A Web-based Electret Filter Performance Modeling and Design Tool

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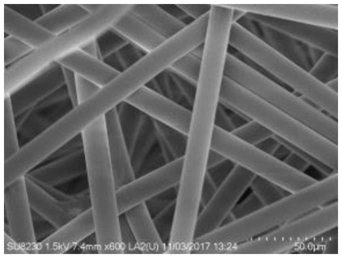
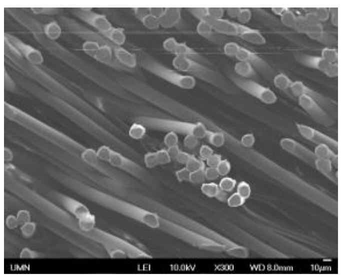
Depth filtration theory

Real filter

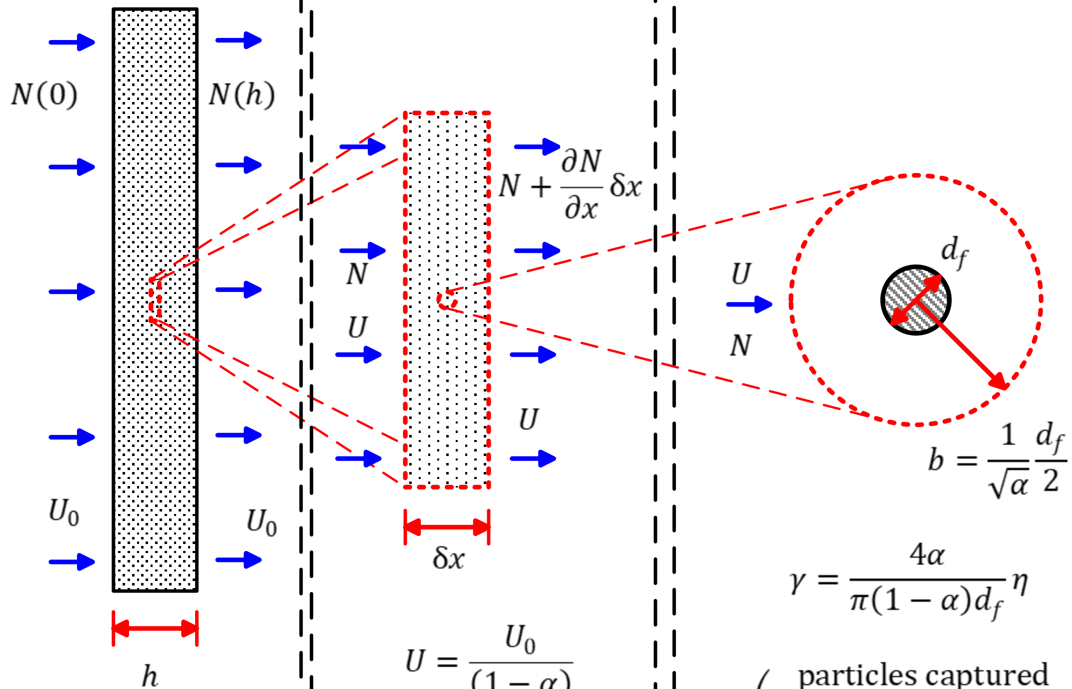


Top-down view



Cross-sectional view

Idealized filter | **Layer of filter** | **Single fiber of filter**



$N(x)$

$$P = \frac{N(h)}{N(0)}$$

$$U = \frac{U_0}{(1-\alpha)}$$

$\alpha =$ solid fraction

$$\frac{\partial N}{\partial x} = -\gamma N$$

$$P = \exp(-\gamma h)$$

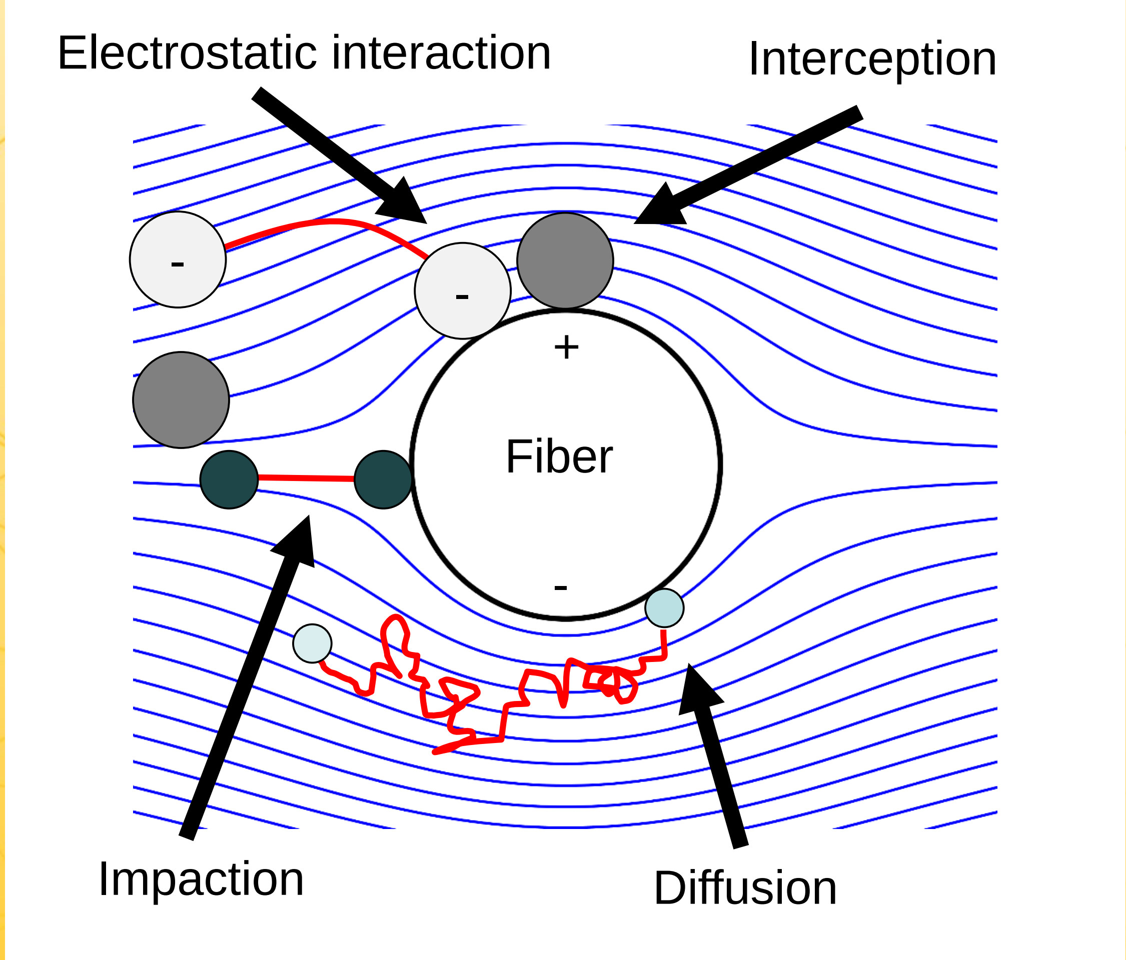
$$\gamma = \frac{4\alpha}{\pi(1-\alpha)d_f}\eta$$

$$\eta = \frac{\left(\begin{array}{c}\text{particles captured} \\ \text{per unit time} \\ \text{per unit length of fiber}\end{array}\right)}{NUd_f}$$

$$P = \exp\left(-\frac{4\alpha h}{\pi(1-\alpha)d_f}\eta\right)$$

Electret filtration

- Mechanical filter media capture particles by:
  - Interception
  - Impaction
  - Diffusion
- Electret filter media have semi-permanently charged fibers
- Electrostatic interactions between particles and fibers increase filtration efficiency without increasing pressure drop



Dielectrophoretic force

- An external electric field will polarize a particle
- The electric field will then attract the induced dipole

$$\vec{F}_{Di} = \frac{\pi {d_p}^3 \varepsilon_0 \varepsilon_g}{4} \left(\frac{\varepsilon_p - \varepsilon_g}{\varepsilon_p + 2\varepsilon_g} \right) \nabla \left(\vec{E}^2 \right)$$

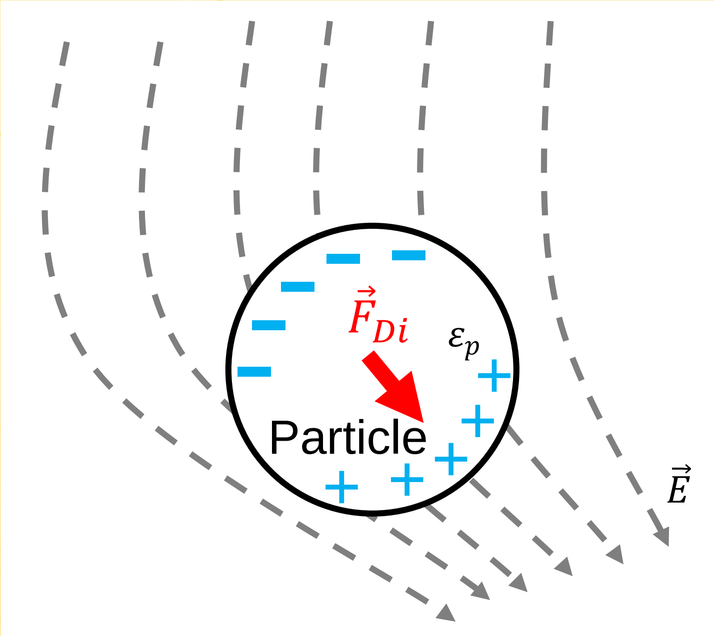
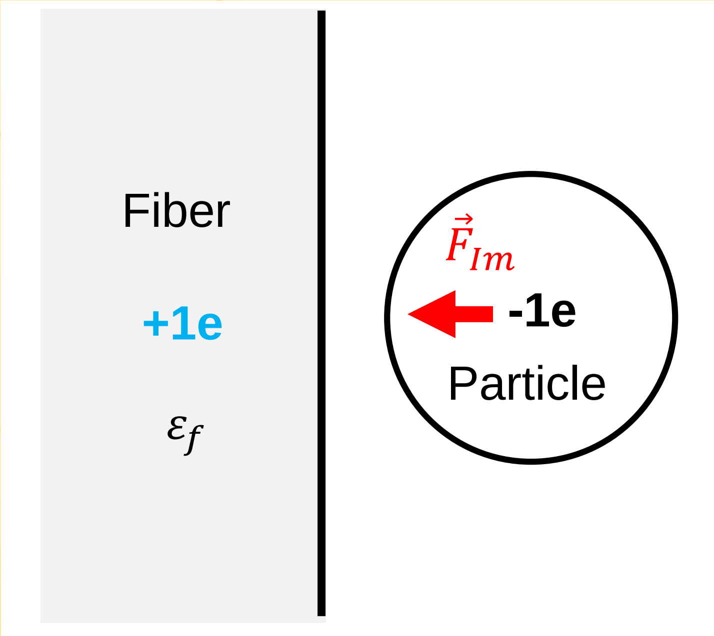


Image force

- A charged particle will induce a charge distribution in the fiber
- There will be an attractive force between the charged particle and induced charge distribution in the fiber

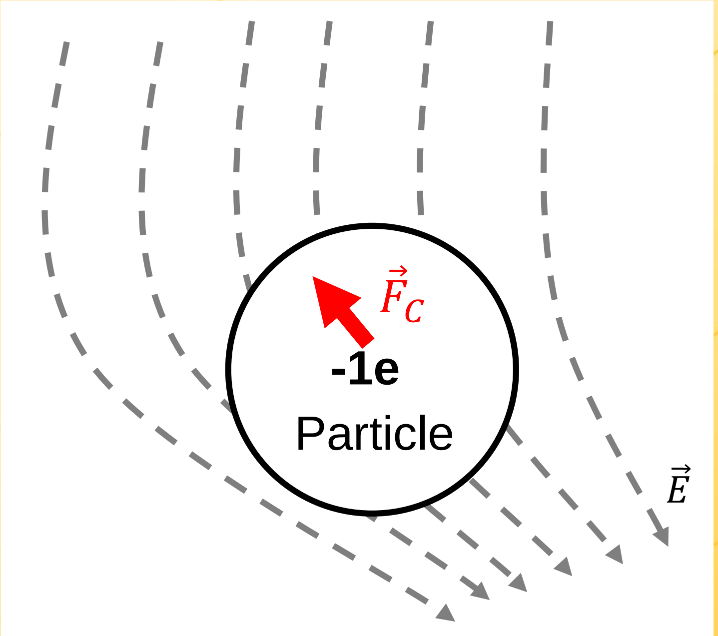
$$\vec{F}_{Im} = -\left(\frac{\varepsilon_f - \varepsilon_g}{\varepsilon_f + \varepsilon_g}\right)\frac{q^2}{16\pi\varepsilon_0\varepsilon_g\left(r - \frac{d_f}{2}\right)^2}\hat{\boldsymbol{r}}$$



Coulomb force

- An external electric field will exert a force on a charged particle

$$\vec{F}_C = q\vec{E}$$



Motivation

- Most models are derived considering one electrostatic force at a time and adding their respective efficiencies together
- Lee et al. (2002) found this assumption no longer holds for higher charge densities (120 μC/m^2, 20x that studied by Otani et al.,1993) due to negative interaction between dielectrophoretic and Coulombic forces
- Semi-empirical theoretical expression by Emi et al. (1987) which accounted for interaction of forces did not agree with experiment, likely due to neglecting the random orientation of fibers
- <u>New model is needed which will account for interaction between electrostatic forces and random fiber orientation</u>

Lee et al. (2002). *J Chem Eng Jpn, 35*(1), 57-62.
Otani et al. (1993). *KONA Powder Part J, 11*, 207-214.
Emi et al. (1987). *Part Sci Technol, 5*(2), 161-171.

Calculation of single fiber efficiency

- Single fiber efficiency assumed to be sum of deterministic mechanisms (e.g., drag and electrostatic forces) and stochastic mechanisms (i.e., diffusion)

$$\eta = \eta_D + \eta_{det}$$

- Diffusional single fiber efficiency was calculated using the empirical power law model of Wang et al. (2007) where $d_{f,R}$ is a pressure drop equivalent fiber diameter (Rubow, 1981)

$$\eta_D = 0.84 \left(\frac{d_f}{d_{f,R}} \right)^{1.43} [(1 - \alpha)Pe]^{-0.43}$$

$$Pe = \frac{U d_f}{D}$$

- Deterministic single fiber efficiency will be found from the limiting trajectories of particles subject to dielectrophoretic, image, and Coulomb forces

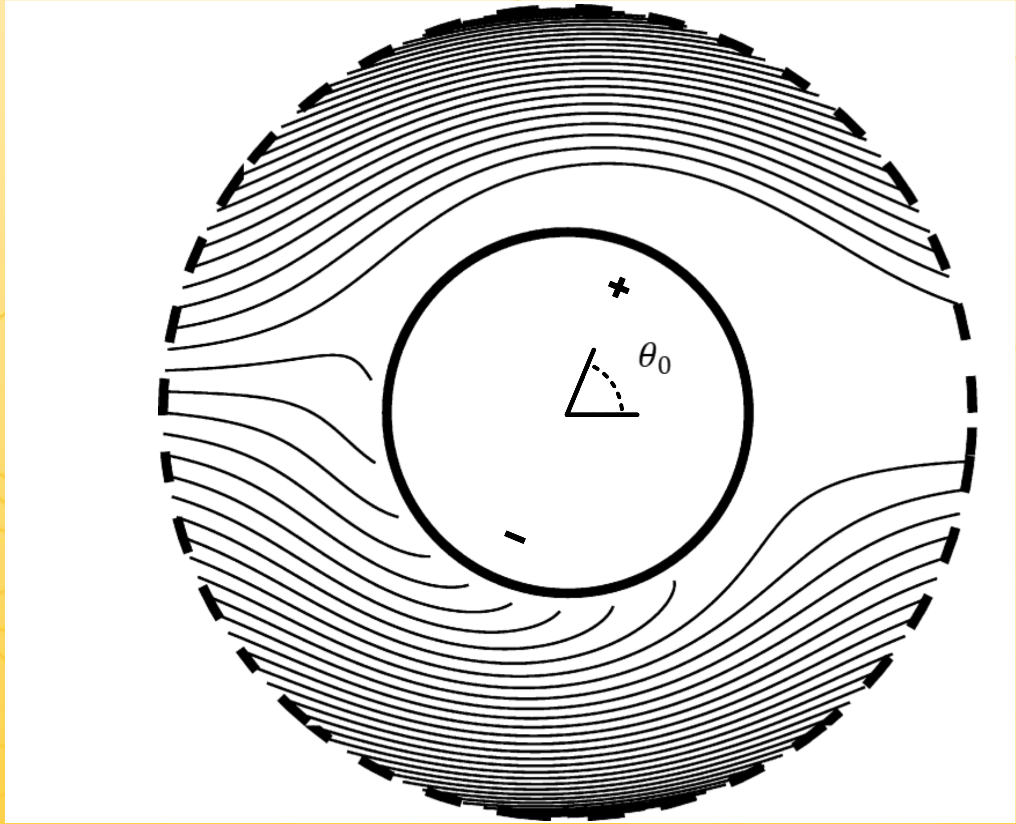
Wang, J., Chen, D. R., & Pui, D. Y. H. (2007) *J Nanopart Res, 9*(1), 109-115.
Rubow, K. L. (1981). *Submicron aerosol filtration characteristics of membrane filters.* (PhD Thesis), University of Minnesota, Minneapolis.

Particle equation of motion

$$\vec{v} = \vec{u} + B\left(\vec{F}_{Di} + \vec{F}_{Im} + \vec{F}_C\right)$$

- Brownian forces and particle inertia are neglected
- Electrostatic forces considered are the dielectrophoretic, image, and Coulomb forces
- Fluid flow is given by Kuwabara (1959)
- A line dipole surface charge distribution as given by Brown (1981) is assumed

$$\sigma \cos(\theta - \theta_0)$$



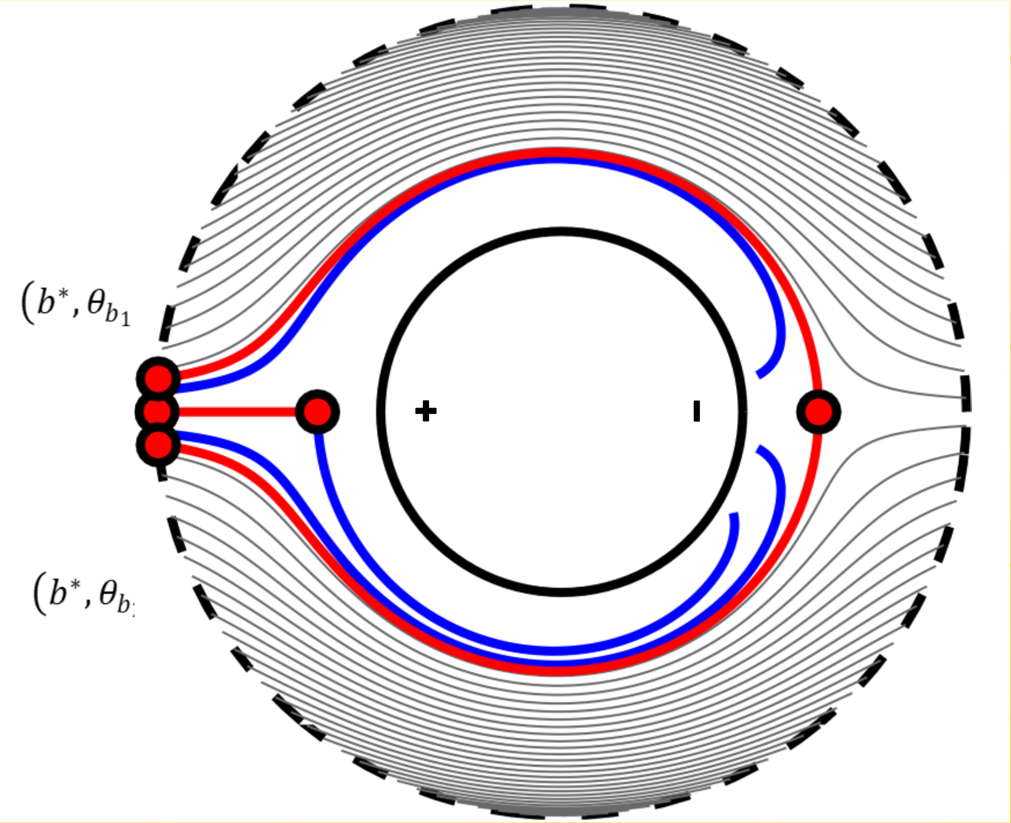
Kuwabara, S. (1959). *J Phys Soc Jpn, 14*(4), 527-532.
Brown, R. C. (1981). *J Aerosol Sci, 12*(4), 349-356.

Calculation of single fiber efficiency

- Deterministic single fiber efficiency is calculated from the particle flux between limiting trajectories

$$\eta_{det} = -\frac{b^*}{2}\int_{\theta_{b_1}}^{\theta_{b_2}} v_r^*(b^*,\theta)d\theta$$

- When a particle is charged, particle motion is dependent on the angle of the fiber. Then, the orientationally averaged η_{det} is found



$$\eta_{det} = \frac{1}{\pi}\int_0^{\pi}\left[-\frac{b^*}{2}\int_{\theta_{b_1}(\theta_0)}^{\theta_{b_2}(\theta_0)} v_r^*(b^*,\theta)d\theta\right]d\theta_0$$

Development of a surrogate model from numerical results

- A surrogate model (or metamodel) for η_{det} using *K*-Nearest Neighbors from more expensive numerical results was obtained
- The mean relative errors of the surrogate models for single fiber efficiency of uncharged and charged particles were less than 1 and 6%, respectively

Filter, operational, and particle properties

α = 0.01 – 0.25

d_f = 1 – 100 μm

σ = 0 – 1,000 μC/m^2

$\varepsilon_f \sim 2$

U_0 = 0.01 – 1 m/s

d_p = 1 – 1,000 nm

q = 0e – 10e

$\varepsilon_p \sim 5$

Parameter space

$\alpha = 0.01 \sim 0.25$

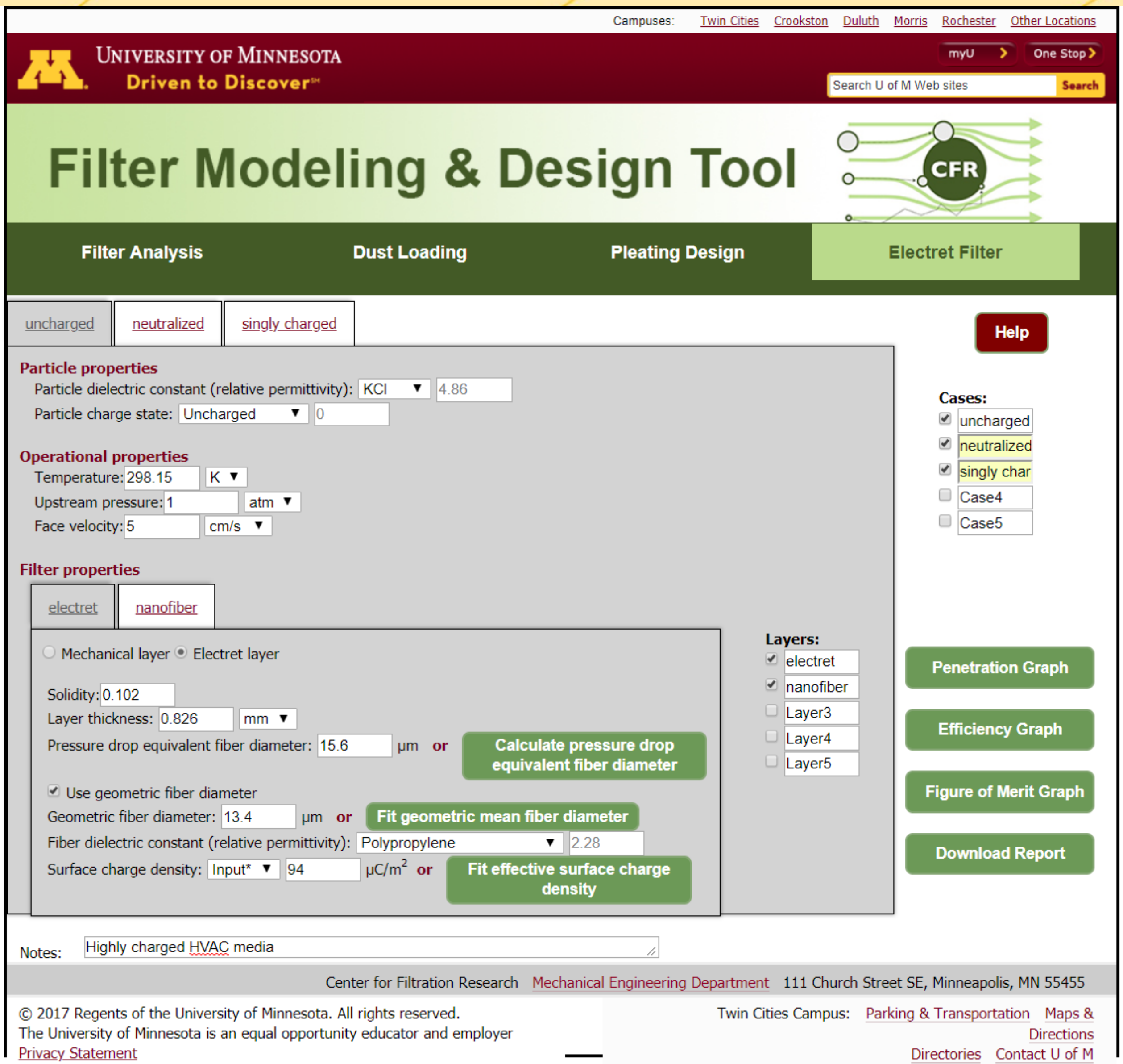
$N_R = 10^{-5} \sim 1$

$N_{Di} = 10^{-14} \sim 10^5$

$N_{Im} = 0, 10^{-11} \sim 10^2$

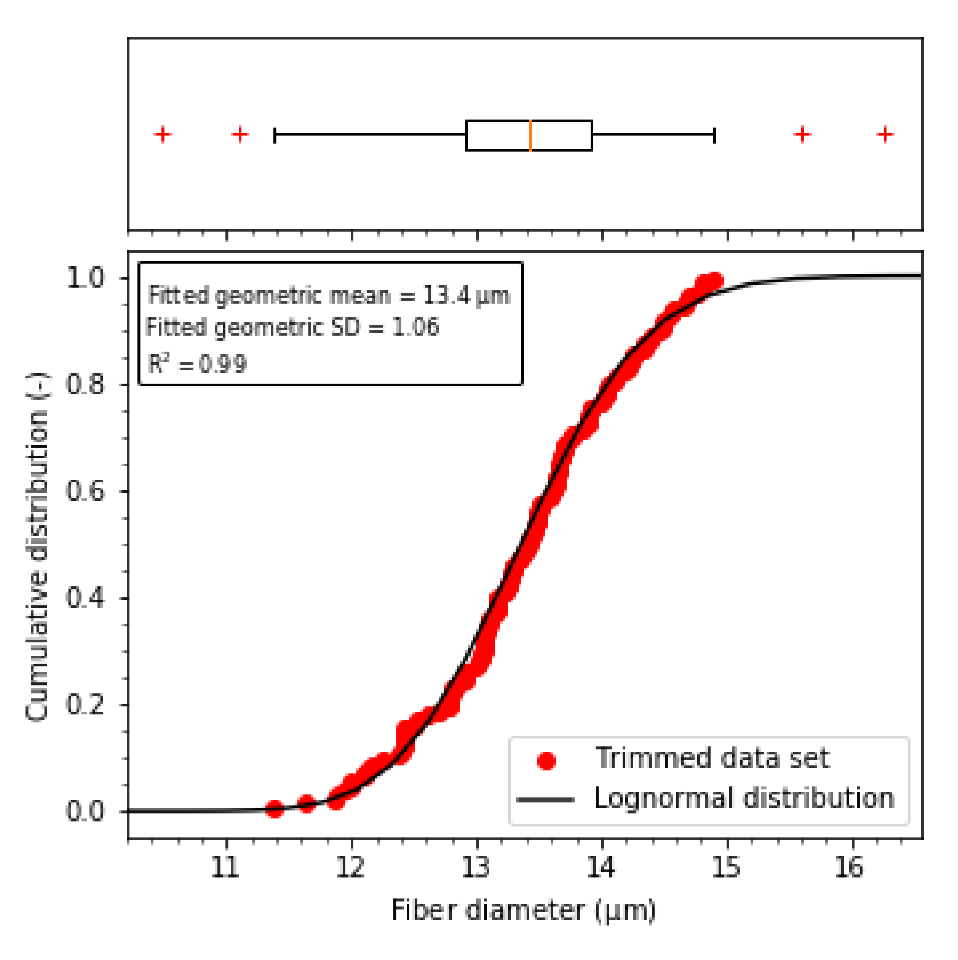
$N_C = 0, 10^{-7} \sim 10^2$

Interface of web-based electret filter performance model and design tool



Fitting of geometric mean fiber diameter

1. Perform microscopy and measure fiber diameters
2. Upload completed spreadsheet containing measured fiber diameters
3. Outliers are removed using an adjusted boxplot for skewed distributions (Hubert, 2008)
4. Lognormal distribution is fitted to trimmed data set



Hubert, M. & Vandervieren, E. (2008). *Comput Stat Data Anal, 52*(12), 5186-5201.

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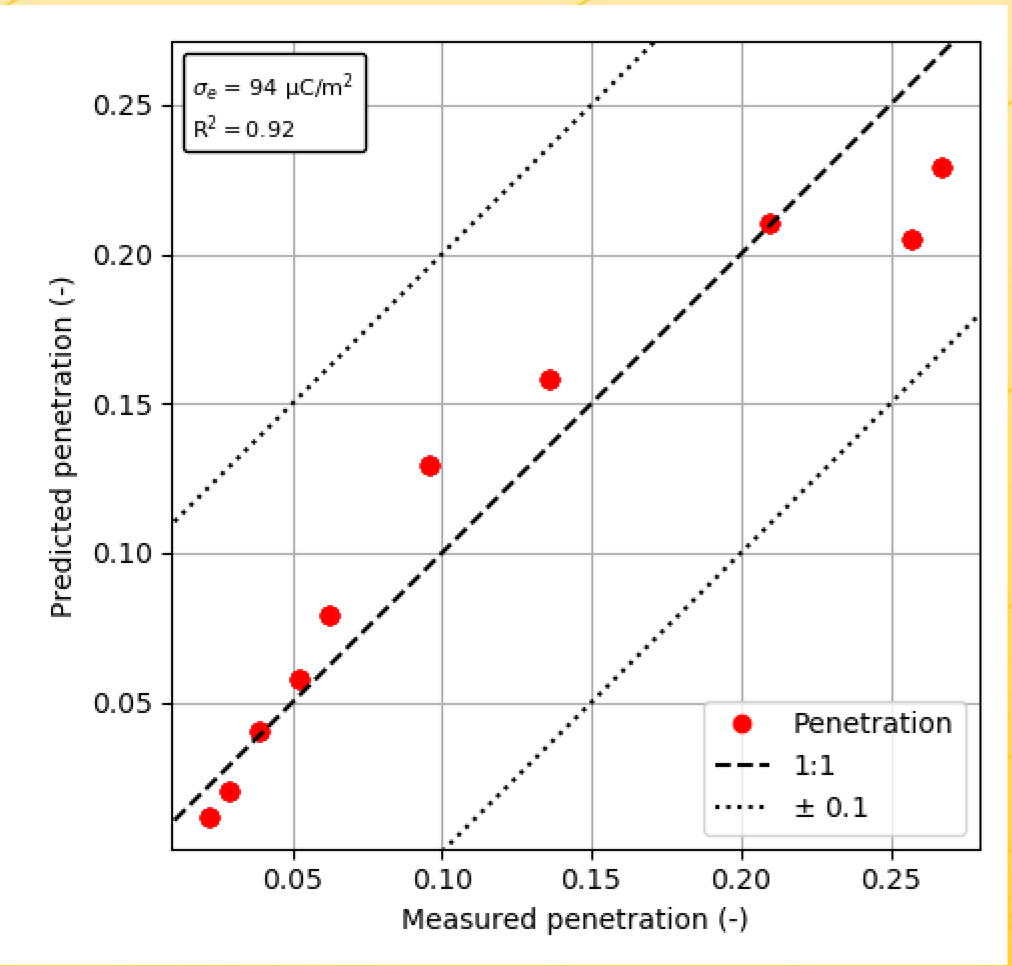
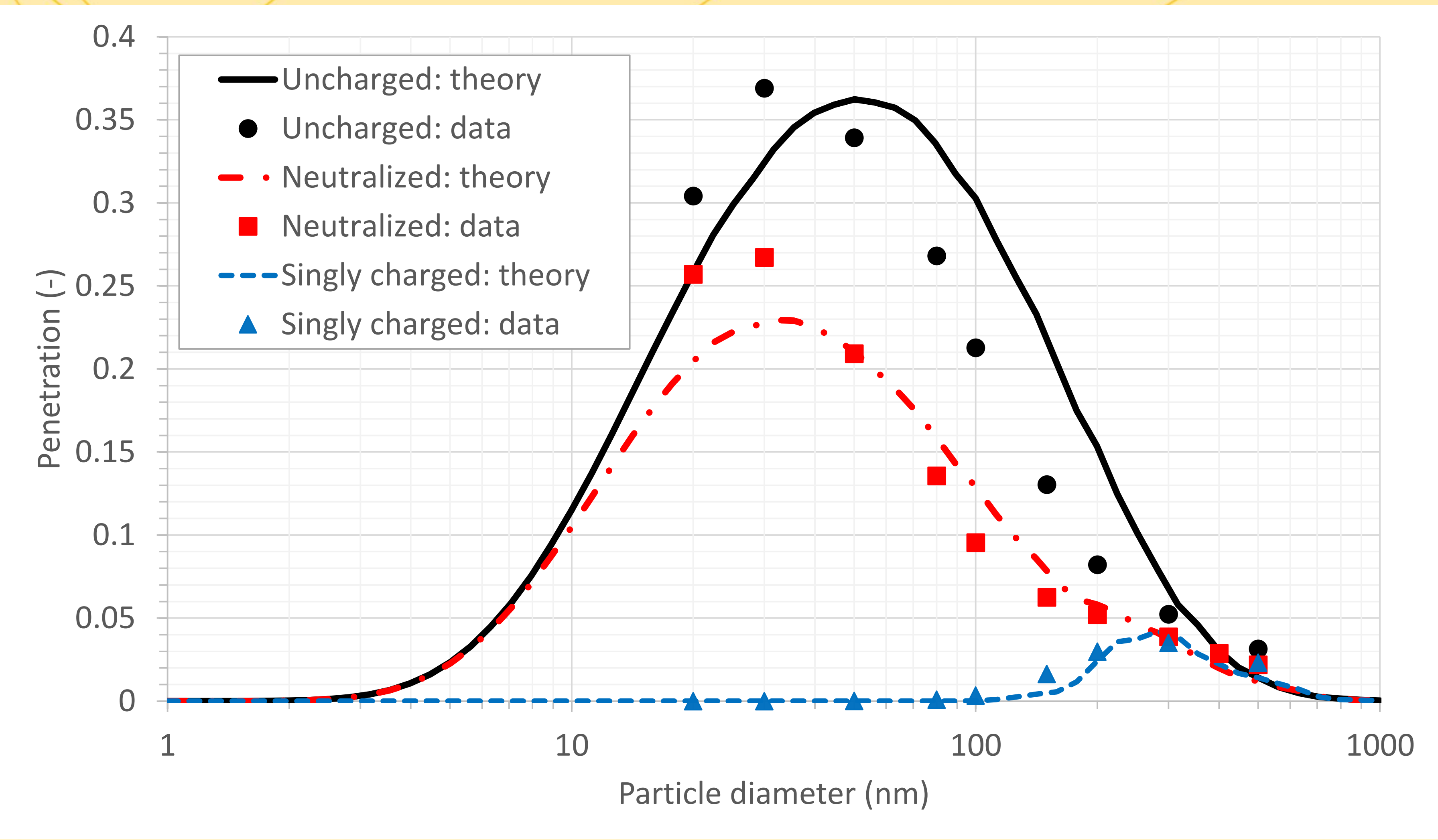
Fitting of effective surface charge density

1. Perform particle size-dependent filtration efficiency test
2. Input particle, operational, and filter properties and measured filtration efficiency into supplied spreadsheet template
3. Upload completed spreadsheet
4. Effective surface charge density σ_e is the surface charge density which minimizes the sum of the squares of the residuals between the experimentally measured and theoretically predicted aerosol penetration



Comparison of predicted and measured penetration



Conclusion

- A numerical model was developed to calculate particle penetration in electret media by considering the diffusional single fiber efficiency calculated by an empirical equation and deterministic single fiber efficiency calculated by limiting trajectories
- A surrogate model was constructed from the numerical results using *K*NN and compared to experimental data
- Model was able to adequately simulate experimental data for fitted surface charge densities which were comparable to values reported in the literature
- Surrogate model was deployed into a web-based electret filter performance model and design tool

Thank you for your attention

Questions and/or comments:
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