Development of Digital Twin Replicas for Computational Analysis of Nonwoven Nanofibrous Air Filter Media

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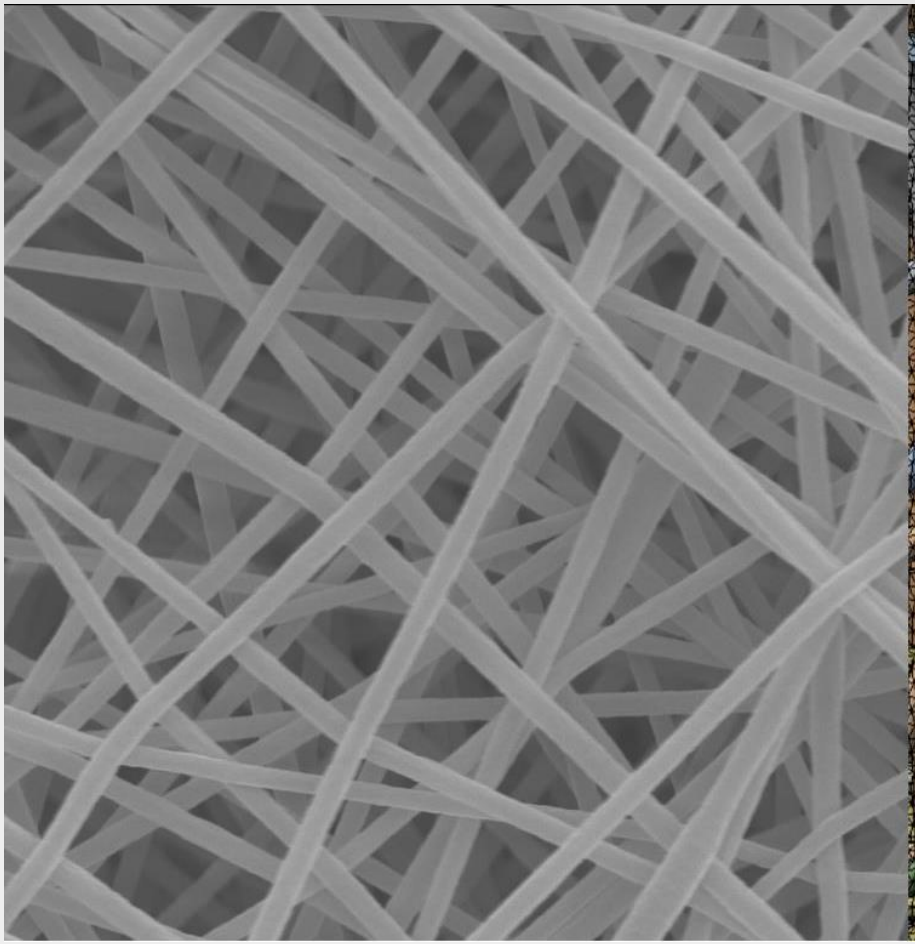
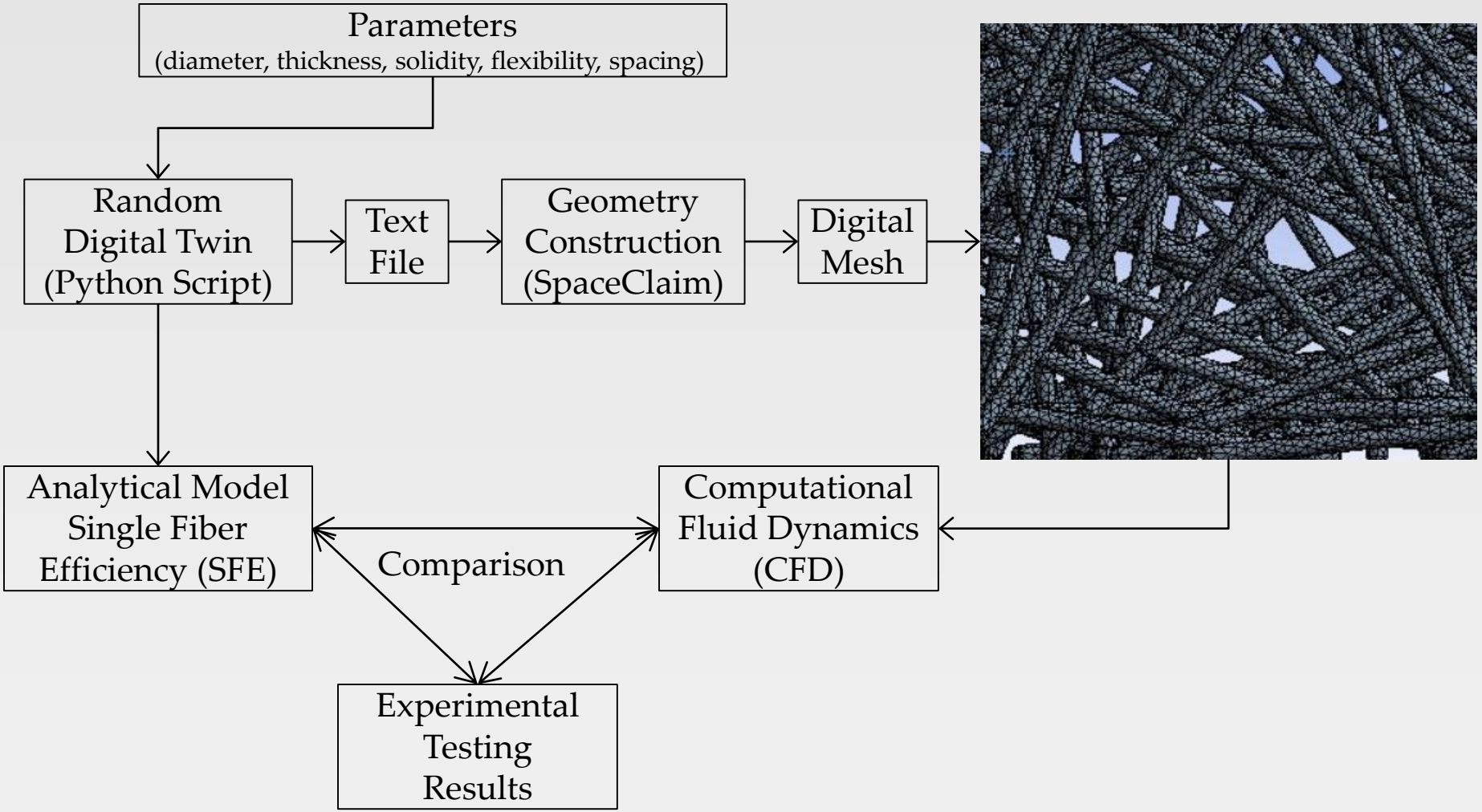
Digital Twins for Air Filtration



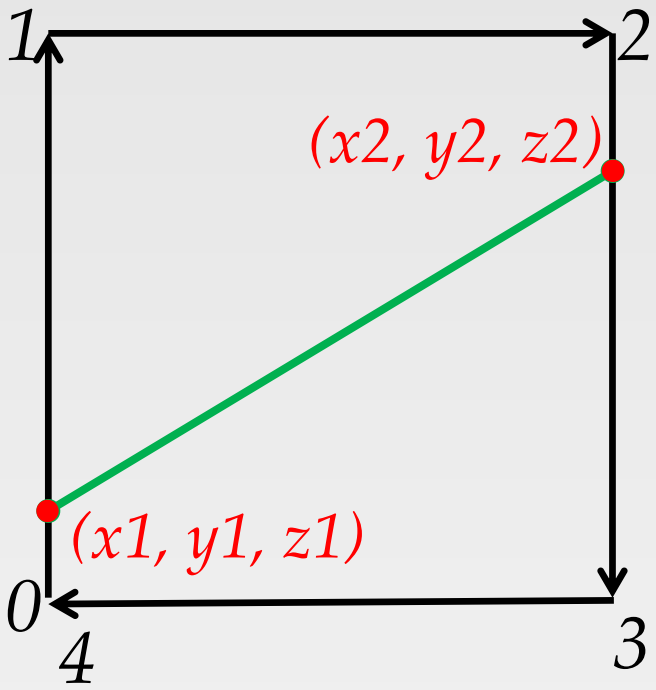
SEM image of PAN fibers.

Digital twin.

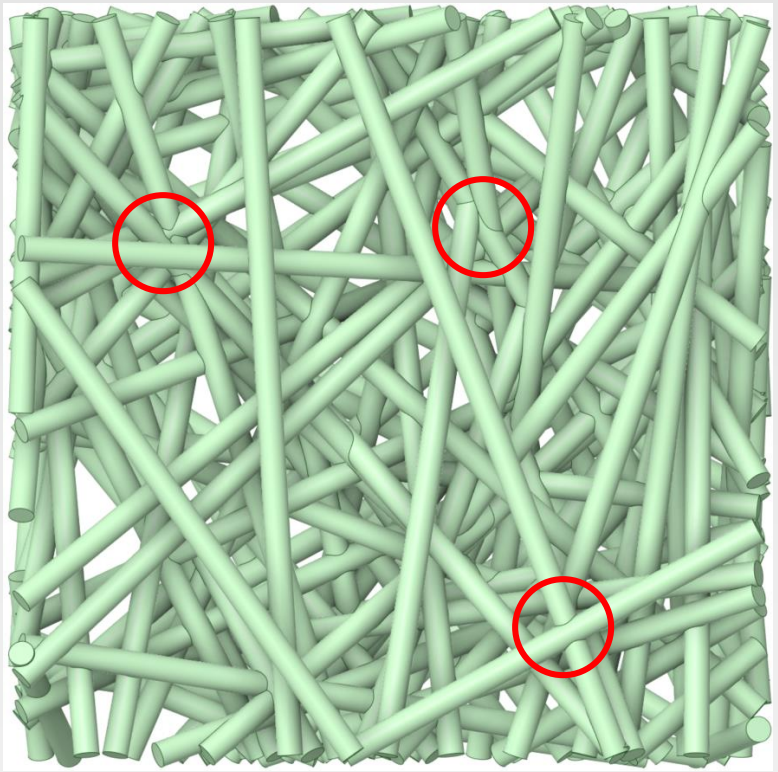
Digital Twin Replica of Filter Media



Geometry Creation with Ansys SpaceClaim

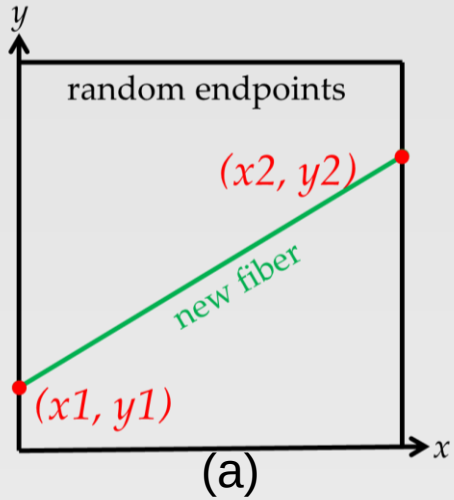


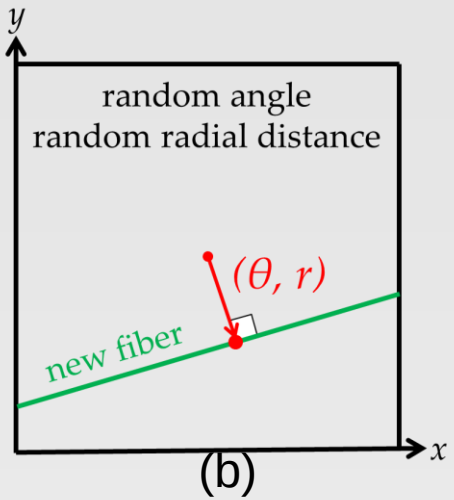
Random selection of endpoints.

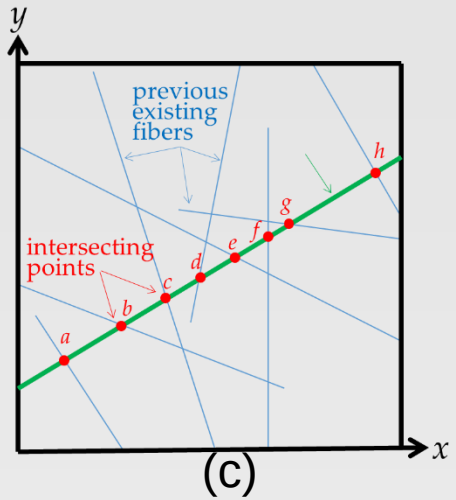


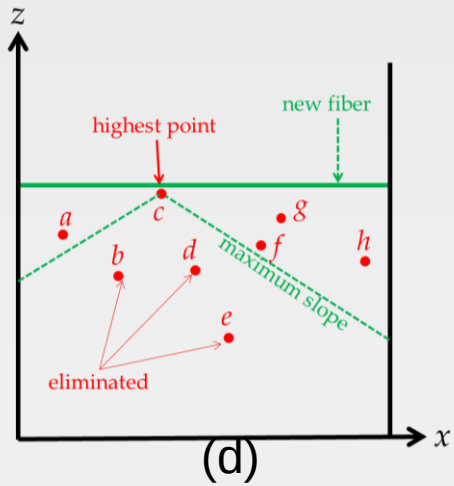
Resulting fibers with interpenetrations.

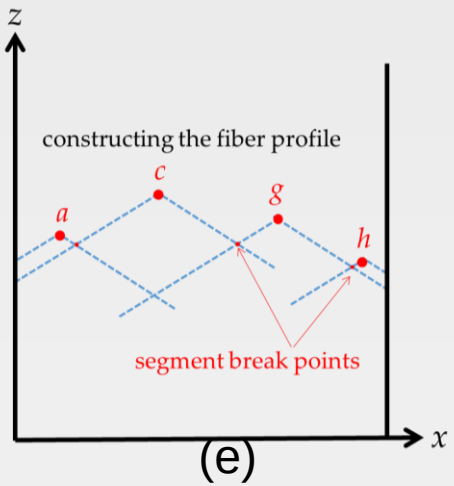
Fiber Placement Algorithm

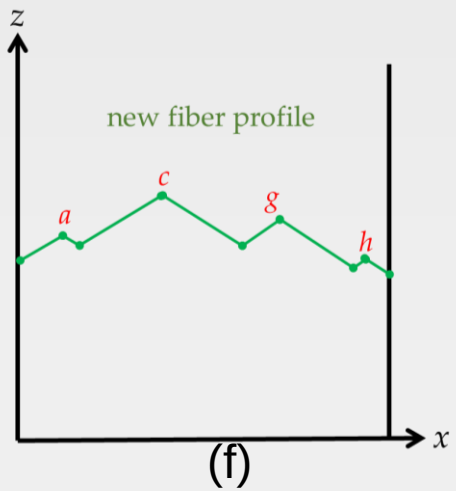






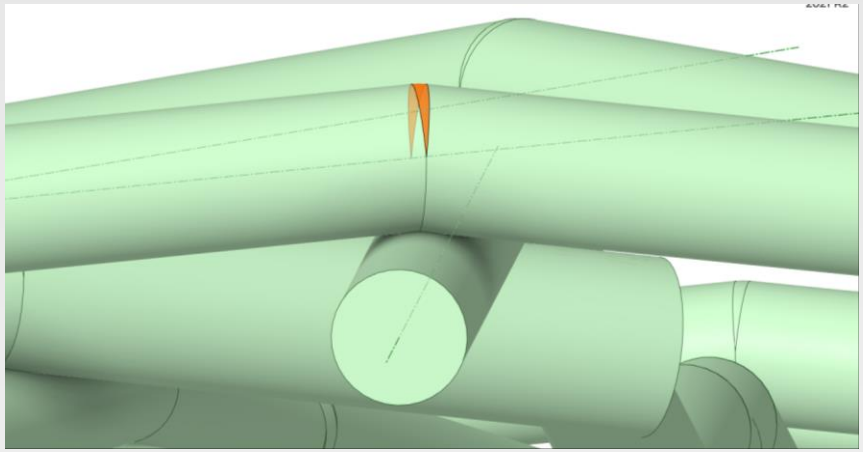




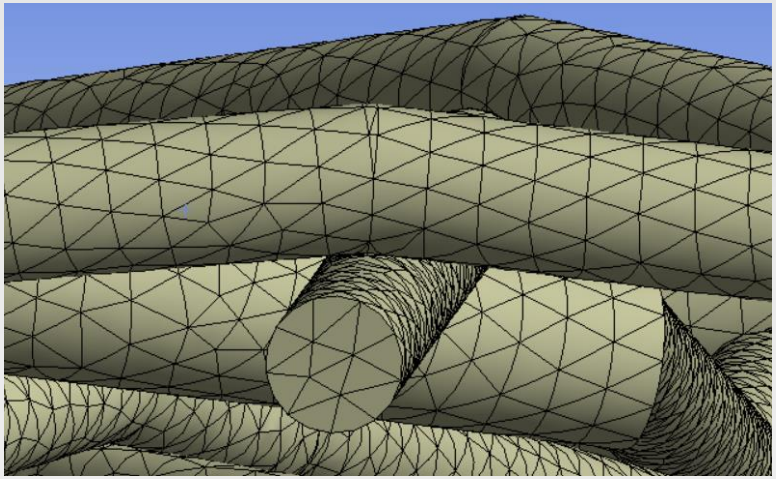


(Beckman et. al., 2021)

Fiber Flexibility



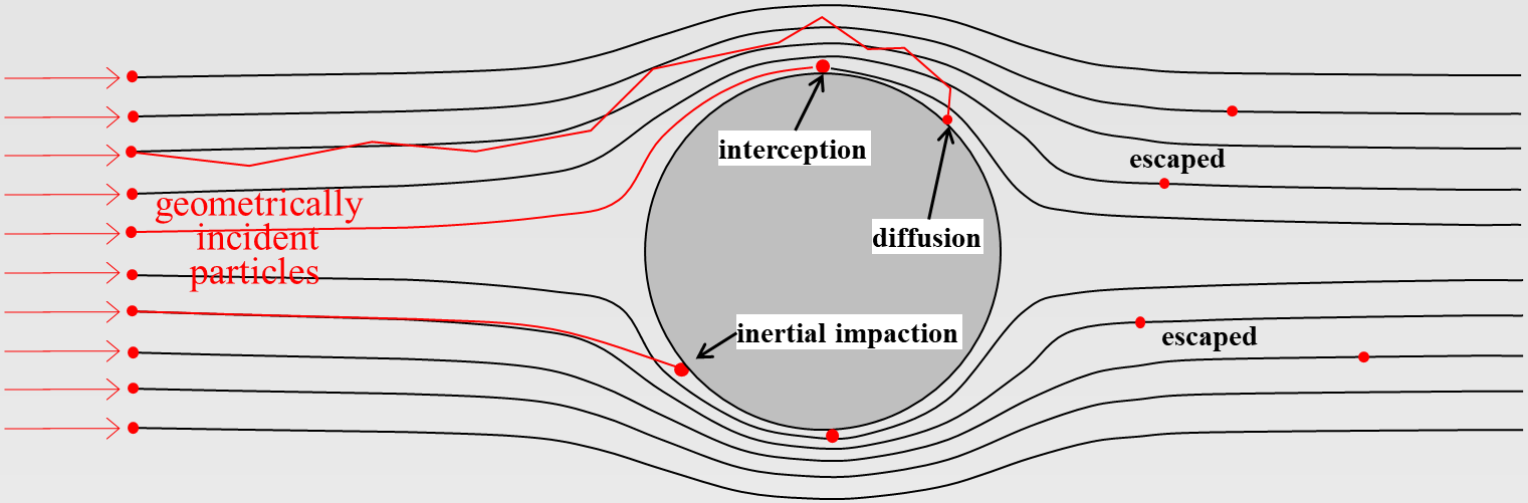
Fiber segment gaps filled with spheres.



Fibers meshed with Ansys.

(Beckman et. al., 2021)

Single Fiber Efficiency Model



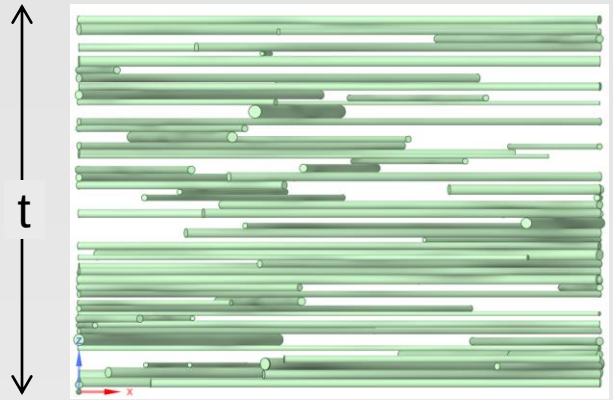
$$E_{\Sigma} = 1 - (1 - E_{\mathrm{R}})(1 - E_{\mathrm{D}})(1 - E_{\mathrm{DR}})(1 - E_{\mathrm{I}})$$

$$E_{\mathrm{F}} = 1 - \exp\left(\frac{-4\alpha E_{\Sigma} t}{\pi d_{\mathrm{f}}}\right)$$

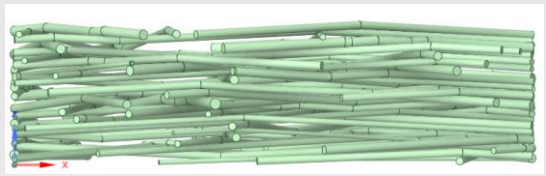
$$\Delta P = \frac{\eta t U_0}{d_{\mathrm{f}}^2}\left[64{\alpha_{\mathrm{f}}}^{1.5}(1 + 56{\alpha_{\mathrm{f}}}^3)\right]$$

(Davies, 1973; Brown, 1993; Hinds, 1999)

Effects of Fiber Flexibility

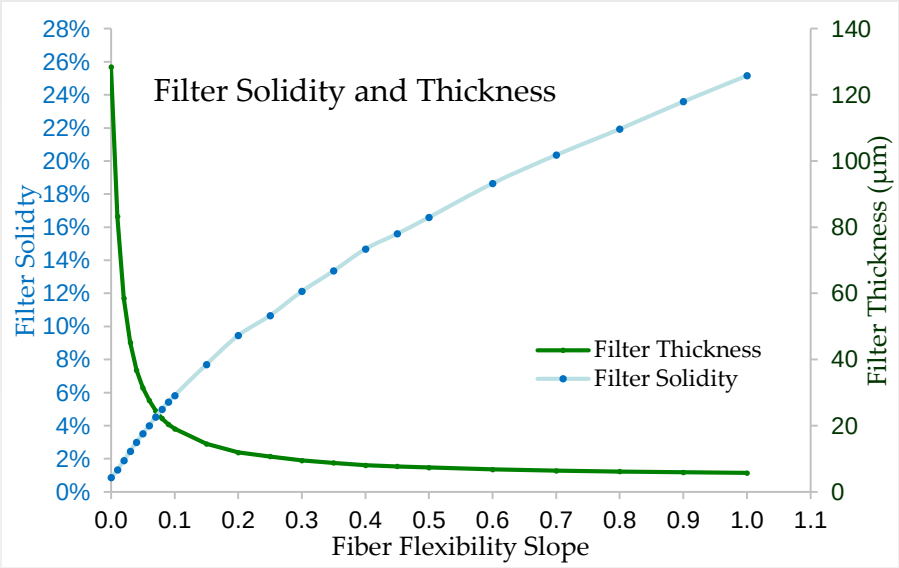


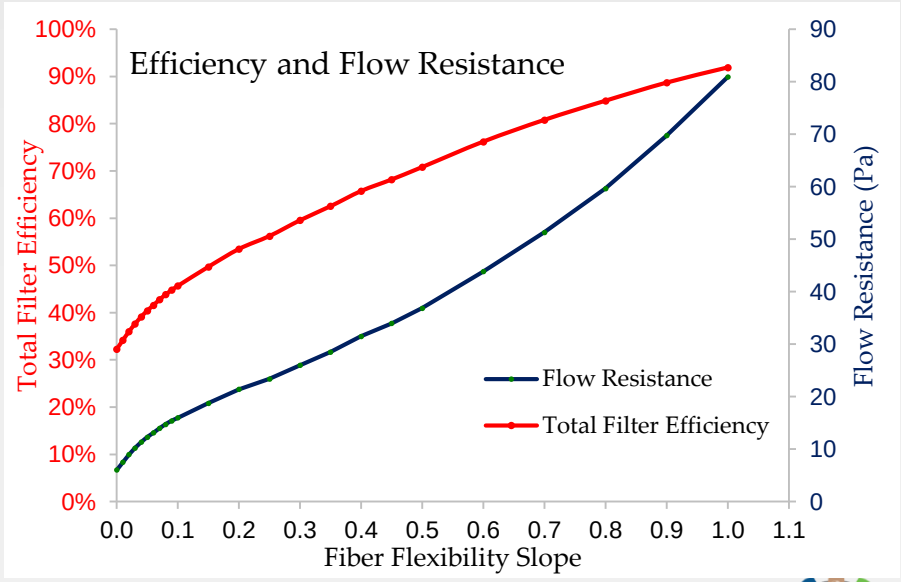
Slope = 0.



Slope = 5%.

Slope = 25%.

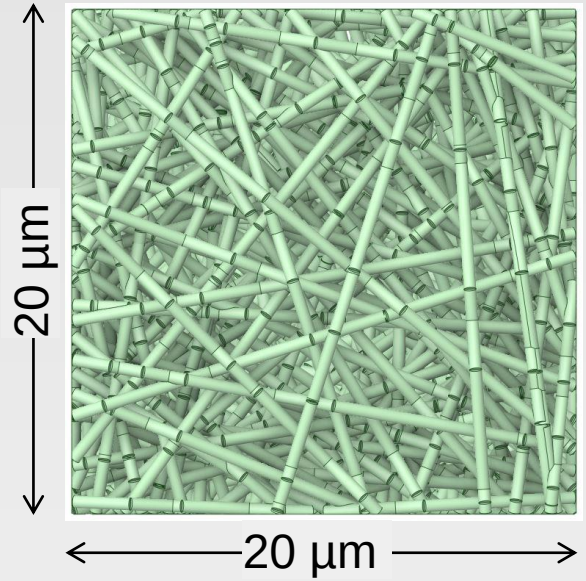




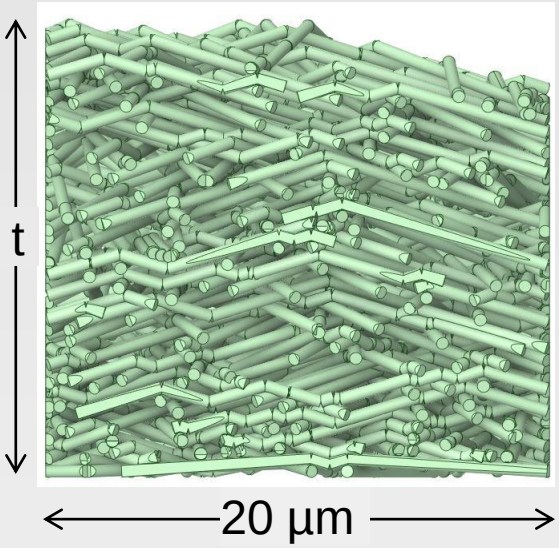
(Beckman et. al., 2021)

Digital Twin Replica (HEPA)

Top View

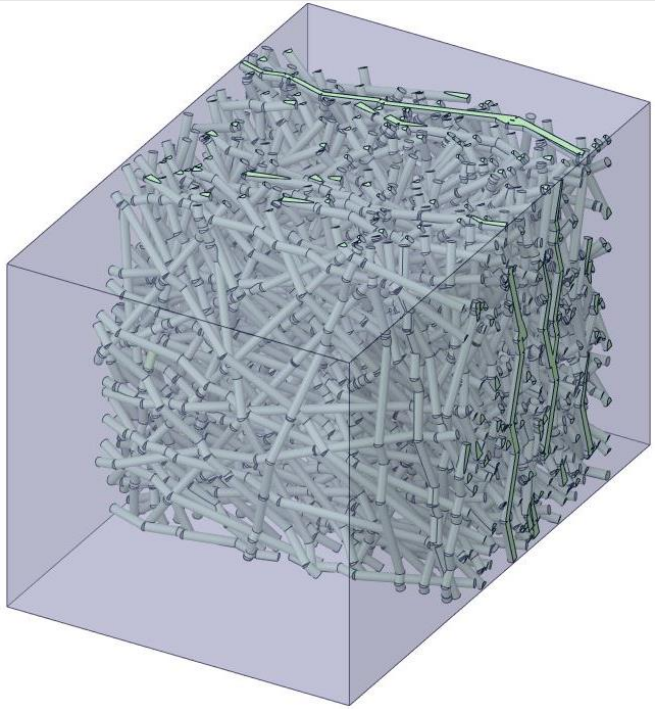


Side Profile

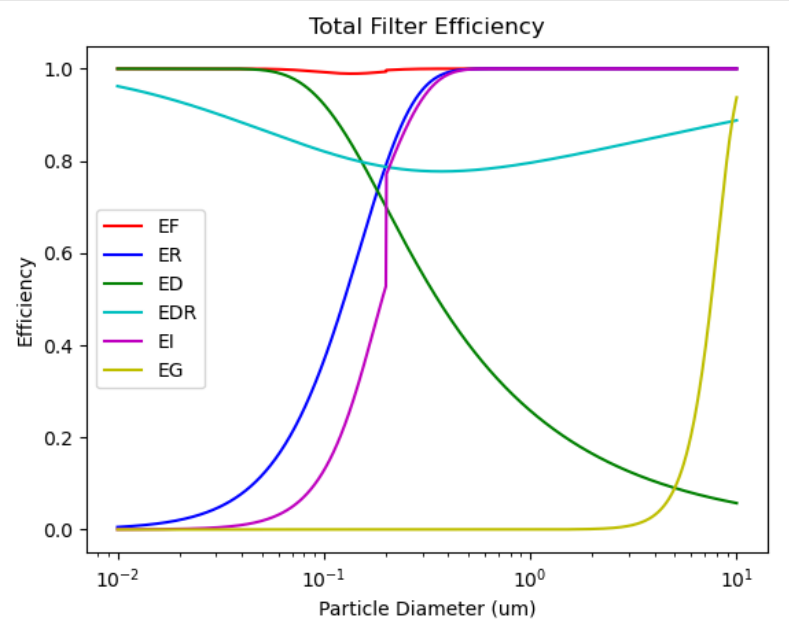


Symbol	Parameter	Description
d_f	500 nm	Fiber diameter
slope	30.0%	Fiber flexibility slope
E_f	99.97%	Total filter efficiency
α	18.9%	Solidity or solid volume fraction
t	18.43 µm	Thickness of the filter media
ΔP	241.8 Pa	Air flow resistance

Analytical SFE Calculations

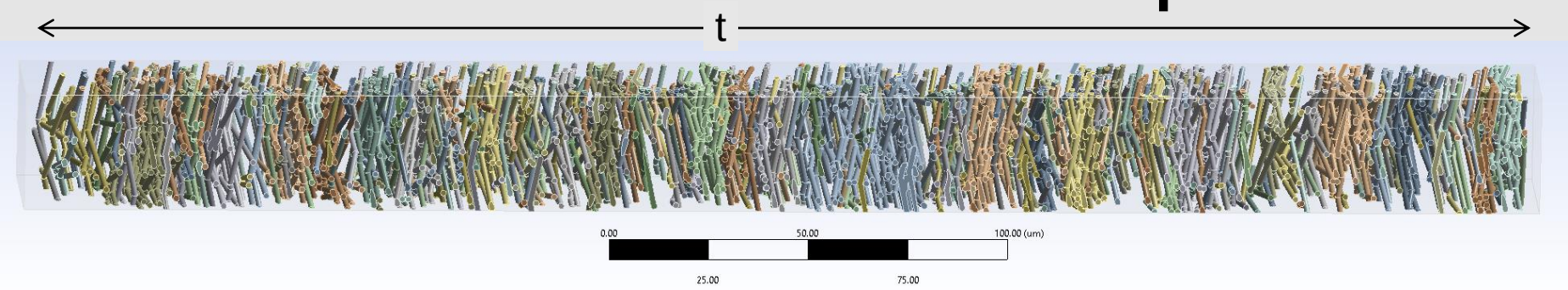


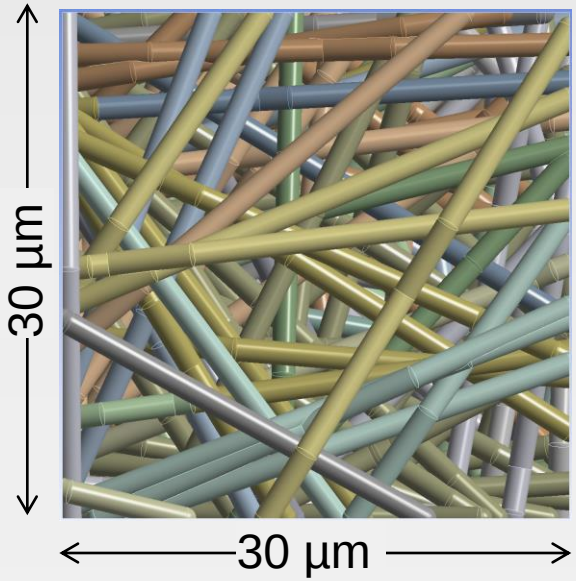
Digital twin with enclosure.



Analytical modeling:
TFE = 99.97% for 0.3 µm particles.
ΔP = 241.8 Pa.

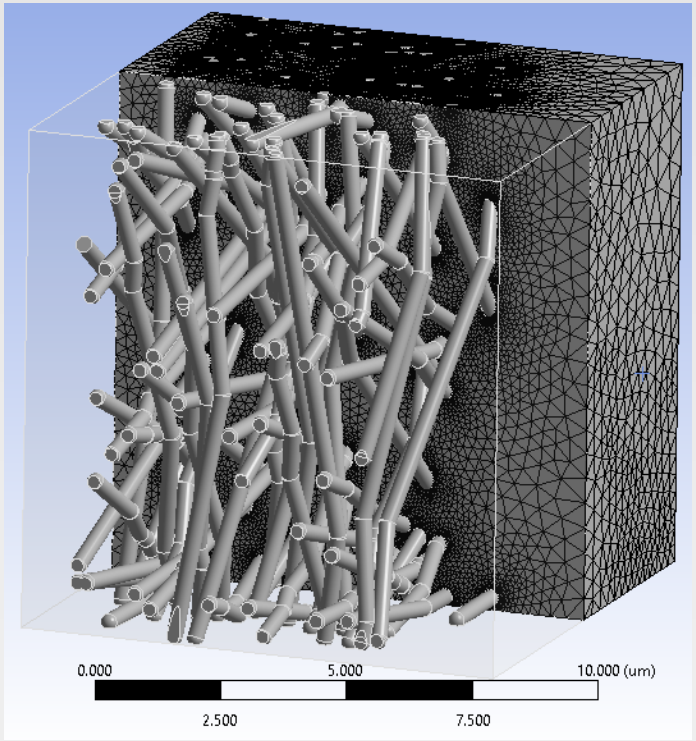
Digital Twin Replica
H14 HEPA Filter Paper



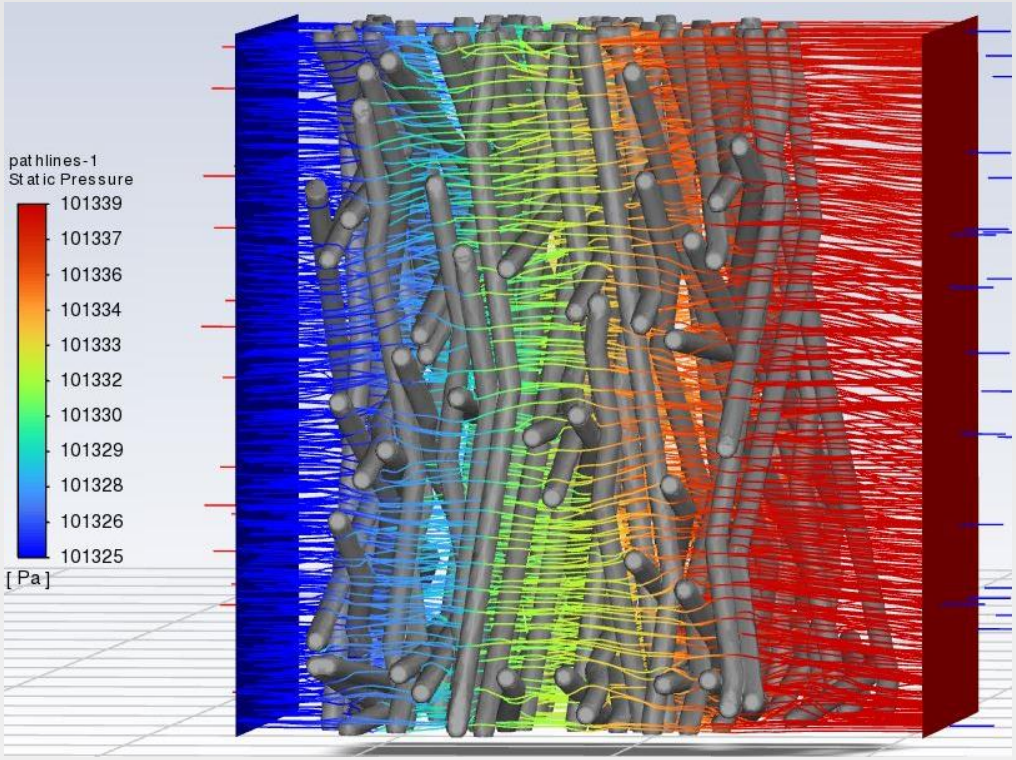


Symbol	Parameter	Description
d_f	1.4 µm	Fiber diameter
slope	20.0%	Fiber flexibility slope
E_f	99.97%	Total filter efficiency
α	13.7%	Solidity or solid volume fraction
t	374.1 µm	Thickness of the filter media
ΔP	319.7 Pa	Air flow resistance

Computational Fluid Dynamics with Ansys Fluent

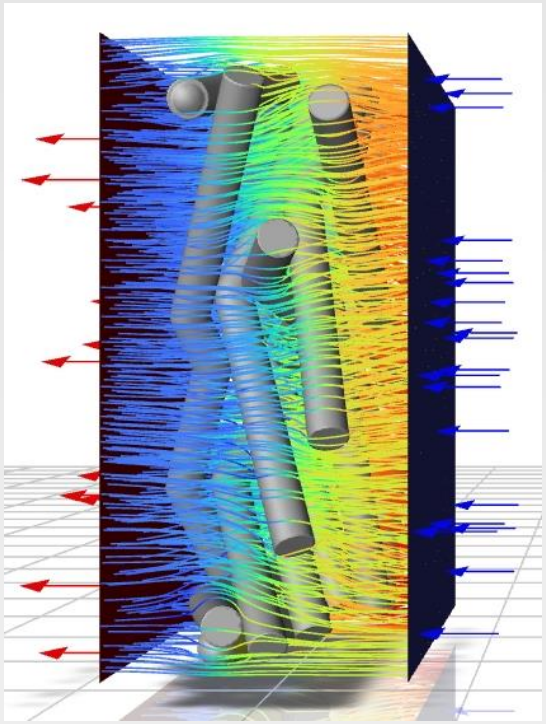


Meshed with Ansys Mechanical.

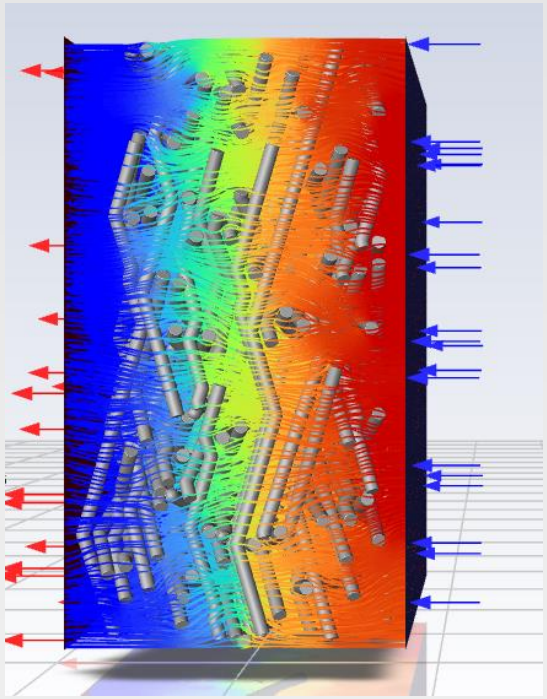


Pressure flow lines with Fluent.

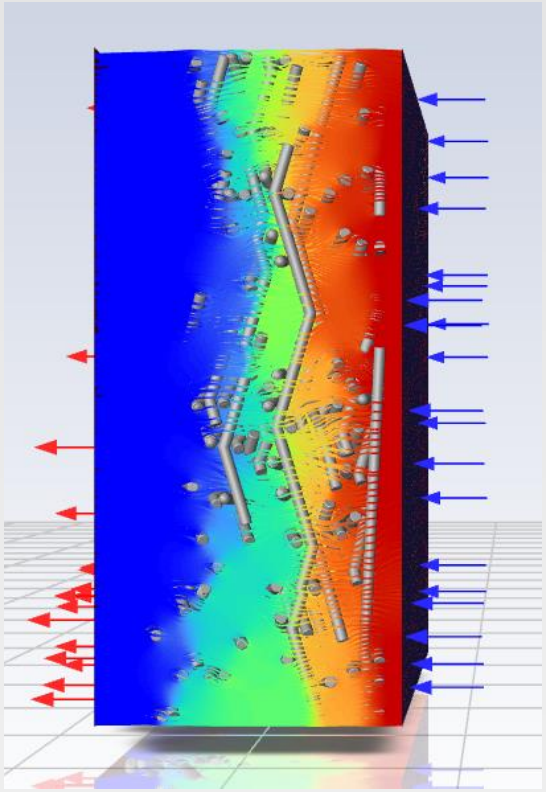
Comparison of Computational (CFD) with Analytical (SFE)



10 µm x 10 µm	
Analytical	16.9 Pa
CFD	5.30 Pa

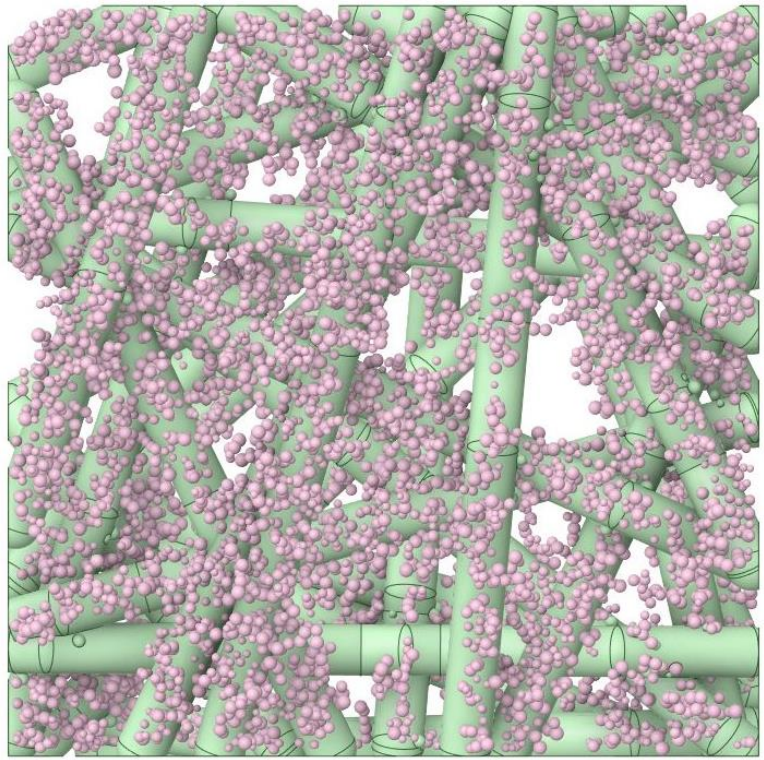


30 µm x 30 µm	
Analytical	36.7 Pa
CFD	20.2 Pa

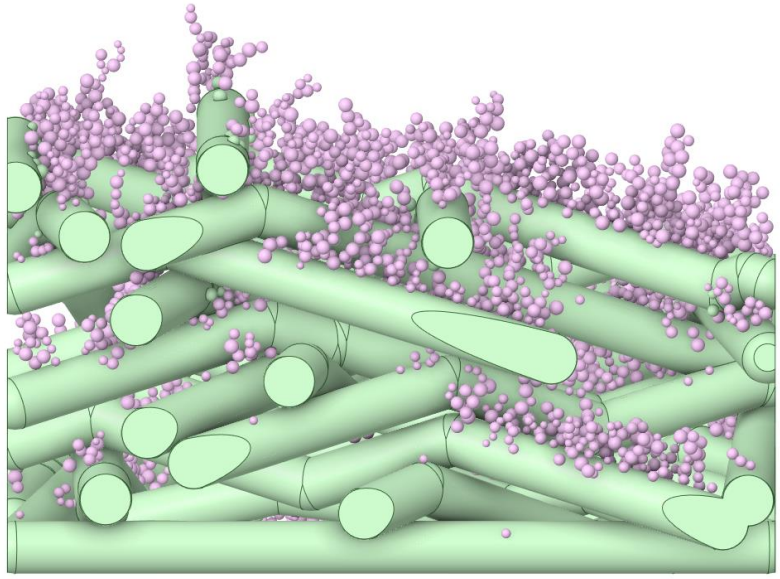


40 µm x 40 µm	
Analytical	34.2 Pa
CFD	31.1 Pa

Effects of Particle Loading

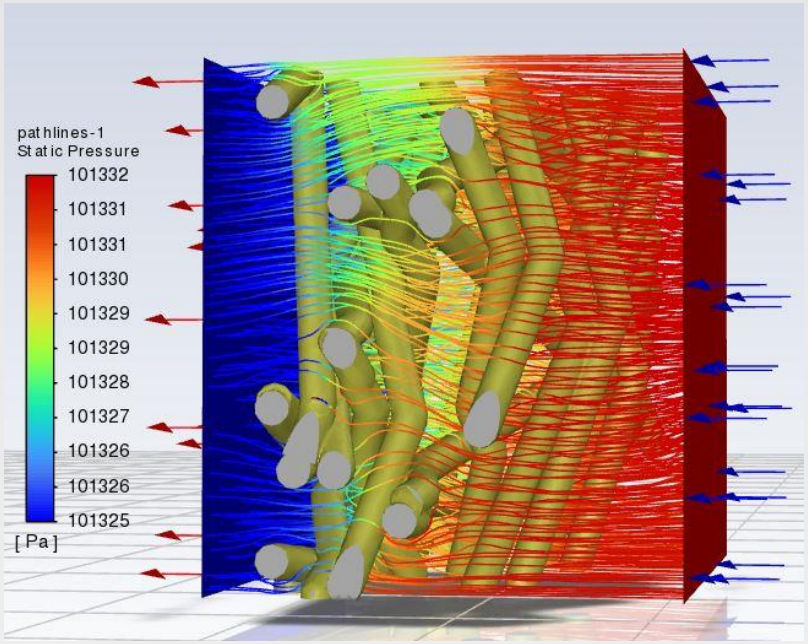


Face view of loaded particles.

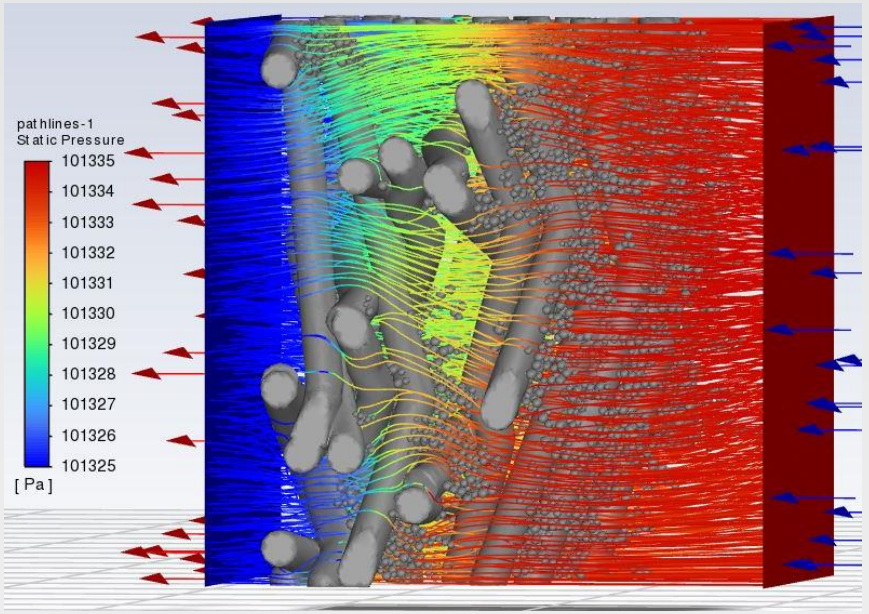


Side view of loaded particles.

Effects of Particle Loading

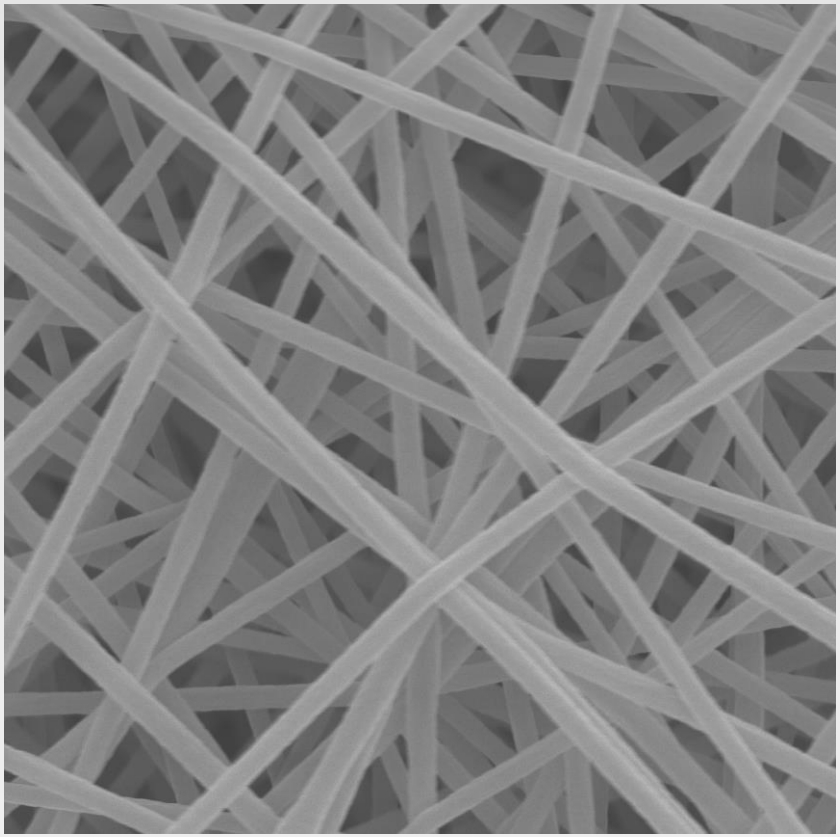


CFD pressure flow lines with no particles.

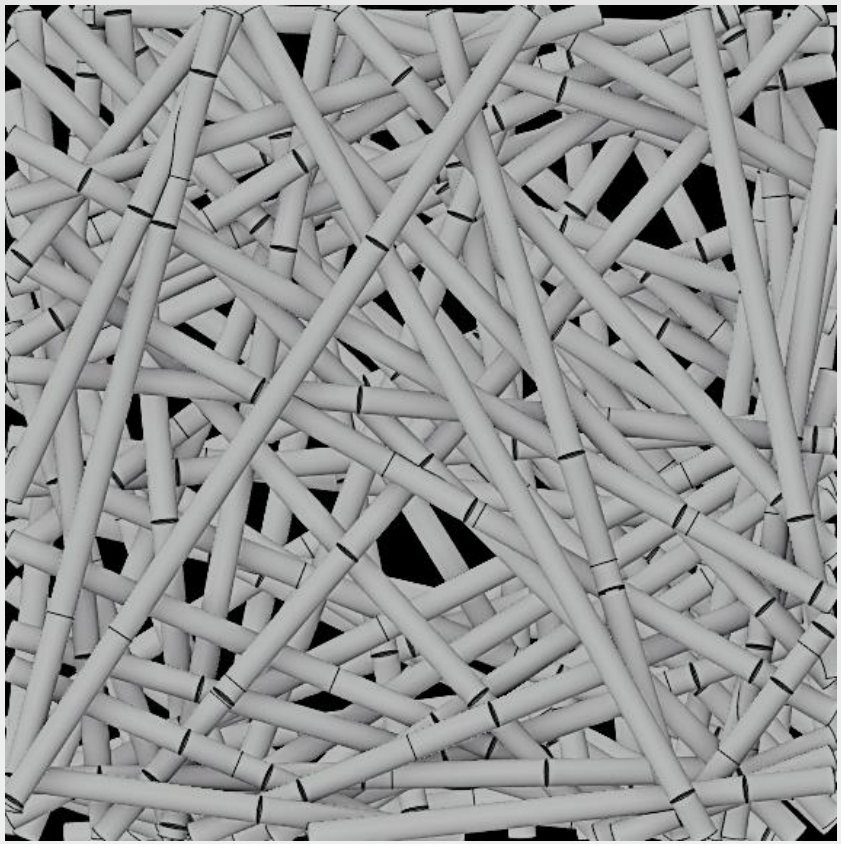


CFD pressure flow lines with particles.

Digital Twin Comparison with SEM Imagery

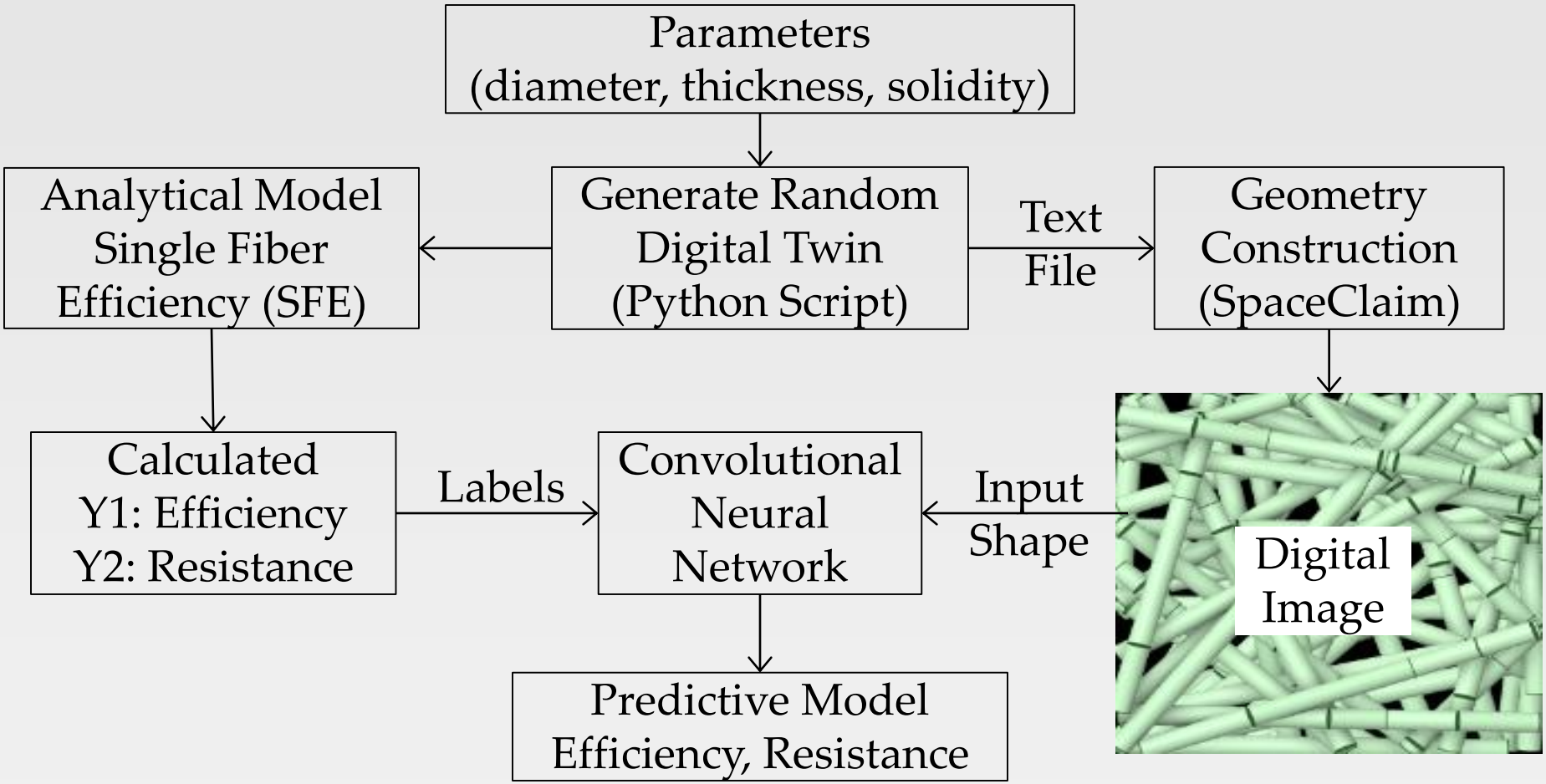


SEM Image

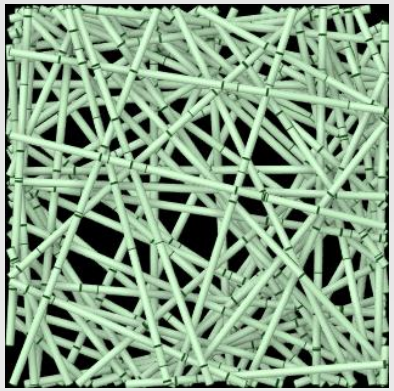


Digital Twin

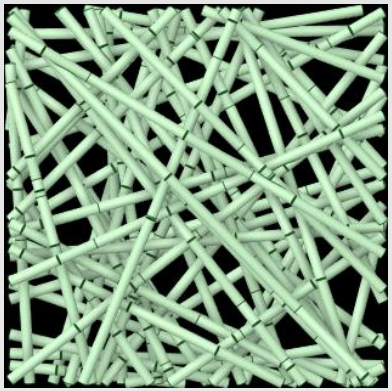
Machine Learning with Convolutional Neural Network



Digital Twin Generated Data



(1)



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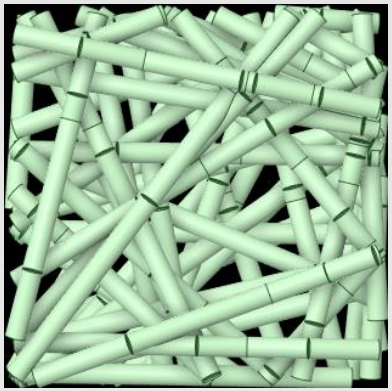

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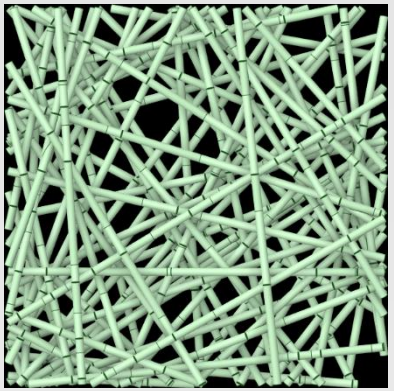
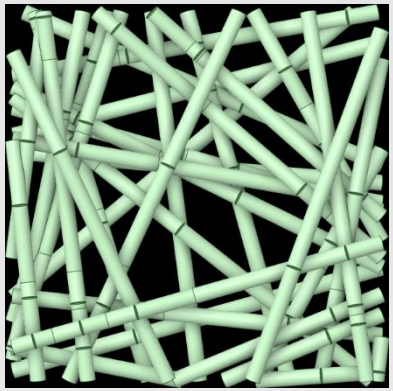


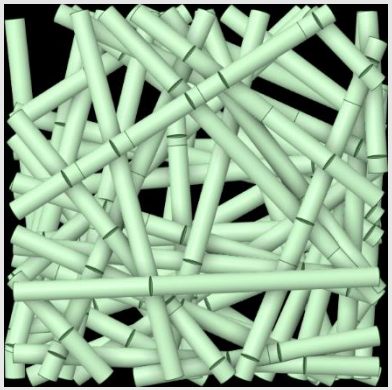
(10,000)

#	Fiber Flexibility (slope)	Fiber Diameter (d_f) (μm)	Face Coverage (FC)	Thickness (t) (μm)	Solidity (α) (%)	Efficiency (E_F) (%)	Air Flow Resistance (ΔP) (Pa)
1	0.15	0.2918	1.3007	4.066	9.726	81.94	44.19
2	0.15	0.2226	1.2886	3.479	8.891	88.88	56.11
3	0.15	0.5795	1.2281	9.007	14.645	83.26	51.27
…	…	…	…	…	…	…	…
10000	0.15	0.2215	1.5915	2.656	11.23	88.53	49.48

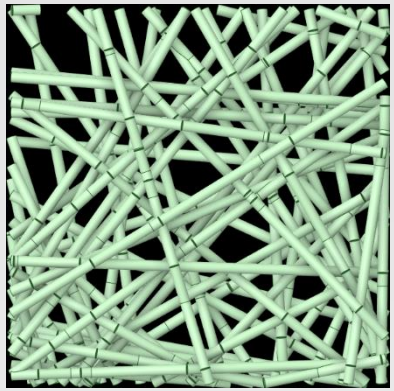
Predictive Model Results



(10,001)



(10,002)



(10,003)

#	Efficiency (EF) (%)			Air Flow Resistance (ΔP)		
	Predicted (%)	Actual (%)	Accuracy (%)	Predicted (Pa)	Actual (Pa)	Accuracy (%)
10,001	57.96	64.10	90.41	25.55	27.88	91.63
10,002	74.65	78.64	94.92	37.88	43.29	87.49
10,003	77.66	84.04	92.41	38.03	47.80	79.56

References

1. American Society of Mechanical Engineers. 2020. “Code on Nuclear Air and Gas Treatment ASME AG-1-2019.” ASME (January 17).
2. Beckman, I. P., G. Berry, H. Cho, and G. Riveros. 2021. “Digital Twin Geometry for Fibrous Air Filtration Media.” *Fibers* 9 (12): 84. doi: 10.3390/fib9120084.
3. Brown, R. C. 1993. *Air Filtration : An Integrated Approach to the Theory and Applications of Fibrous Filters*. New York: Pergamon Press.
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