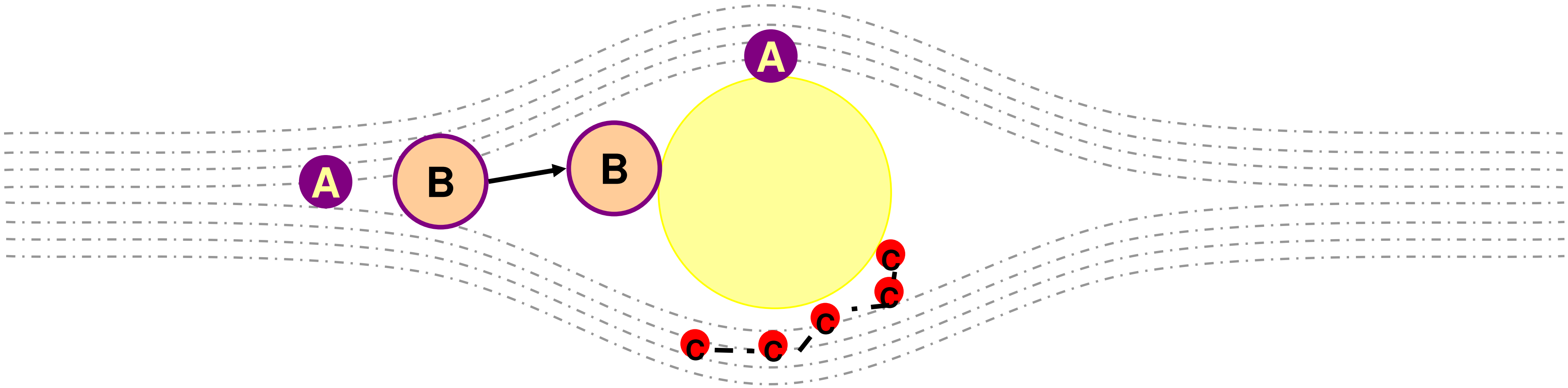
A. Latz and A. Wiegmann, *Simulation of fluid particle separation in realistic three dimensional fiber structures*, Filtech, Düsseldorf, October 2003.

Filtration Effects I

A: direct interception

B: inertial impaction

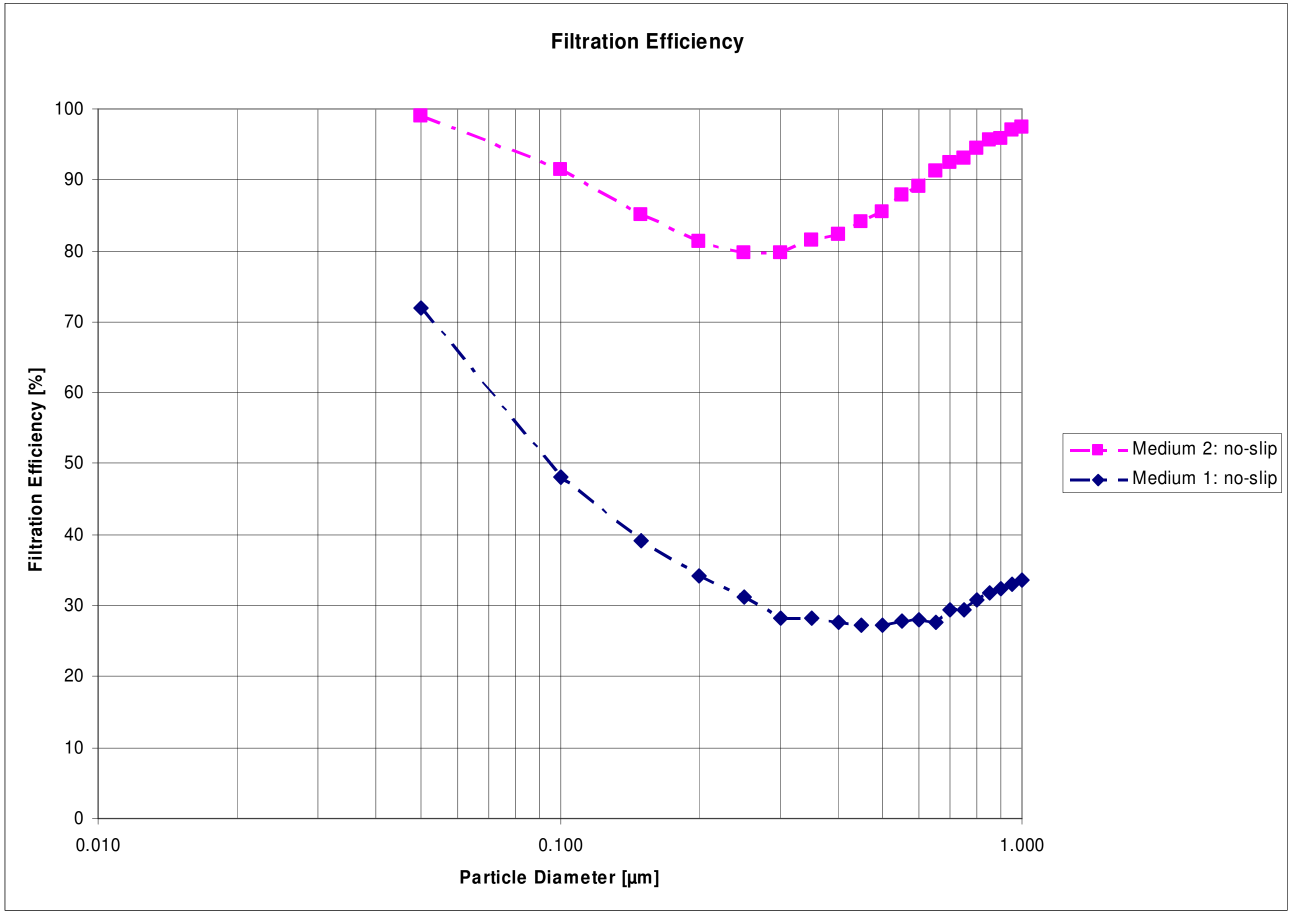
C: diffusional deposition

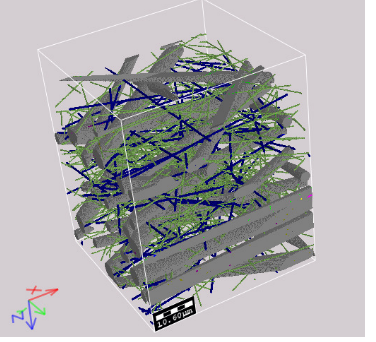


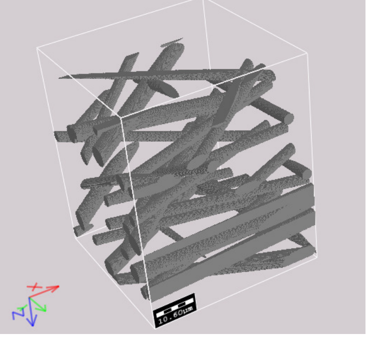
Micro fibers vs. Micro + Nano fibers

- Air at 20°C
- NaCl, d_p 50 to 1000 nm; 1 cm/s

Media	1	2
ΔP	1.45	8.25



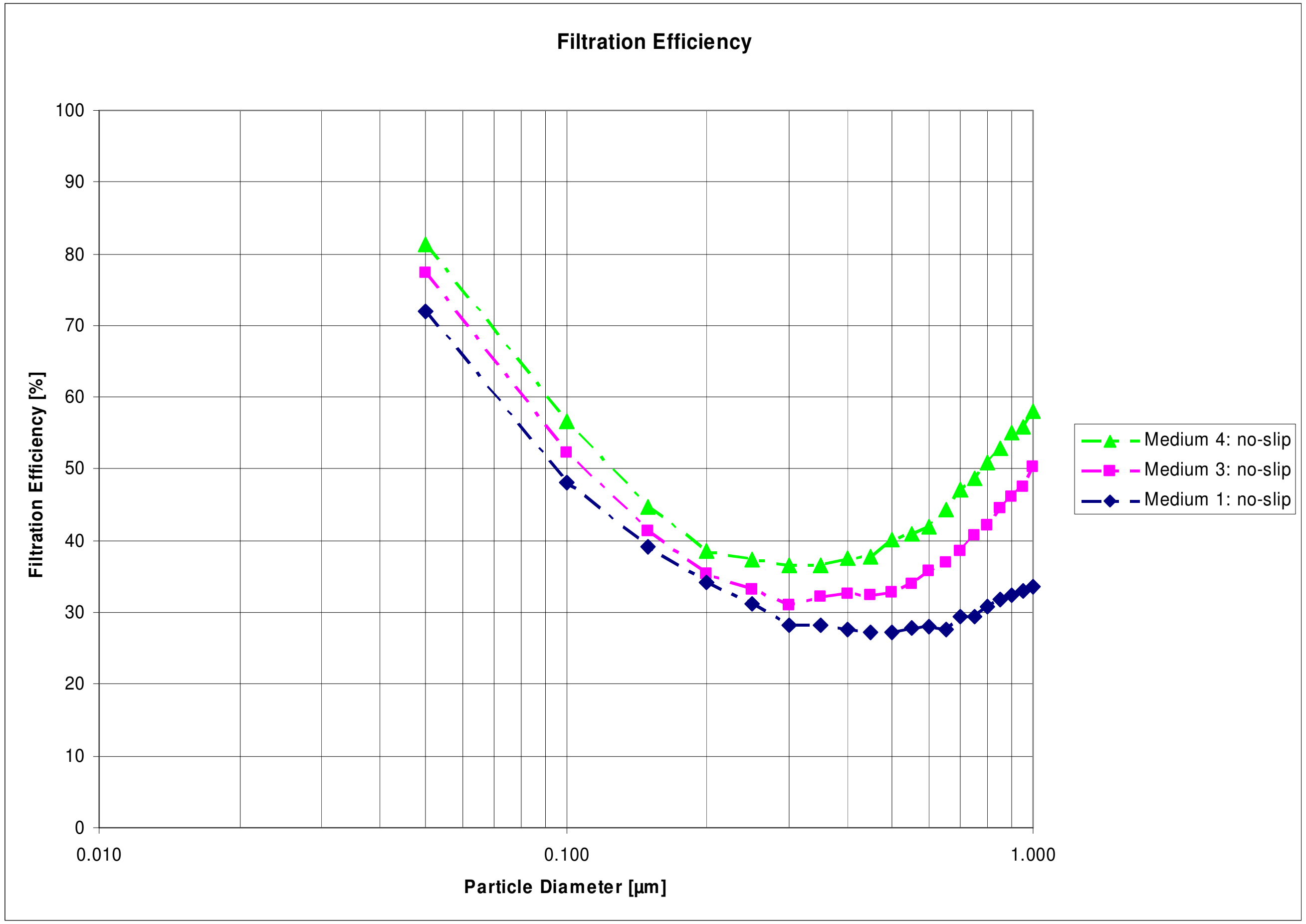


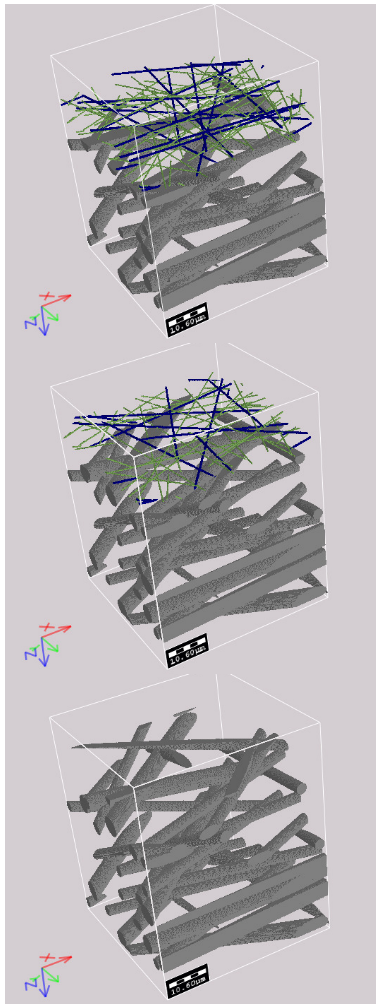


Micro fibers vs. Nano fiber layer

- Air at 20°C
- NaCl, d_p 50 to 1000 nm; 1 cm/s

Media	1	3	4
ΔP	1.45	1.99	2.16



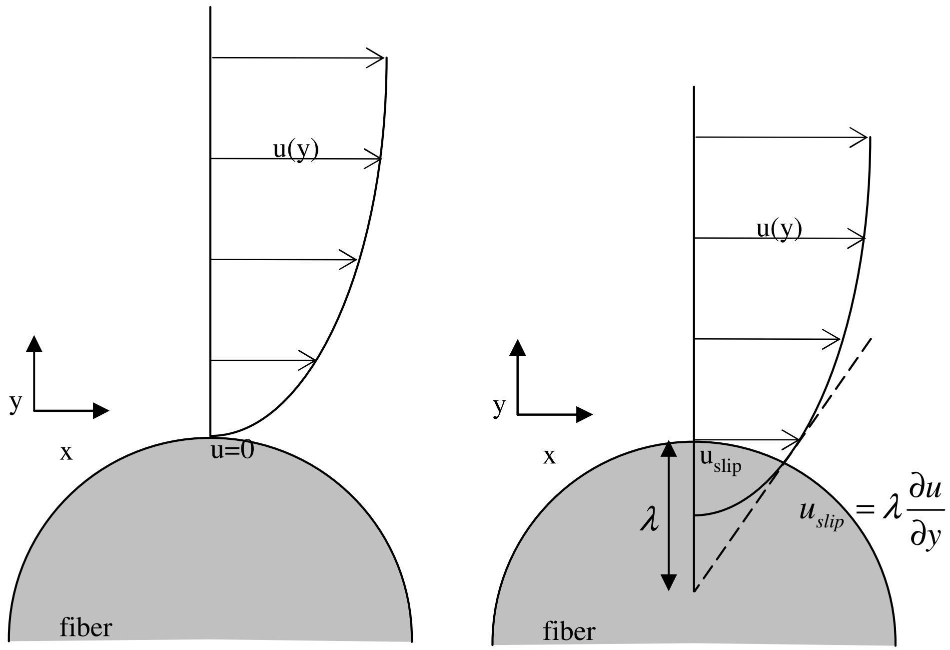


Slip boundary condition

Slip models the tangential velocity as proportional to the shear stress [1,2]

$$u = \lambda \frac{\partial u}{\partial y}$$

λ , the slip length
in air at 20° C is ~ 100 nm.



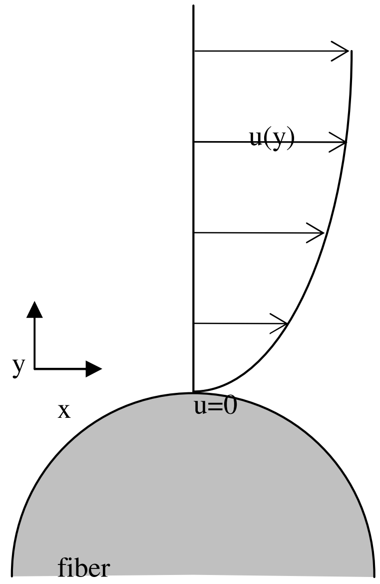
No-Slip boundary condition

Slip boundary condition

[1] C. L. M. H. Navier, Mem. Acad. R. Sci. Inst. France 1, 414 (1823).

[2] S. Goldstein, Modern Developments in Fluid Dynamics (Dover, New York, 1965), vol. 2, p. 676

➢ Eulerian Description of Stationary Stokes Flow
No slip vs fractional slip boundary condition

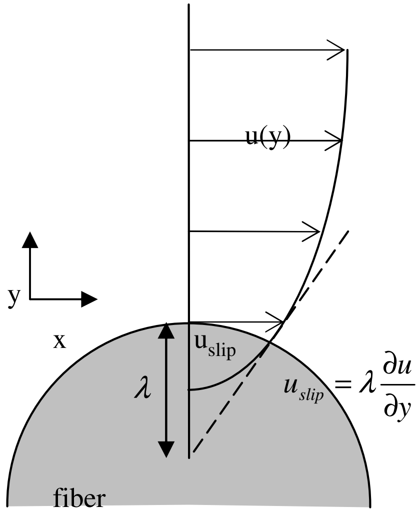


$$
\begin{aligned}
-\mu\Delta\vec{u} + \nabla p &= 0 \text{ (momentum balance)} \\
\nabla \cdot \vec{u} &= 0 \text{ (mass conservation)} \\
\vec{u} &= 0 \text{ on } \Gamma \text{ (no-slip on fiber surfaces)} \\
P_{in} &= P_{out} + c \text{ (pressure drop is given)}
\end{aligned}
$$

μ : fluid viscosity,

$\vec{u}$: velocity, periodic,

p : pressure, periodic up to pressure drop in flow direction.



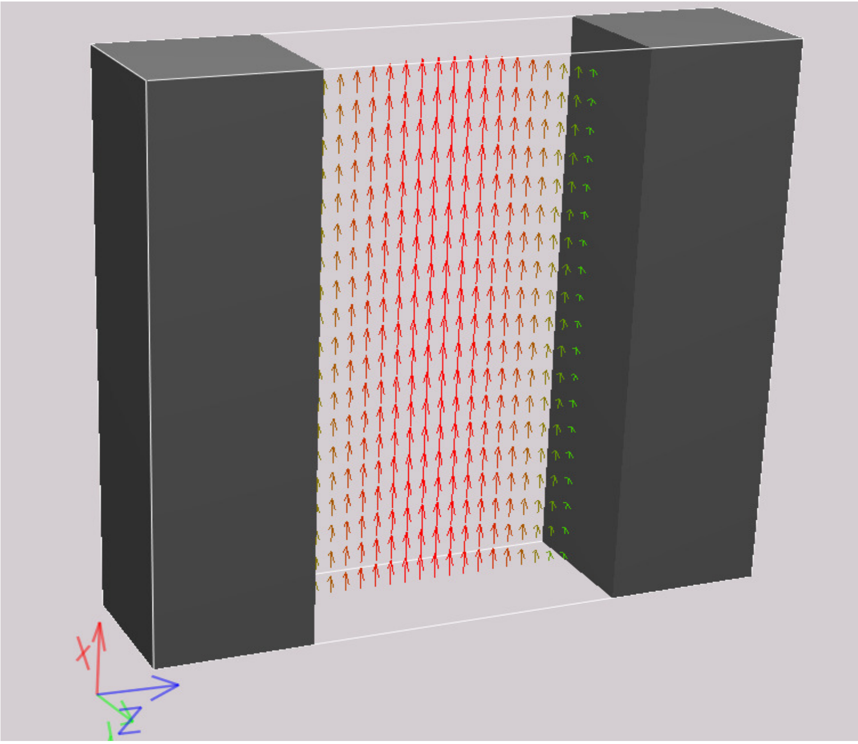
$$
\begin{aligned}
-\mu\Delta\vec{u} + \nabla p &= 0 \text{ (momentum balance)} \\
\nabla \cdot \vec{u} &= 0 \text{ (mass conservation)} \\
\vec{n} \cdot \vec{u} &= 0 \text{ on } \Gamma \text{ (no flow into fibers)} \\
\vec{t} \cdot \vec{u} &= -\lambda \vec{n} \cdot \nabla \left(\vec{u} \cdot \vec{t}\right) \text{ on } \Gamma \text{ (slip flow along fibers)} \\
P_{in} &= P_{out} + c \text{ (pressure drop is given)}
\end{aligned}
$$

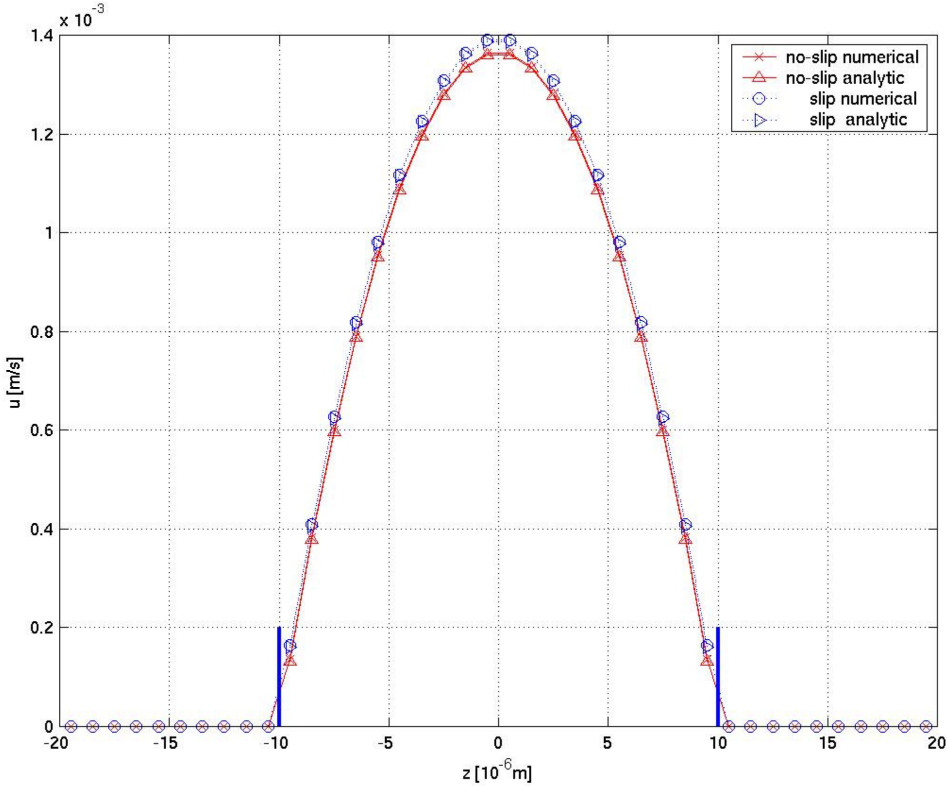
$\vec{n}$: normal direction to the fiber surface,

λ : slip length,

$\vec{t}$: any tangential direction with $\vec{t} \cdot \vec{n} = 0$.

Benchmark: parabola-shaped Poiseulle profile
(flow between two infinite and parallel plates)

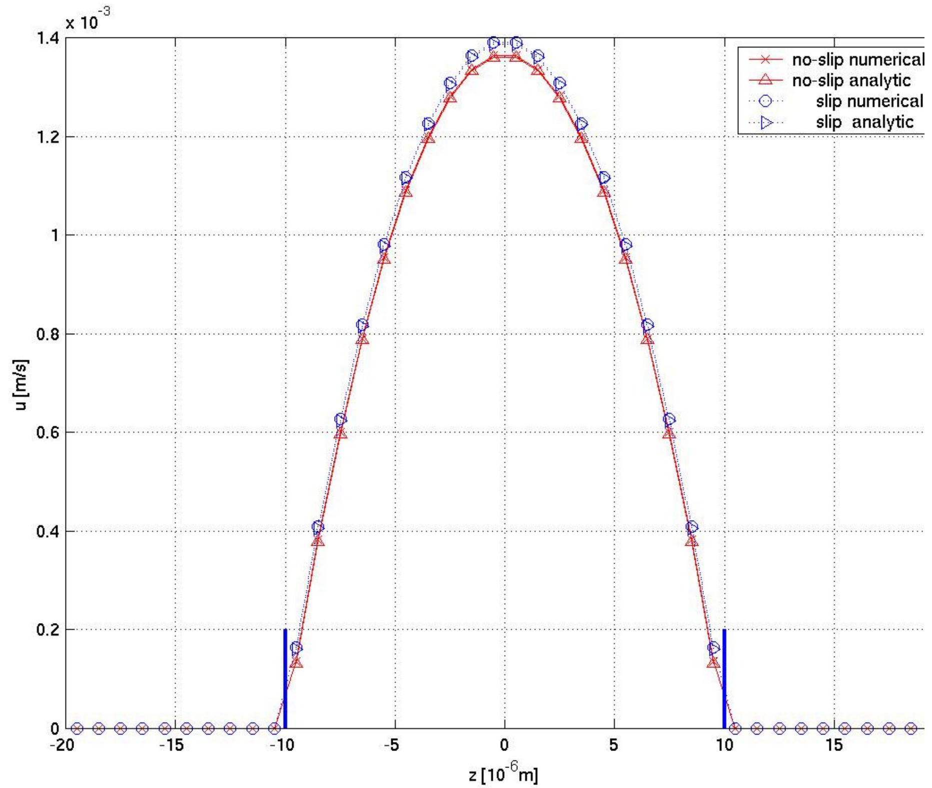




Distance between plates = 20µm;

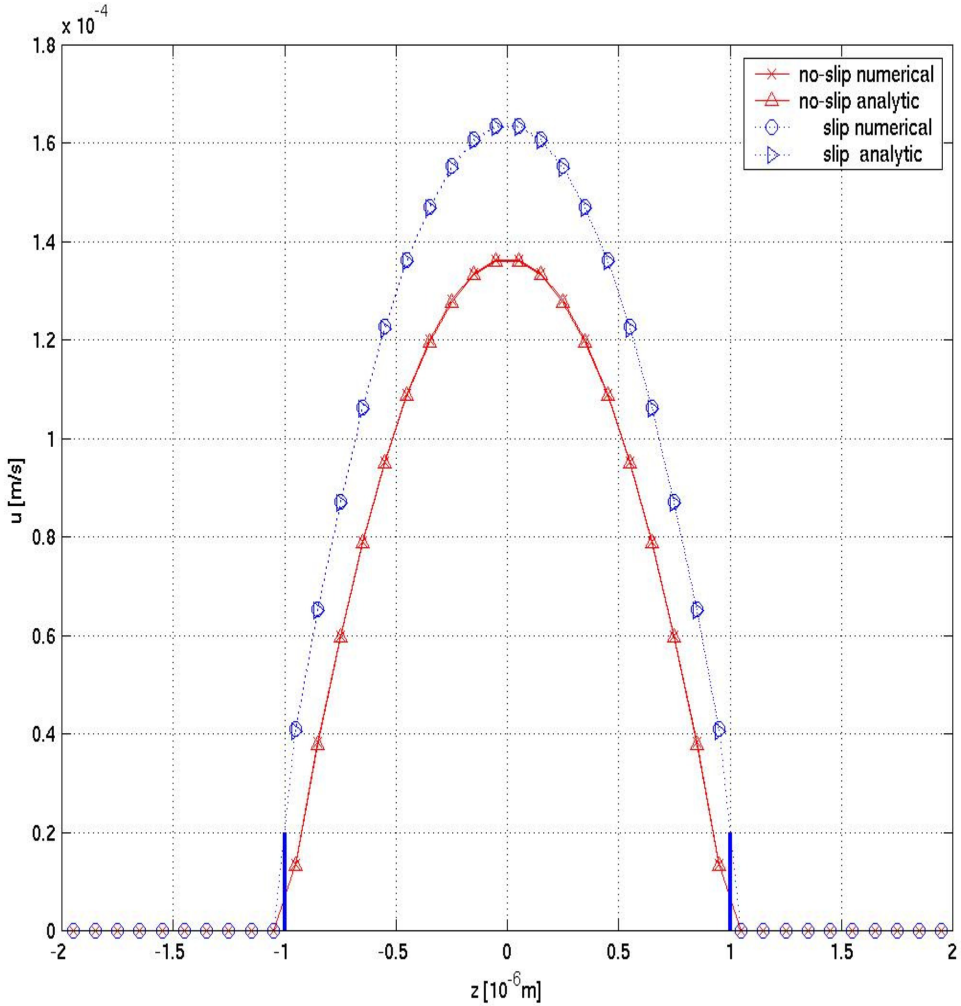
λ = 100 nm; dp/L = 5000Pa/m;

Benchmark: parabola-shaped Poiseulle profile
(flow between two infinite and parallel plates)



Distance between plates = 20μm;

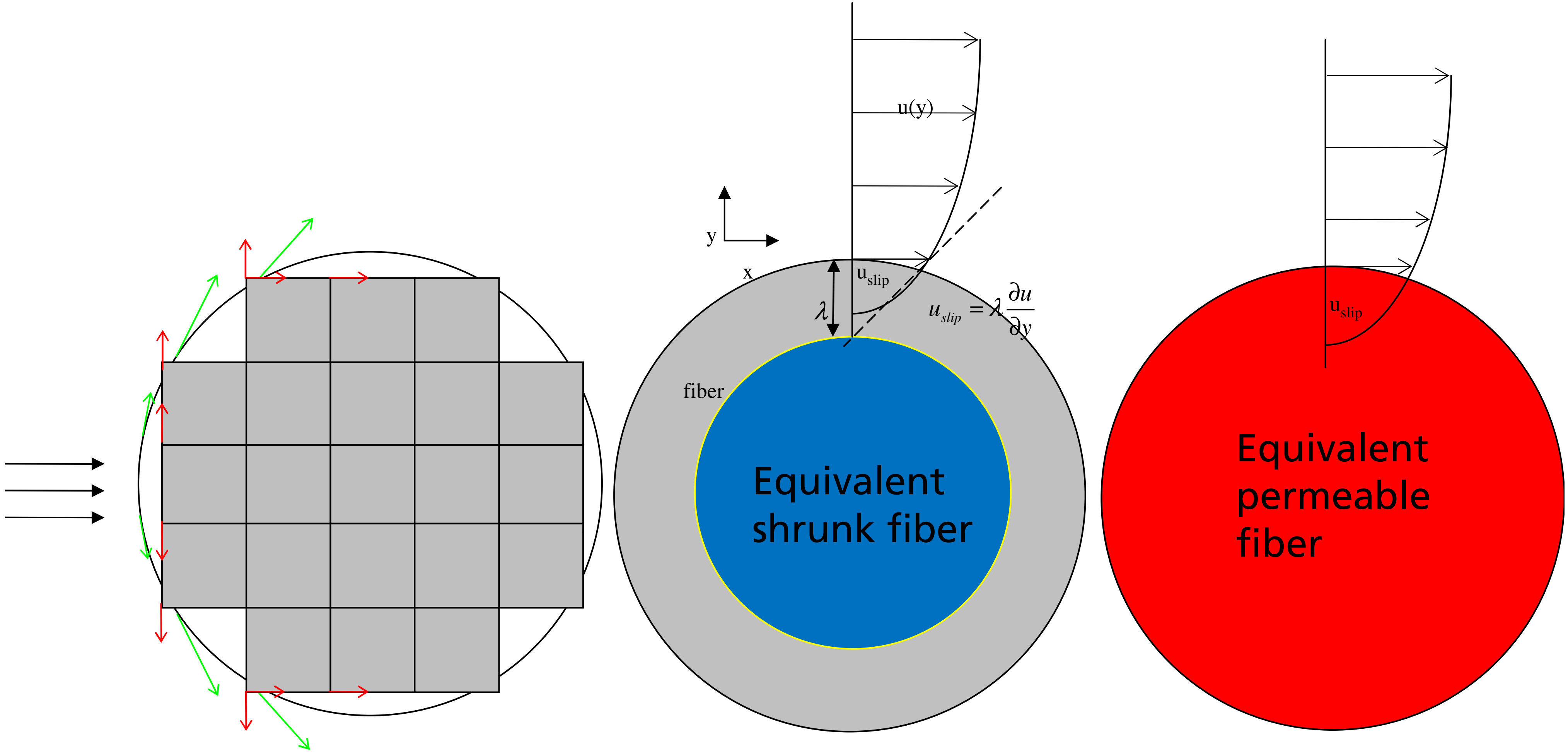
λ = 100 nm; dp/L = 5000Pa/m;



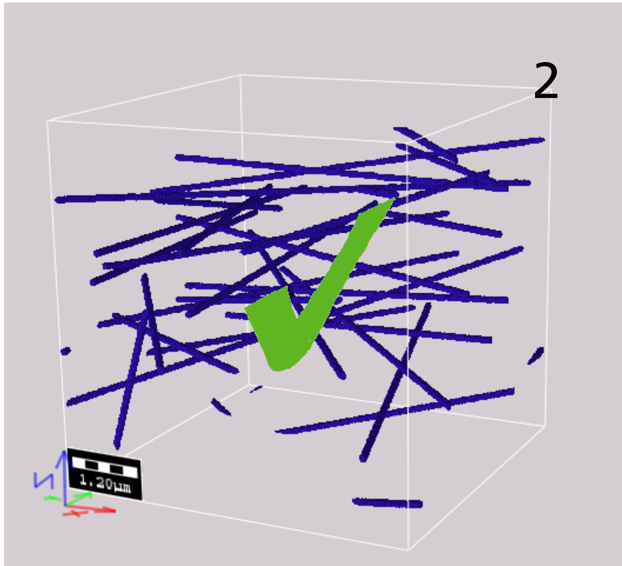
Distance between plates 2μm;

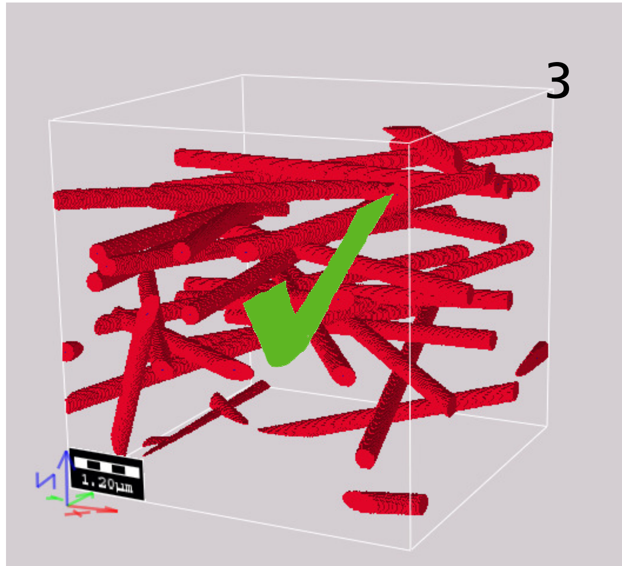
λ = 100 nm; dp/L = 5000Pa/m;

Voxelized fiber
Equivalent shrunk fibers with no-slip and
Equivalent permeable fibers (replace b.c. by NS-Brinkman equ.)

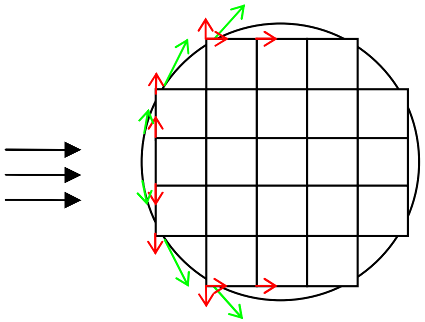


3 ways to simulate slip flow





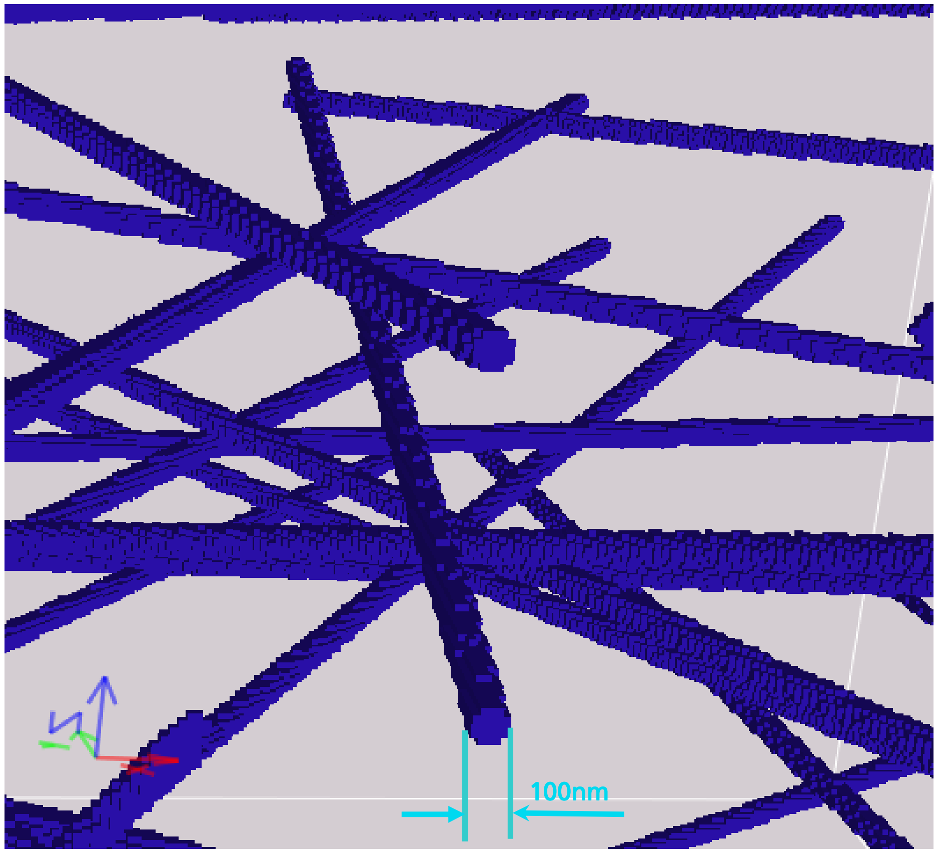
flow

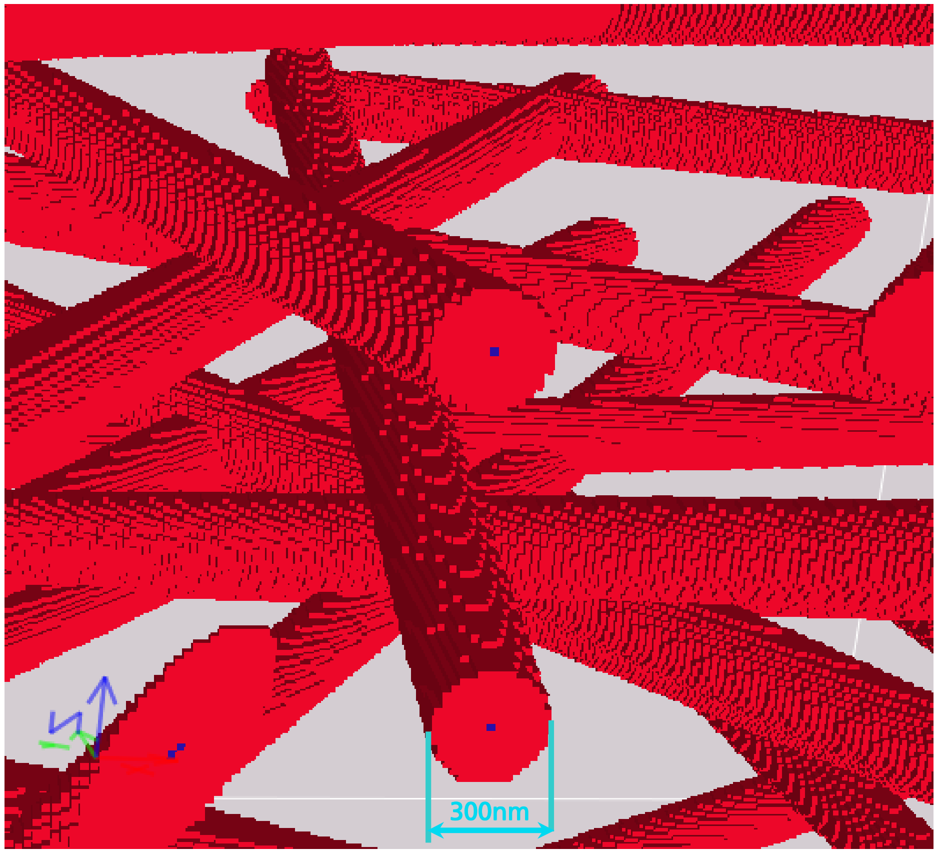


- Equivalent shrunk fibers with no-slip
- Fast
- Requires 1 for collisions

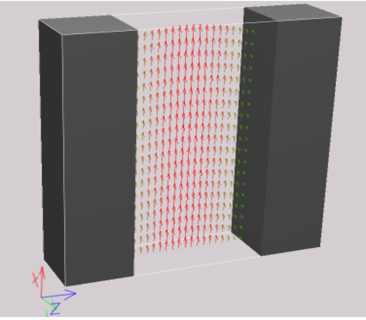
- Equivalent permeability fibers with no-slip on core
- Slower
- Can be used for collisions

Detail: Equivalent shrunk and equivalent permeable fibers





Benchmark: parabola-shaped Poiseulle profile
(flow between two infinite and parallel plates)

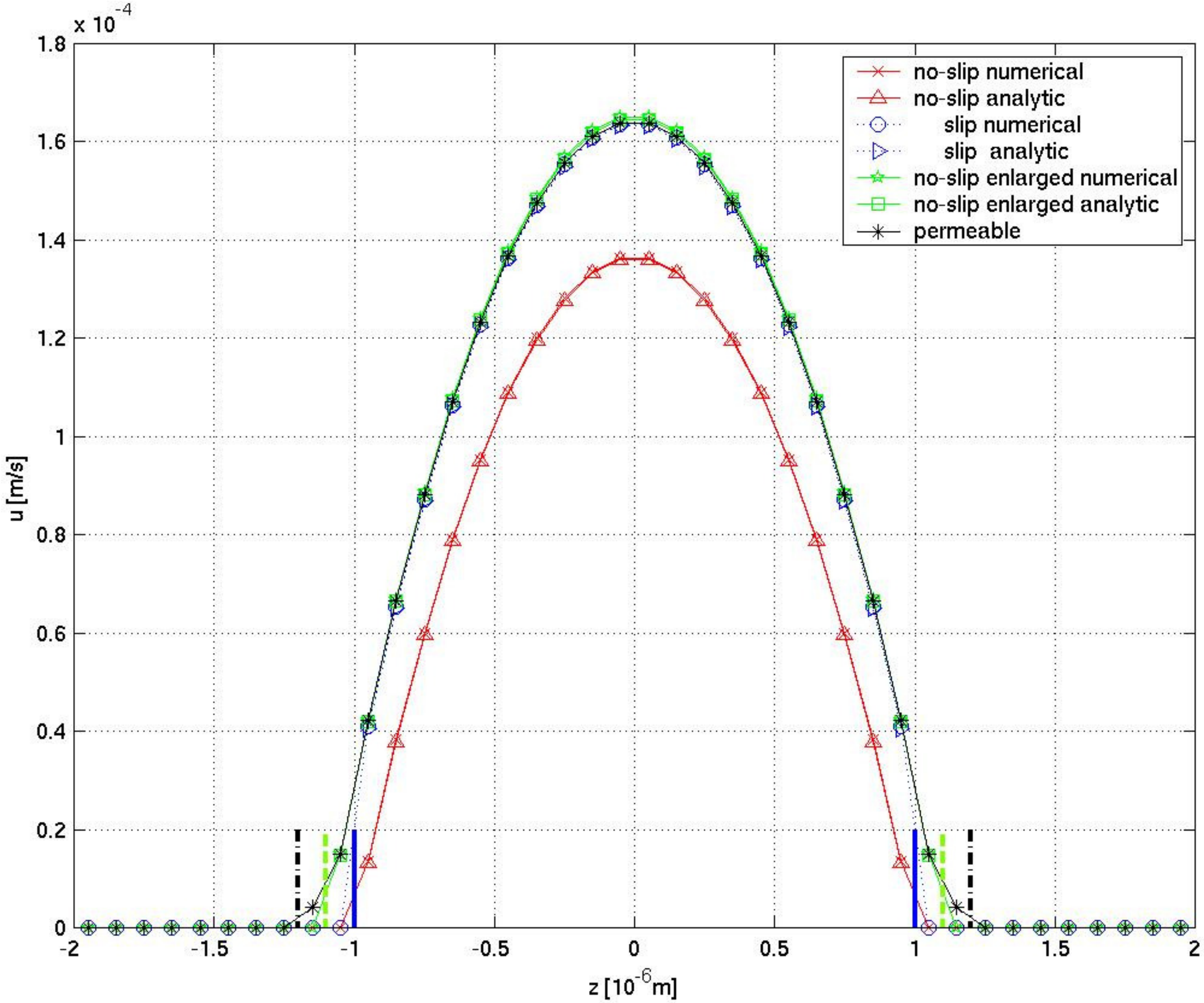


Distance between plates

2 µm

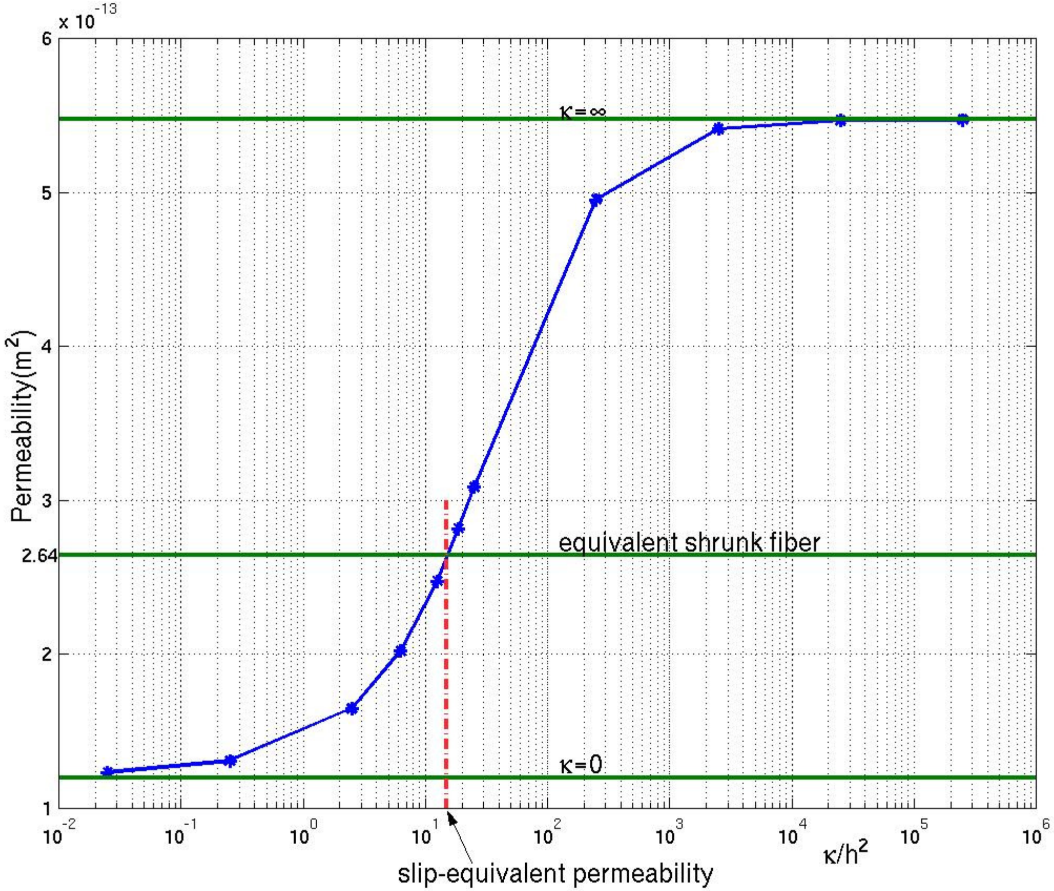
λ = 100 nm

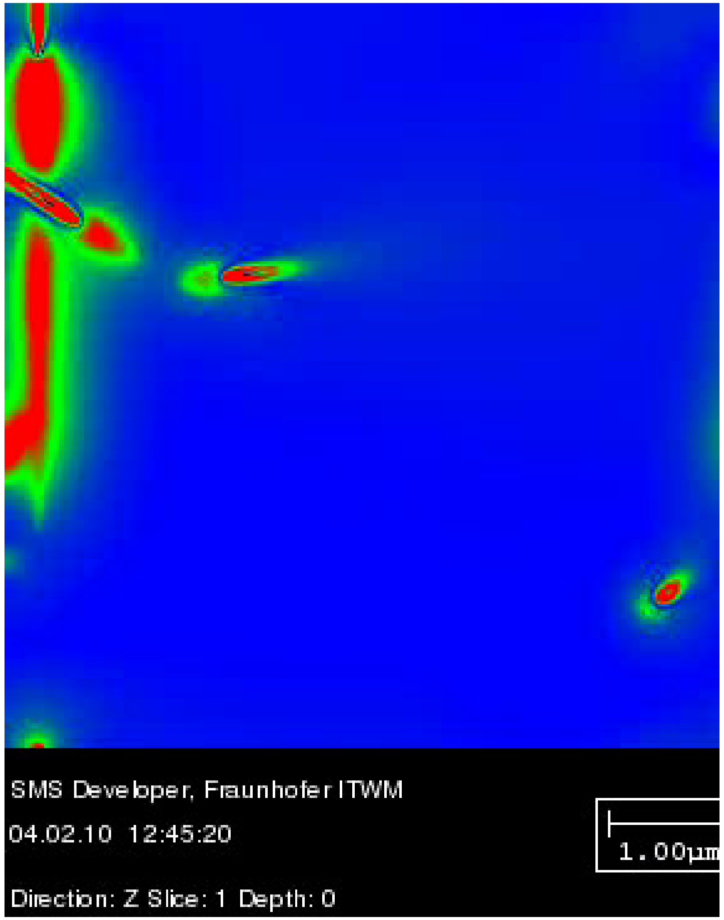
dp/L = 5000Pa/m



Permeable zones (blue – black), equivalent permeability is found by getting the same mean velocity as equivalent shrunk fiber

Permeability of equivalent permeable fibers



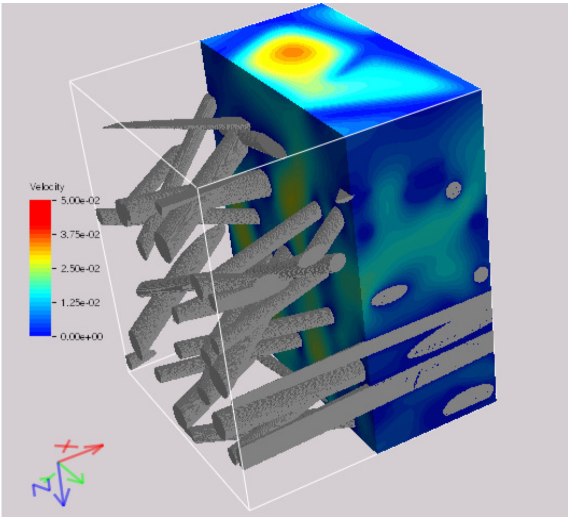


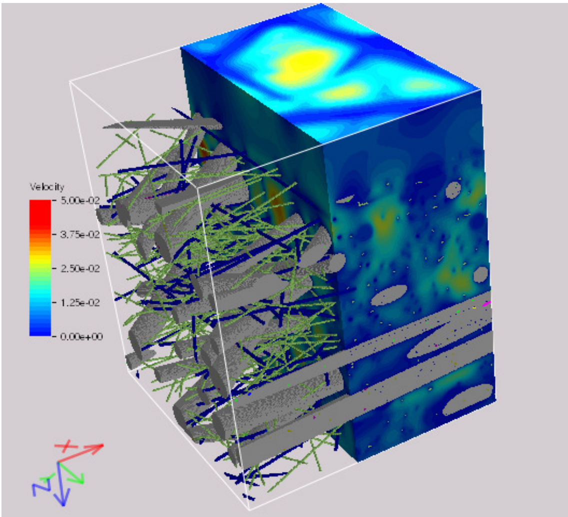
Voxel length: 20nm
Size: 300 x 300 x 300

Difference between flow fields from equivalent permeable fibers and equivalent shrunk fibers

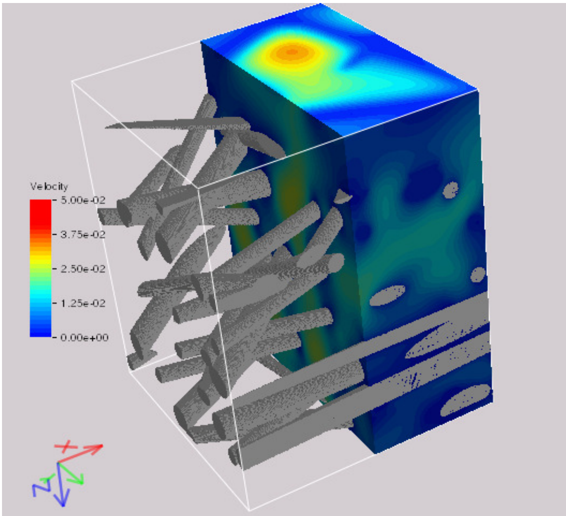
Local Velocity: no-slip vs slip flow

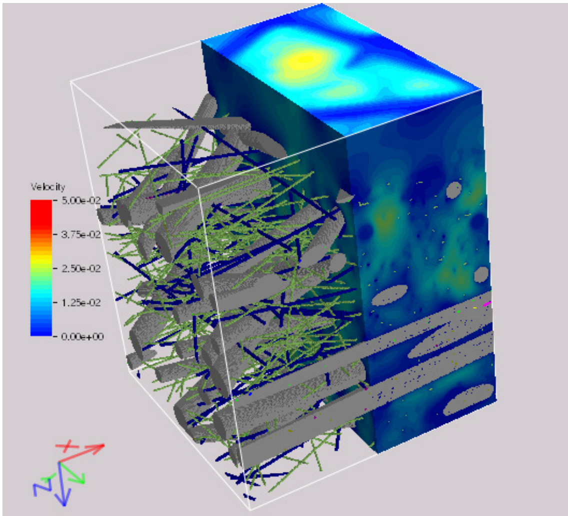
No_slip





Slip



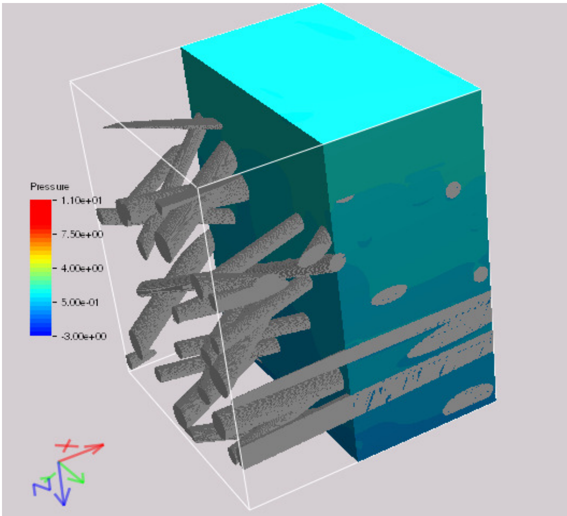


Medium 1 Medium 2

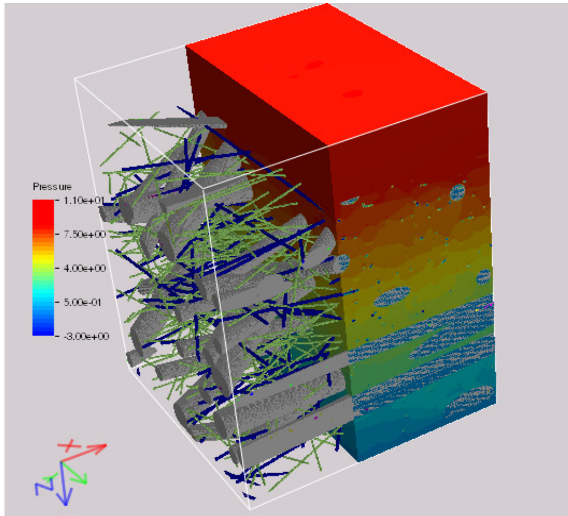
Mean velocity 0.01m/s

Local pressure: no-slip vs slip flow

No_slip

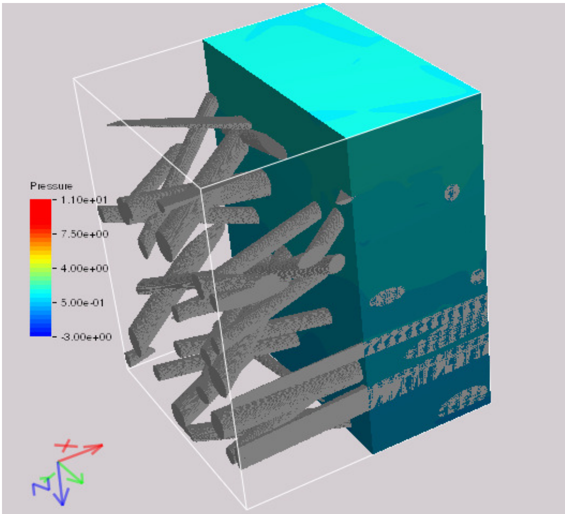


ΔP=1.45 Pa

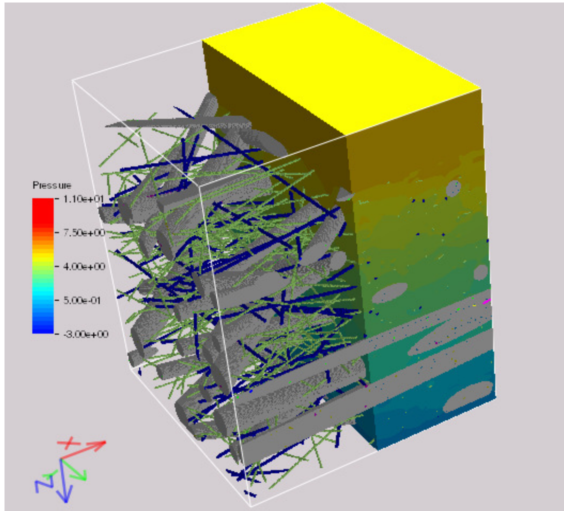


ΔP=8.25 Pa

Slip



ΔP= 1.34 Pa



ΔP= 5.44 Pa

Medium 1: diff 7.6%

Medium 2: diff 34%

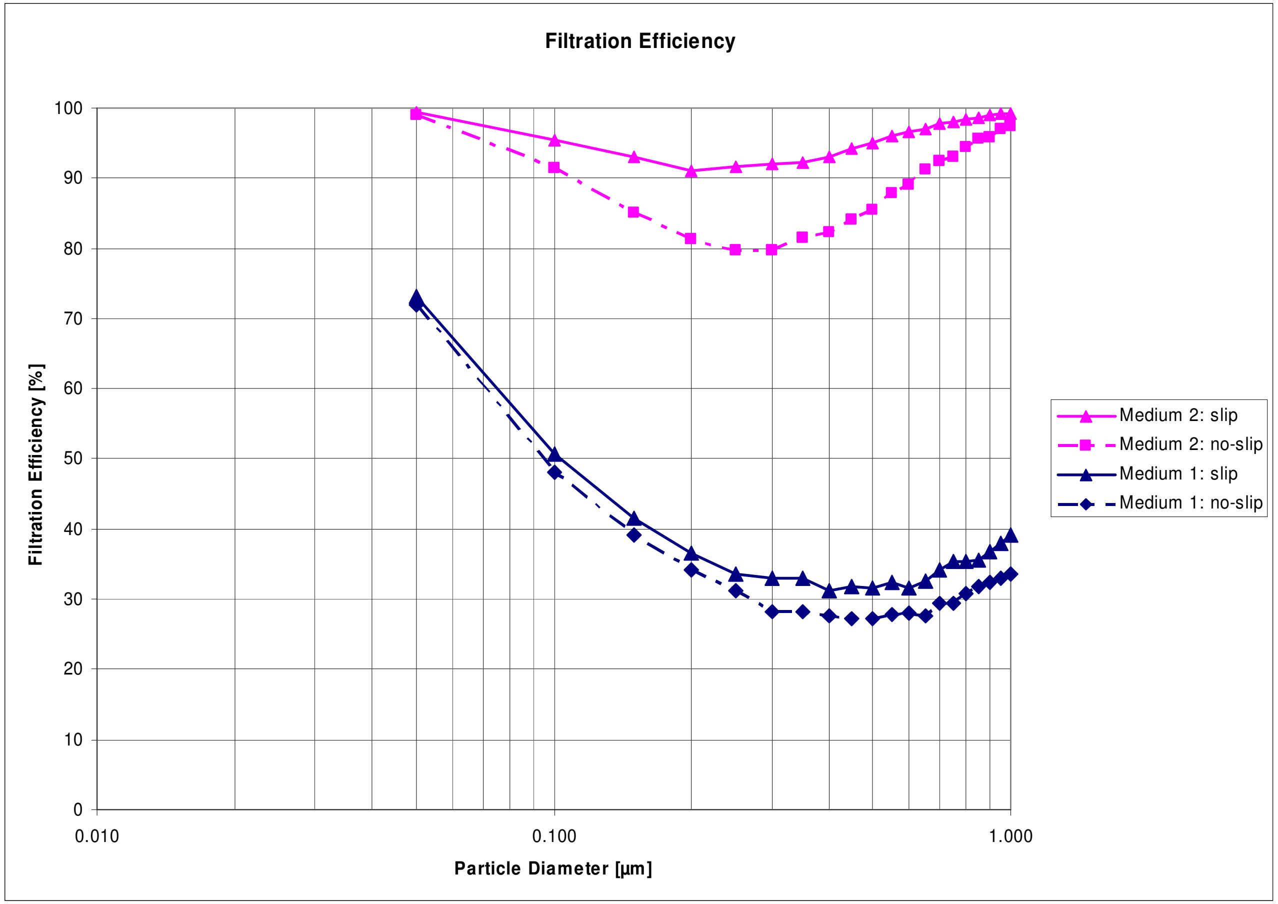
Mean velocity 0.01m/s

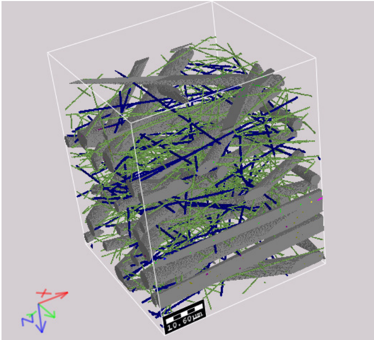
Result I: Micro fibers vs. Nano fibers

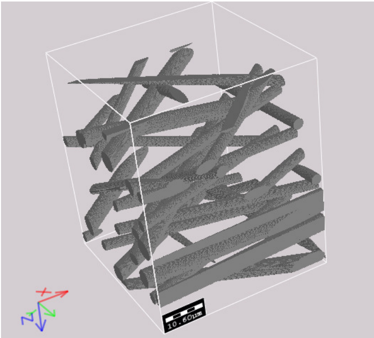
- Pressure drop at 1cm/s

Media	1	2
ΔP (no-slip)	1.45	8.25
ΔP (slip)	1.34	5.44

- Filter efficiency





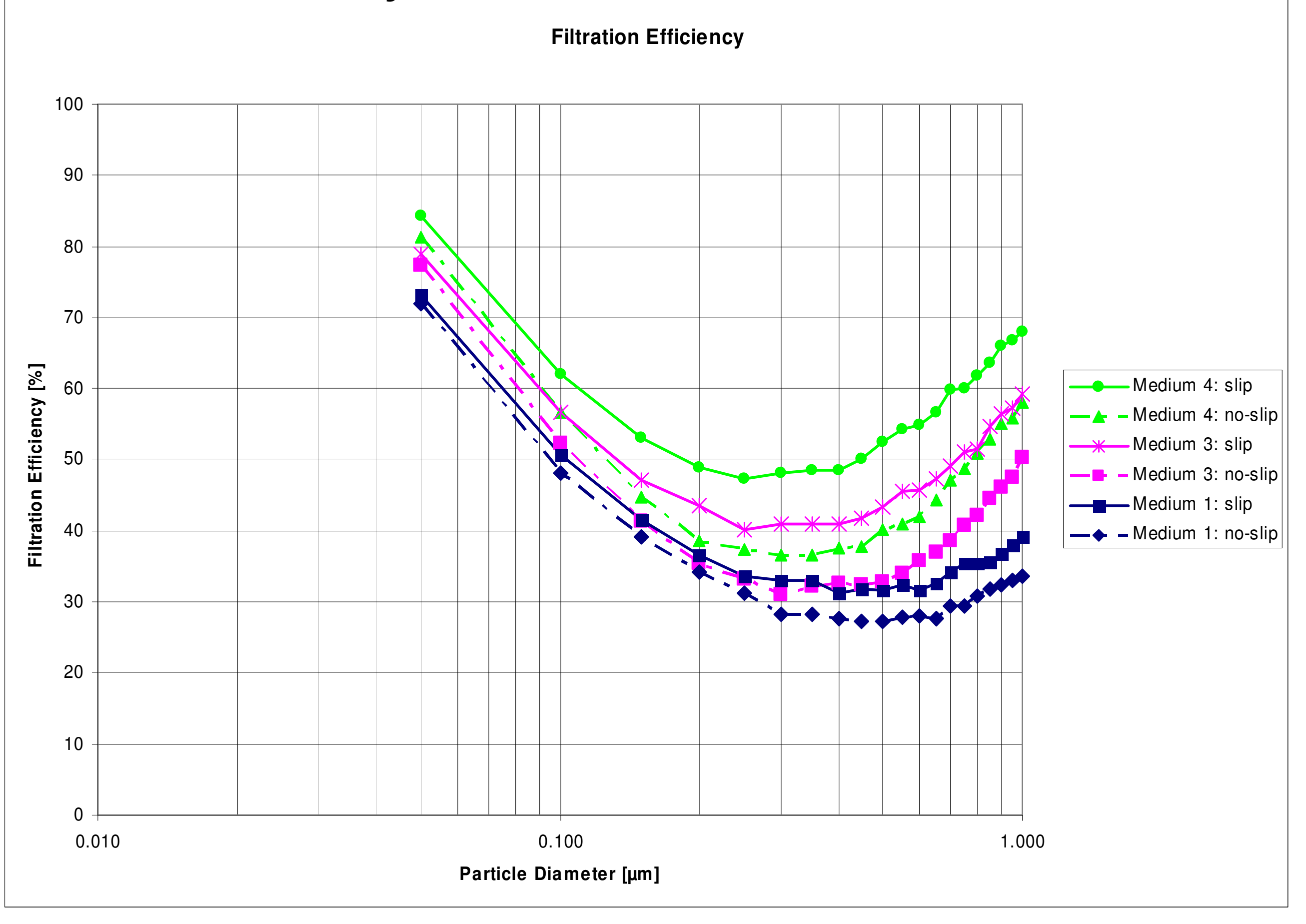


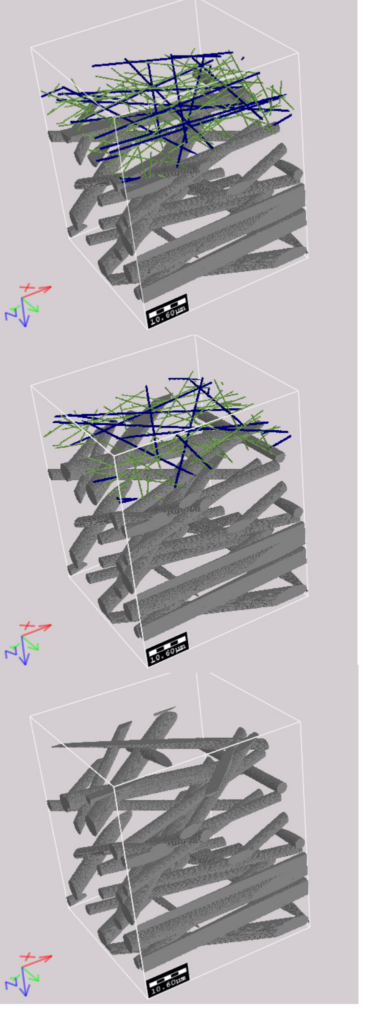
Micro fibers vs. Nano fiber layer

- Pressure drop at 1cm/s

Media	1	3	4
ΔP(no-slip)	1.45	1.99	2.16
ΔP(slip)	1.34	1.63	1.68

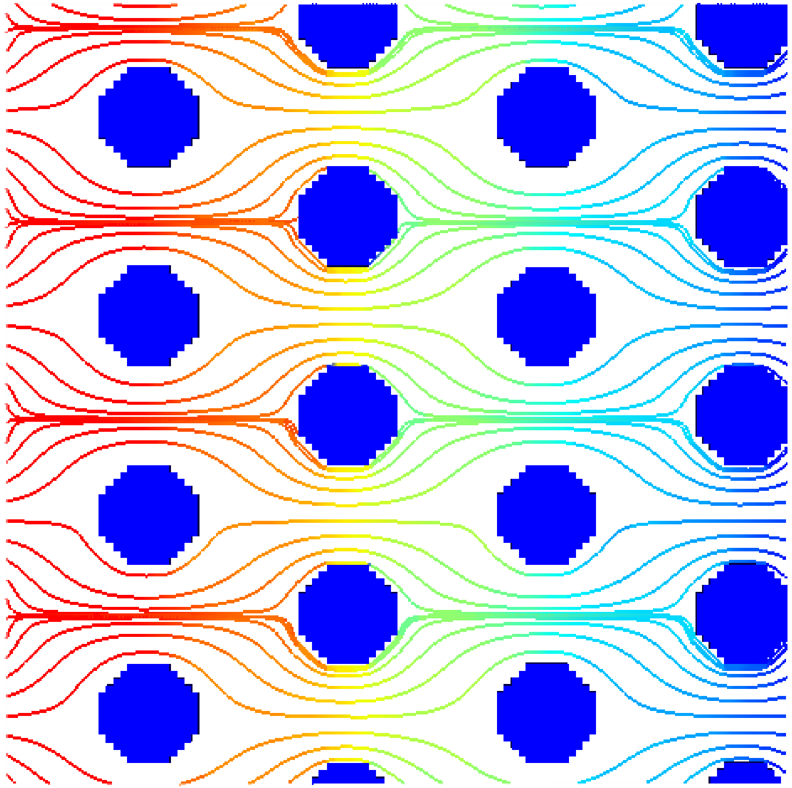
- Filter efficiency



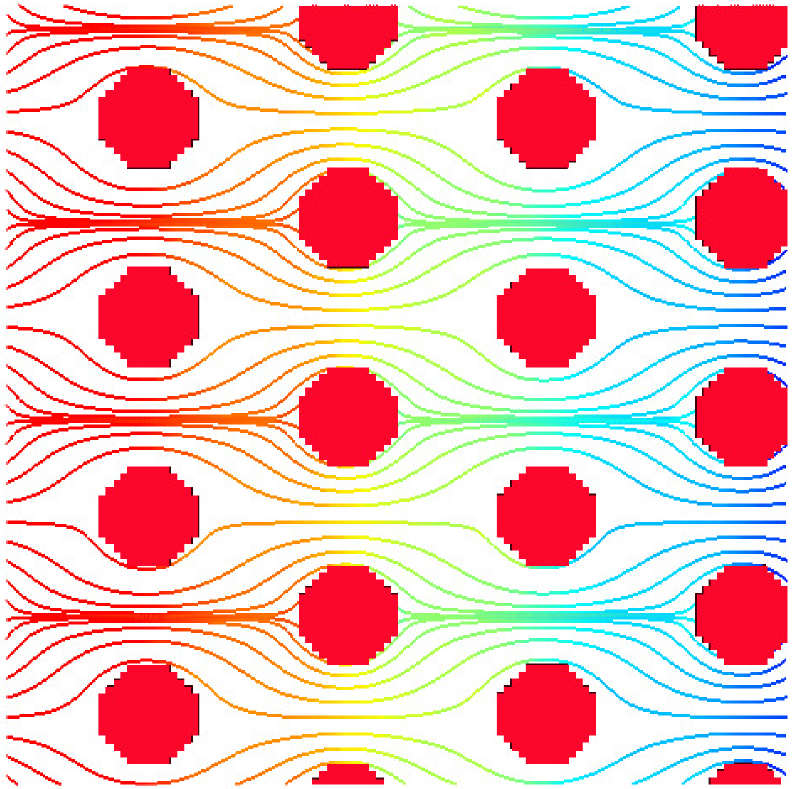


Slip flow (permeable fibers) gives stream lines closer to fibers:

Better collection for interception, impaction and diffusion



No-slip



Slip flow

Summary

- Simulation of pressure drop and filter efficiency
- Models for nano fibers „in depth“ and „on the surface“
- Nano fibers improve filter efficiency, increase pressure drop
- Slip flow further increases filter efficiency AND lowers pressure drop

- Slip flow via equivalent shrunk fibers and equivalent permeable fibers
- Shrunk fiber computations to calibrate equivalent fiber permeabilities

- Equivalent shrunk fibers only for fiber diameters > 2 * slip length
- Equivalent shrunk compute faster than permeable fibers
- For filter life time, need permeable fibers

- Comparison with measurements currently inconclusive, no trend for no-slip

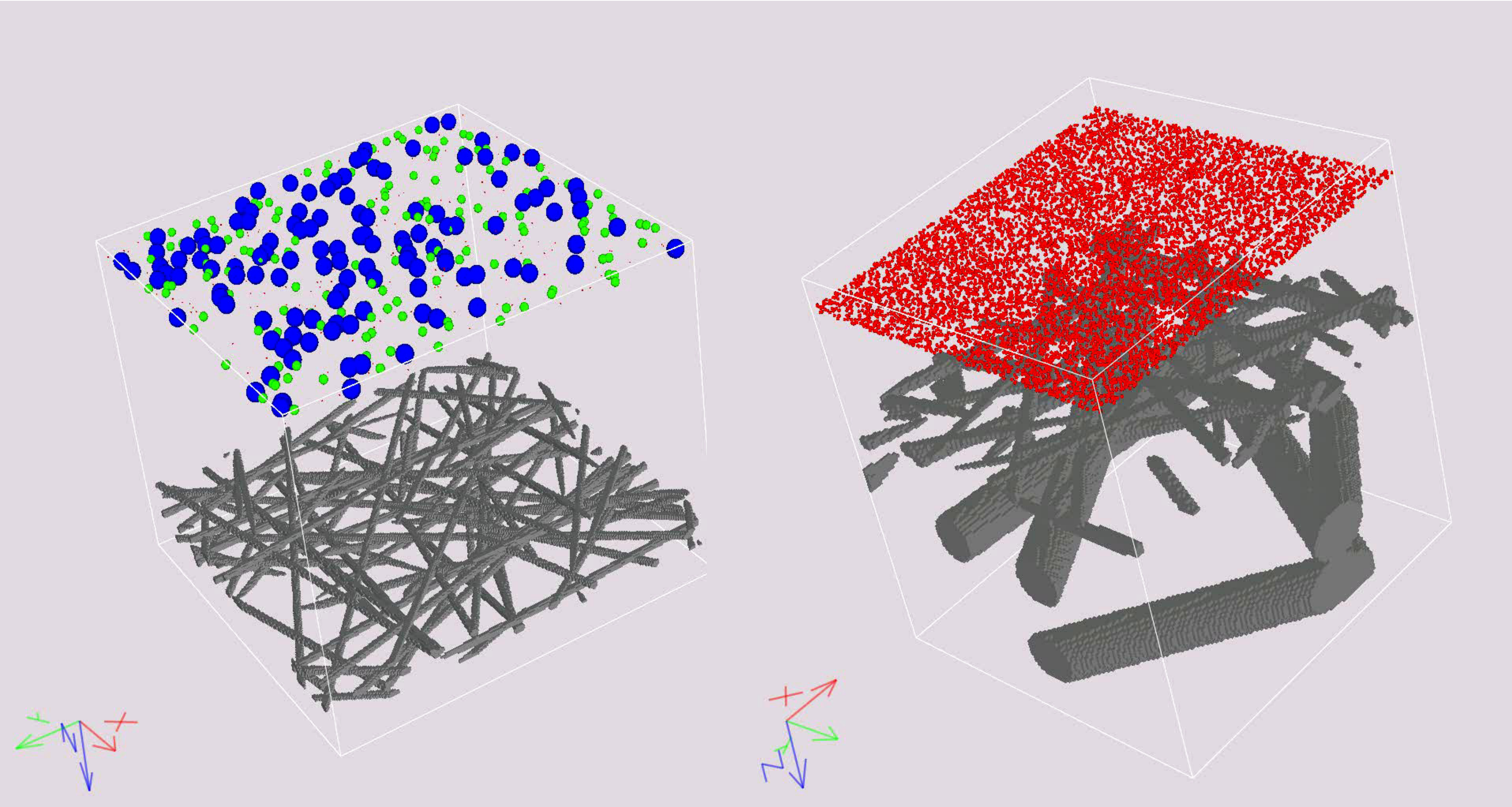
Find out more about GEO DICT

www.geodict.com

Fraunhofer
ITWM

We thank the German ministry for education and research (BMBF) for support under FKZ 13N9861, in the project

Nano-Meltblown-Fibers for Filter media (NaBlo) - subproject: Modeling, Simulation and Optimization of Meltblown processes and nano fiber filter media.



...and thank you

for your attention