Designing Composite Filters for High Efficiency, Low Pressure Drop, and High Loading Capacity

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Outline

- **Introduction and Background**
  - **Energy-efficiency and filtration efficiency of air filtration for a sustainable environment**
- **Objectives:**
  - **Find a good composite media with energy-effectiveness and high efficiency for both initial and loading filtrations**
- **Experiments**
  - **Initial and loading experiments**
- **Modeling**
  - **Theoretical models for both initial and loading filtration**
- **Results and Discussion**
  - **Performance of proposed filter media**
  - **Comparison between data and models**
- **Conclusion and Future work**

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Energy Consumption of Air Filtration

- Many large cities, e.g. Beijing, Shijiazhuang, Mumbai, New Delhi, etc., are being exposed to extremely high PM concentrations (Chang, Chen, Pui, 2016).
- Providing clean air for indoor environments by HVAC system and indoor air cleaner (IAC) is in high demanded (Tang, Chen, Pui, 2017).
- Increasing filter thickness, solidity or reducing the filter fiber diameter to enhance efficiency will result in an increased pressure drop (Chang et al. 2015).
- Particles loaded on or inside the media will also contribute to the pressure drop. A dirty filter can account for up to 20% of system pressure drop in commercial building HVAC systems (Roth et al. 2002).
- Nassif (2012) modeled the effects of the pressure drop of dirty filters for constant-speed fan and found the fan and air-conditioning system need to run longer to meet the same cooling load, resulting in annual increases in fan energy consumption and cooling energy use of up to 5% and 9%, respectively.
- It was estimated the total energy for the fan and cooling in the commercial building HVAC in the US was 1.3% and 2.5%, respectively, of the total primary energy consumption (U.S. Energy Information Administration 2016).

=0.3%+home+school+industry

Chang et al., Aerosol Science and Technology, 49:966–976 (2015)
Chang et al., Aerosol Air Quality Research, 16: 3349-3357 (2016)
Tang et al., Separation and Purification, in press (2017)
Nassif, Building Simulation 5:345-350 (2012)
Roth et al. US Department of Energy (2016)

Energy Consumption of Air Filtration

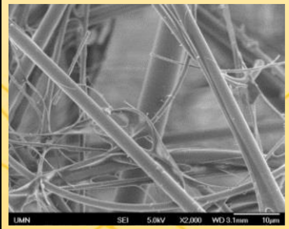
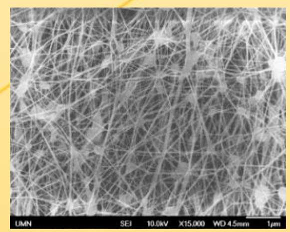
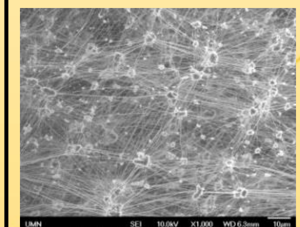
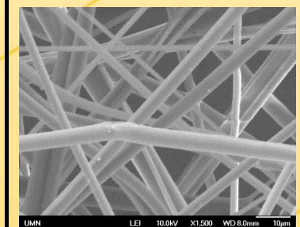
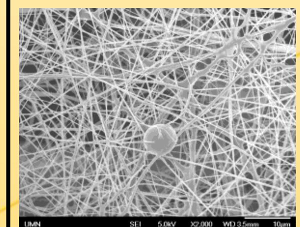
- As sustainability becomes more and more of the global concern, there has been a push by ASHRAE as well as EUROVENT to develop classifications of energy efficiency for air filters (EUROVENT 2014; Sun and Woodman 2009).
- However, the current methods used relatively coarse dusts for loading. Energy consumption in real applications (finer particles) may increase significantly. Mimicked $PM_{2.5}$ were produced to load the HVAC filters (Tang, Thompson, Chen, Pui, 2017).
- For solving the energy issue, electret filter media, where charge added to the fibers increases the filtration efficiency without increasing pressure drop, are well-suited for HVAC and IAC applications (Chang, Chen, Fox, Viner, Pui, 2015; Chen, Wang, Pui, 2014).
- However, there are two major concerns: 1. low efficiency for 10-30 nm particles at initial filtration condition, and 2. significant efficiency reduction during the loading process due to the shielding of fiber charge (Tang, Chen, Pui, 2017).

Chang et al., Aerosol Science and Technology, 49: 966-976 (2015)
Chen et al., Aerosol Science and Technology, 48:997-1008 (2014)
Sun and Woodman, ASHRAE Transactions, 115:581-585 (2009)
Tang et al., Aerosol Air Quality Research, revision (2017)
Tang et al., Separation and Purification, in press (2017)

Objectives and Goal

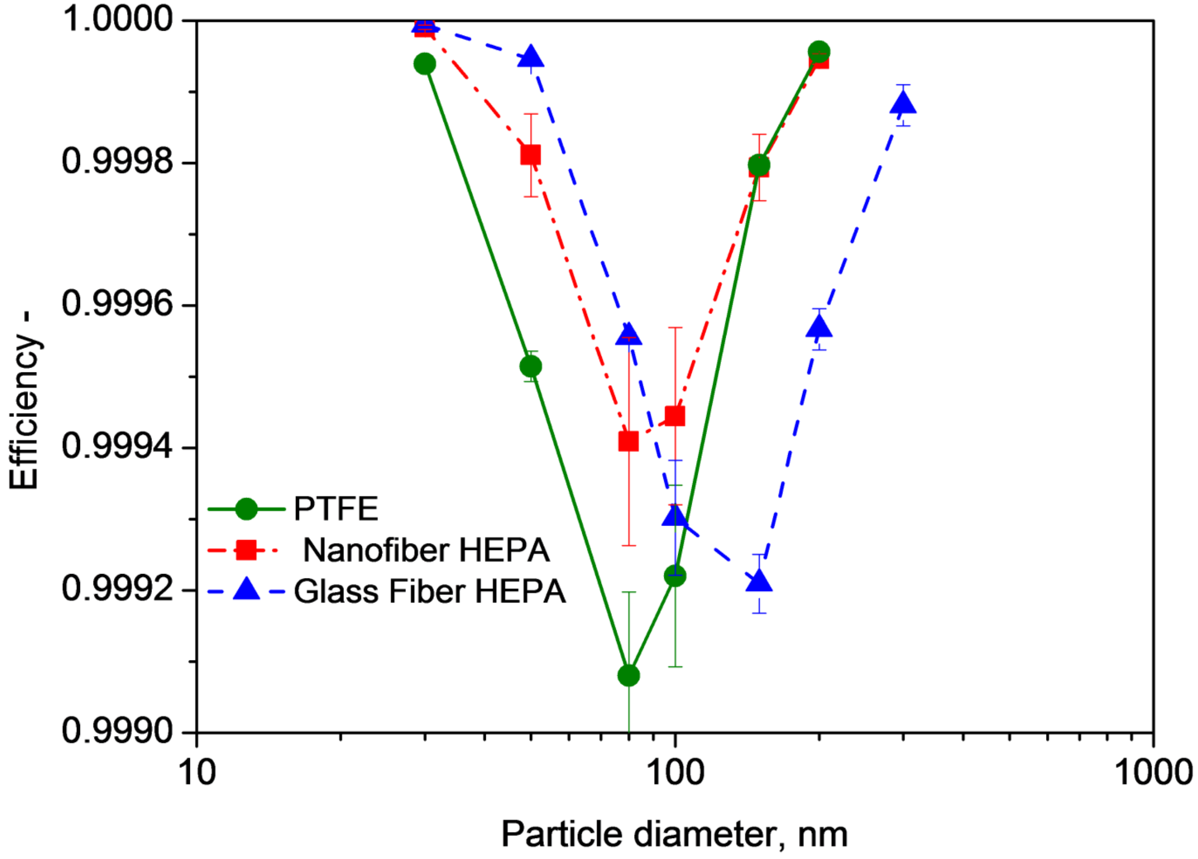
- Introduce some widely used filters in HVAC and compare their performance and applicability.
- Conduct a series of filtration experiments for filters with different materials, structures and compositions.
- According to the data, investigate how to achieve the design of a filter with high efficiency and low pressure drop.
- Develop models to predict the filter efficiencies for both initial and in-use (or loaded) conditions and validate the models with data.
- Use the model to design energy-efficient and high-efficiency filters for air purification systems, including HVAC, cleanroom make-up air, IAC, etc.

Comparison of Different Types of Filter media

Types	**Fiberglass**	**PTFE**	**Ultrafine Nanofiber**	**Electret**	**Traditional nanofiber**
SEM Image					
Fiber diameter (μm)	0.4-0.5	0.02-0.12	0.02-0.15	10-20	0.15-0.3
Thickness (μm)	350-500	5-15	80-150	500-800	5-20
Efficiency (%) for 0.3 um @ 5 cm/s	≥ 99.97	≥ 99.97	≥ 99.97	≥ 95	≥ 80
Pressure drop (Pa)	~300	~150	~150	~10-15	~15-25
Mechanism (cross-section)	Depth filtration	Surface filtration	Depth filtration	Depth filtration	Surface + Depth

Efficiency of Clean HEPA Filter Media

Face Velocity: 5cm/s



Pressure Drop

PTFE
92 Pa (0.37 in-H_2O)

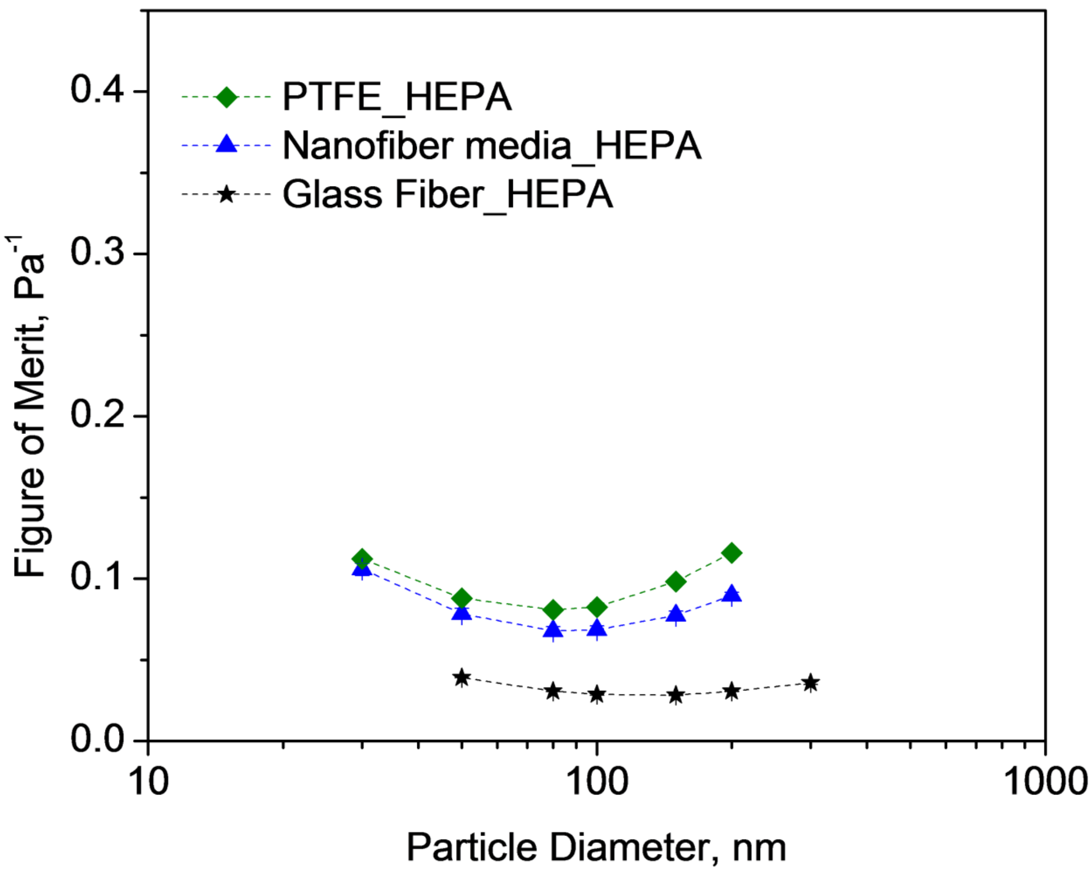
U-Nanofiber HEPA
115 Pa (0.46 in-H_2O)

Glass fiber HEPA
257 Pa (1.03 in-H_2O)

- The lowest efficiencies of Nanofiber, PTFE and Glass Fiber HEPA media are very close.

Figure of Merit (FOM) of different HEPA Filter Media

Face Velocity: 5 cm/s



$$FOM = \frac{-\ln(1-E)}{\Delta P}$$

E: Filtration efficiency
Δp: Pressure drop

FOM: Quality factor

- FOM: Nanofiber > PTFE > Glass Fiber
- FOM of electret media is much higher than the other three mechanical filters.

Important Performance Parameter for IAC and HVAC: Clean Air Delivery Rate (CADR)








Indoor Air Cleaners

HVAC Systems

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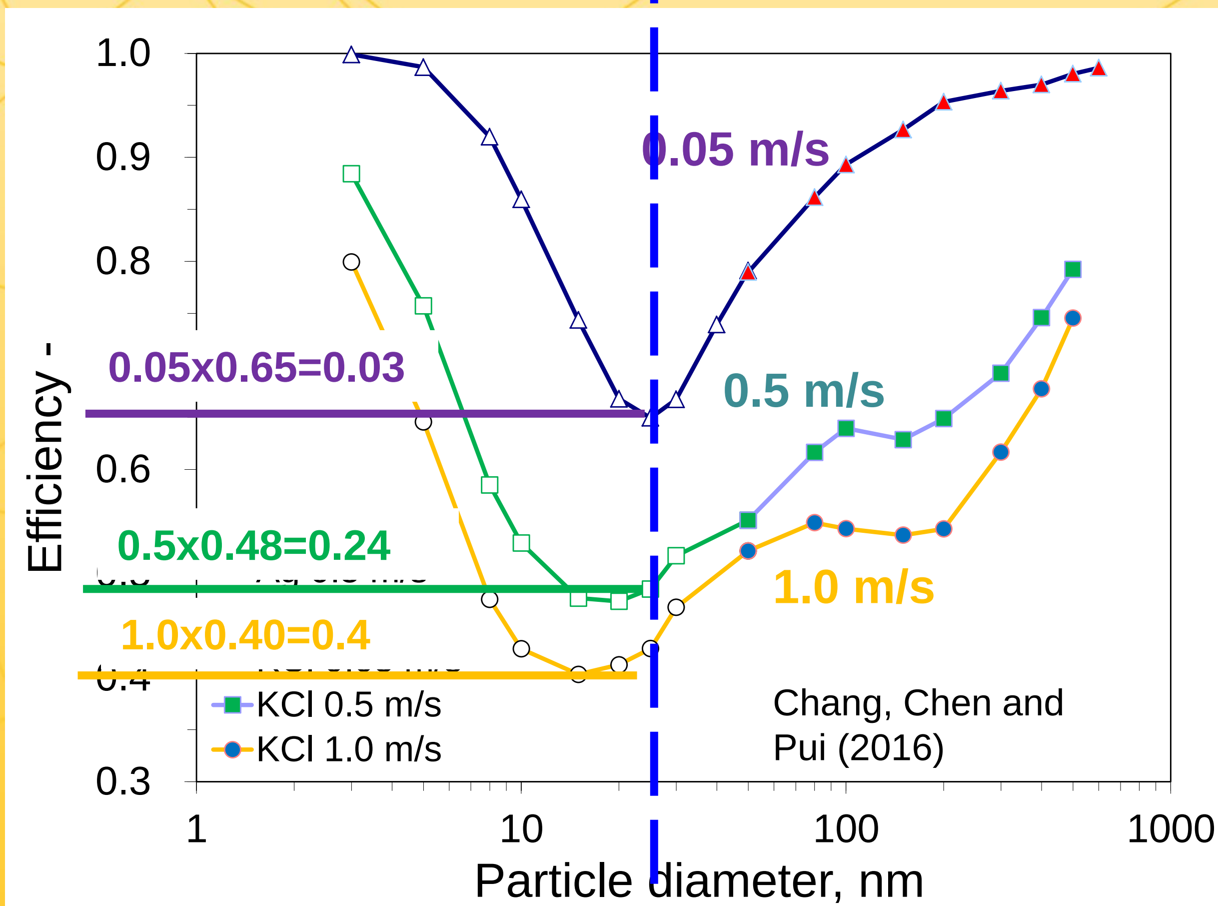
https://www.google.com/search?q=portable+indoor+air+cleaner
https://www.google.com/search?q=hvac&source

CADR - Clean Air Delivery Rate

CADR=Q x Eff.

Example:
CADR 1= 300 cfm x <u>99.99%</u>=300
CADR 2= 400 cfm x <u>75.00%</u>=300

Ptak (2016)



If pressure drop is not considered, The CADR of 1.0 m/s is about **2x** of 0.5 m/s and **10x** of 0.05 m/s.

- Chang et al., Aerosol Air Quality Research, 16: 3349-3357 (2016)
- Ptak. AFS Fall conference (2016)

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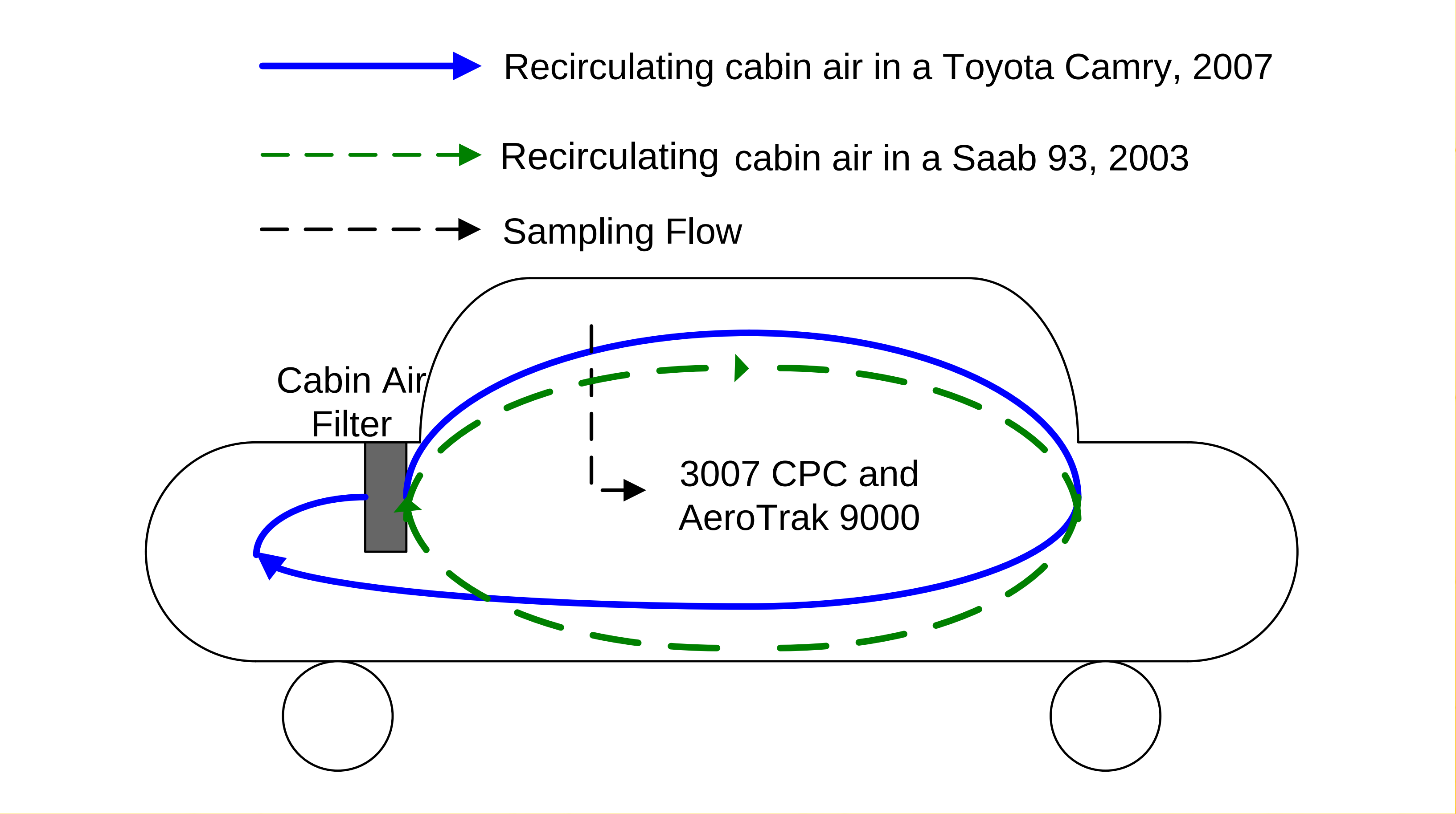
Cabin air filter – recirculation mode



Qi et al., *Env Sci Tech* 42:4128-4132 (2008)

Pui et al., *Env Health Perspectives* 116:863-866 (2008)

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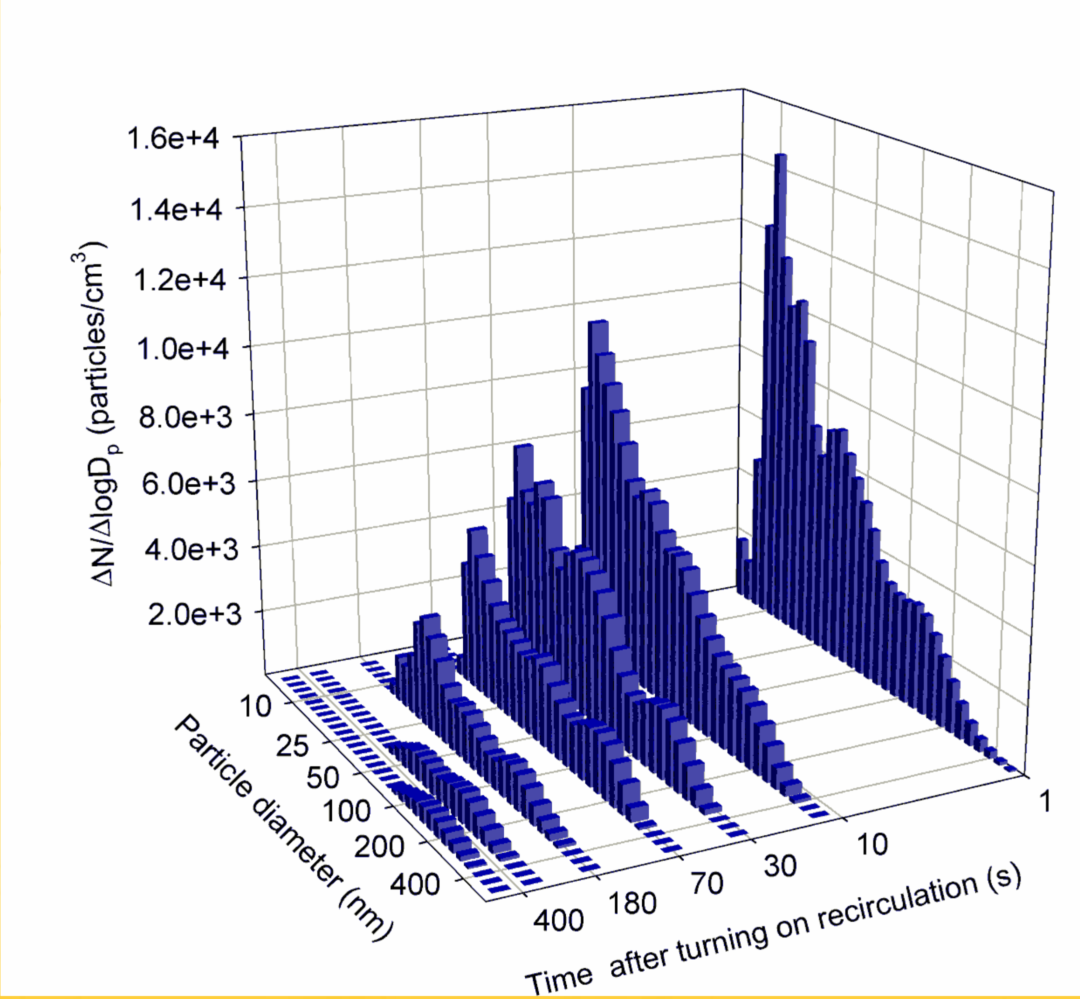
Evolution of Particle Size Distribution in Recirculating Air



Pui et al. *Env Health Perspectives* 116:863 (2008)

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In-room Recirculation Test

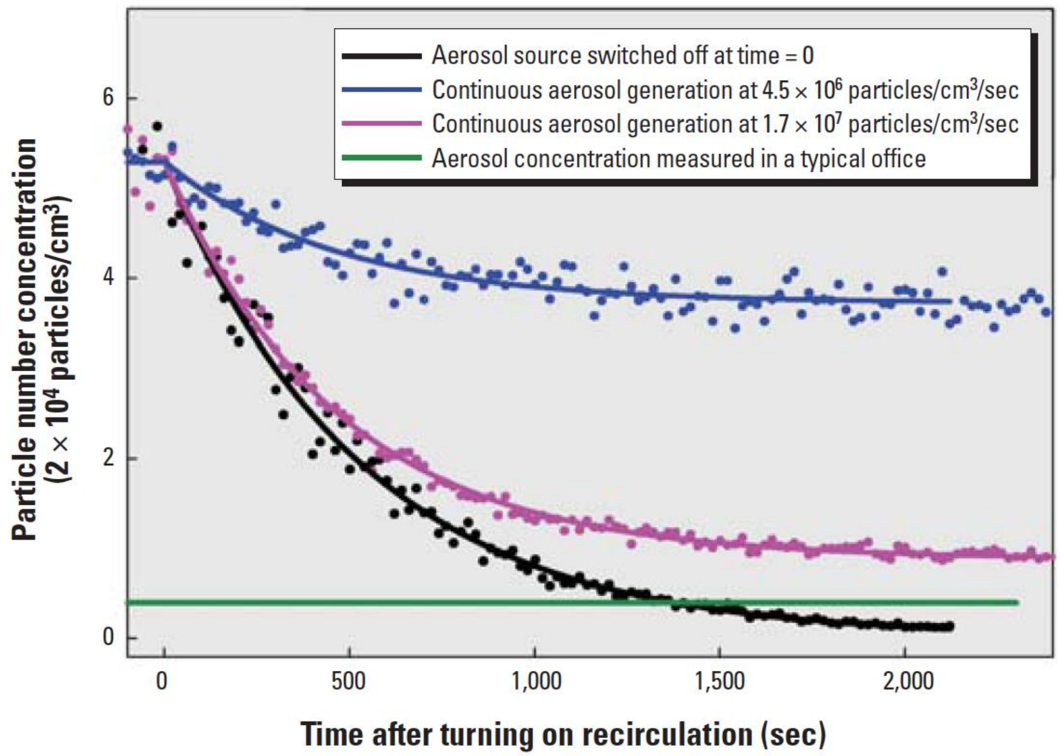


Figure 4. Measured particle number concentration in an enclosed room containing a source of silver nanoparticles with time, while recirculating air through an HVAC filter at 50,970 L/min. Dotted lines, experimental data. Solid lines, data fit using the developed empirical model. For comparison, the aerosol particle number concentration measured in a typical office is shown (4,000 particles/cm^3).

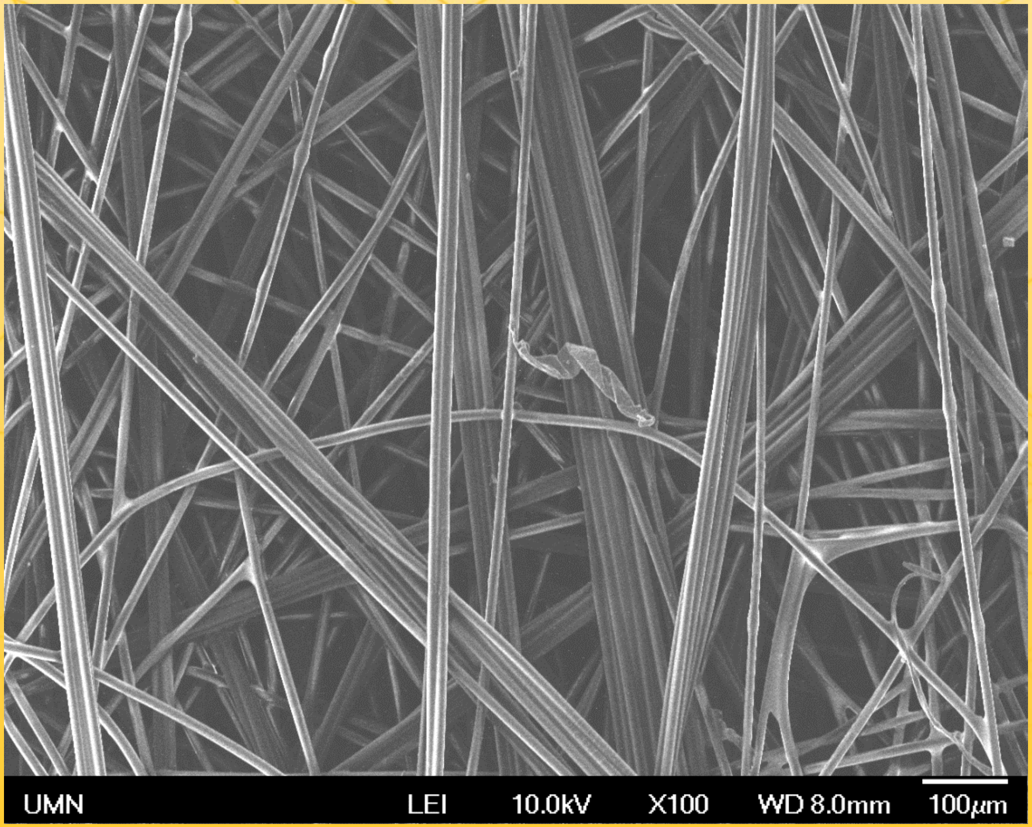
- Dots: Experimental data
- Solid line: Modeling results

Pui et al. *Env Health Perspectives* 116:863 (2008)

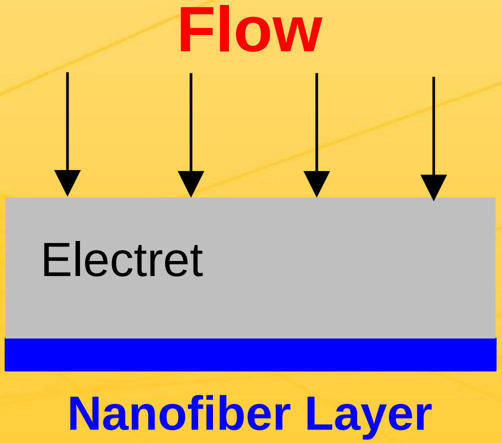
Electret + Nanofiber Layer

- Low efficiency for 10-30 nm particles
- Significant efficiency reduction during the loading process due to the shielding of fiber charge

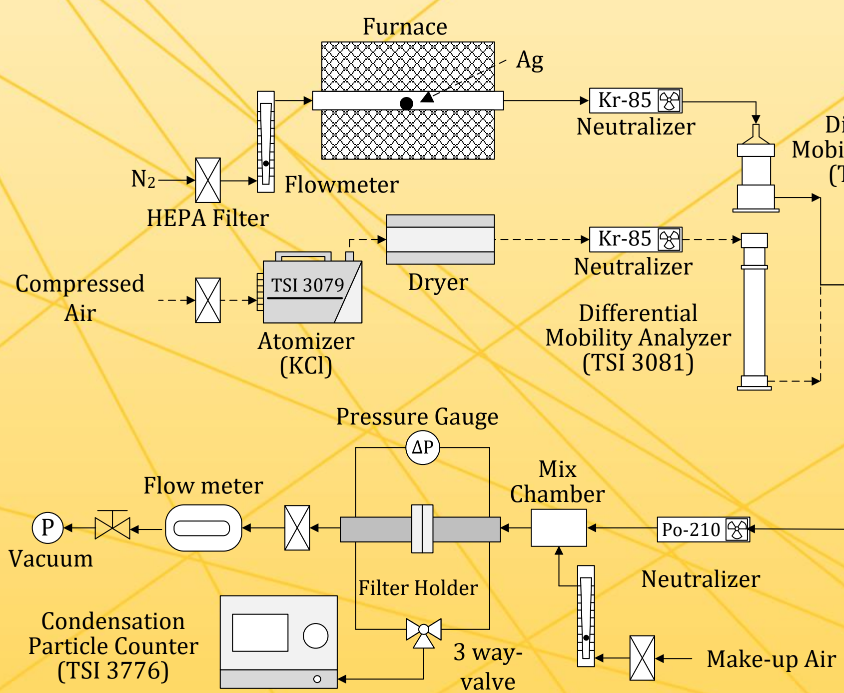
Electret (highly charged)

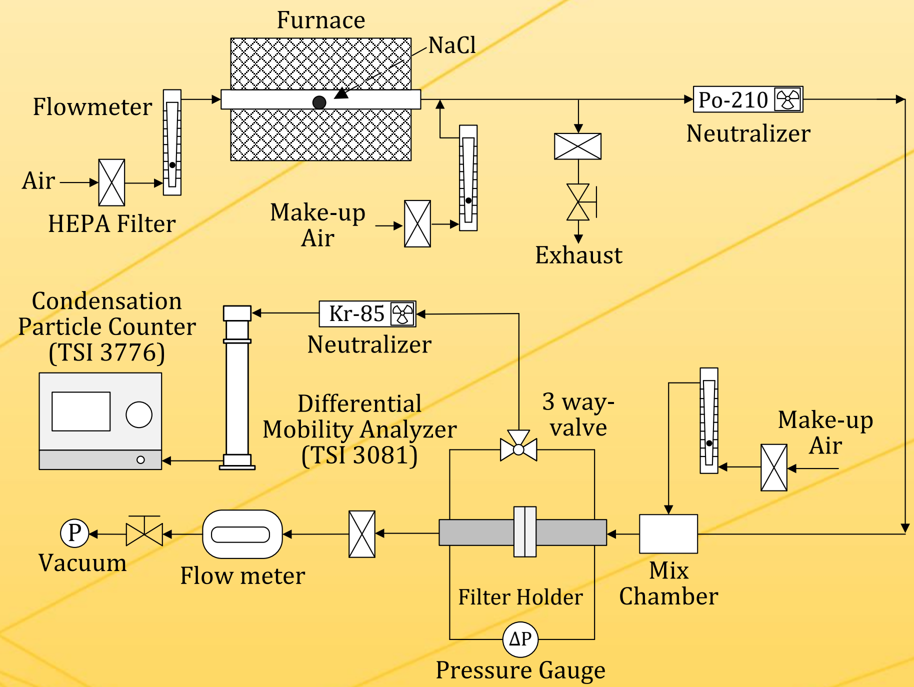


Types	Electret+ Nanofiber
Fiber diameter (μm)	10/0.3
Thickness (μm)	500-1000
Efficiency (%) for 0.3 um @ 5 cm/s	≥ 90
Pressure drop (Pa)	~25-40
Pore diameter (μm)	--
Mechanism (cross-section)	Depth



Experimental setup- initial vs. loading test





- **Initial efficiency measurement**
  - ➢ Monodisperse particles classified by DMA were used to challenge the filter
  - ➢ Efficiency was determined from the up- and down-stream particle concentration of the filter
- **Efficiency during loading process**
  - ➢ Particles mimicking the size distribution of ambient $PM_{2.5}$ were used to challenge the filter
  - ➢ Efficiency was determined along the loading process by the SMPS and confirmed by the weighing method

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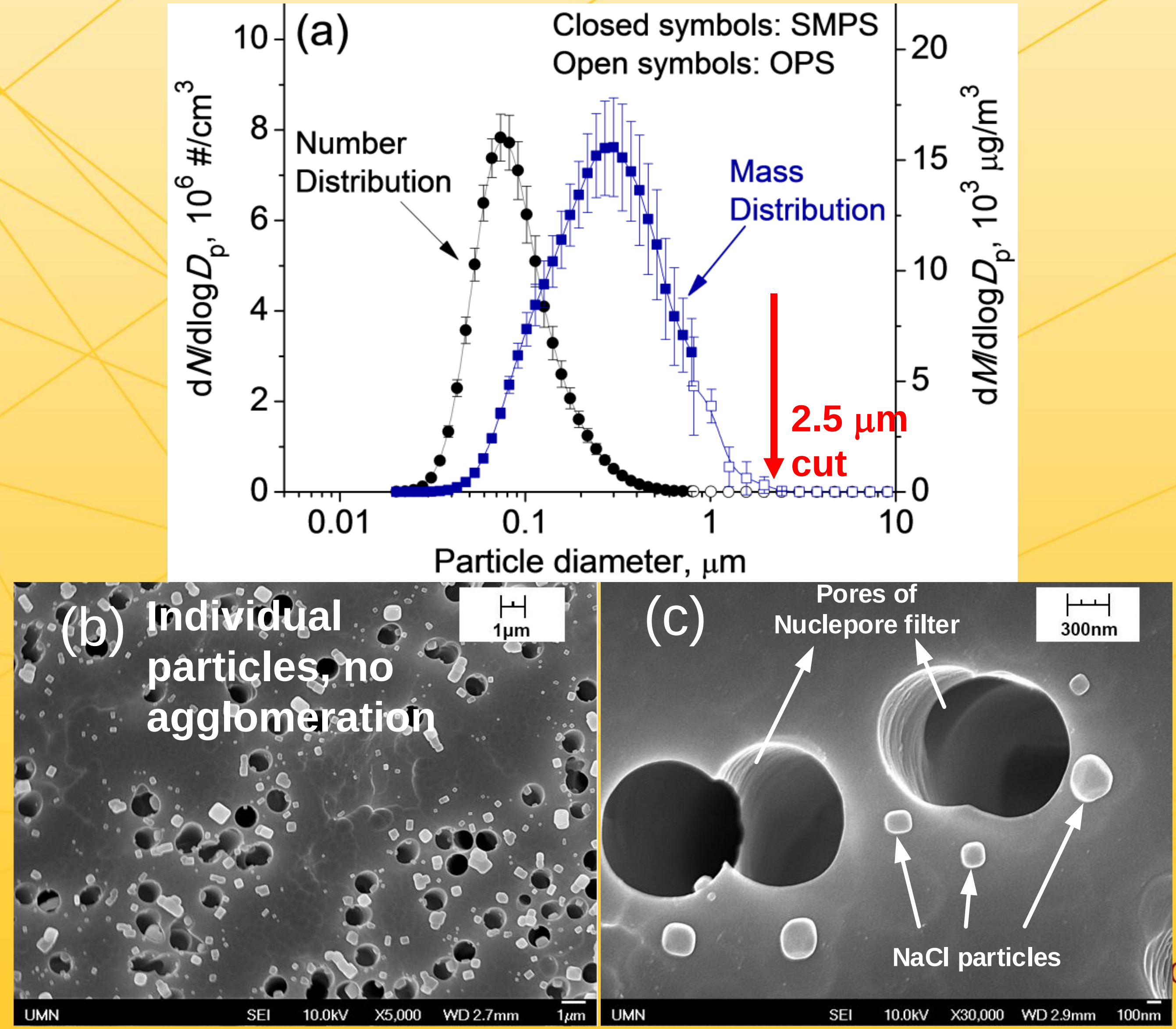
Size distribution of the mimicked $PM_{2.5}$ (NaCl) and their SEM images



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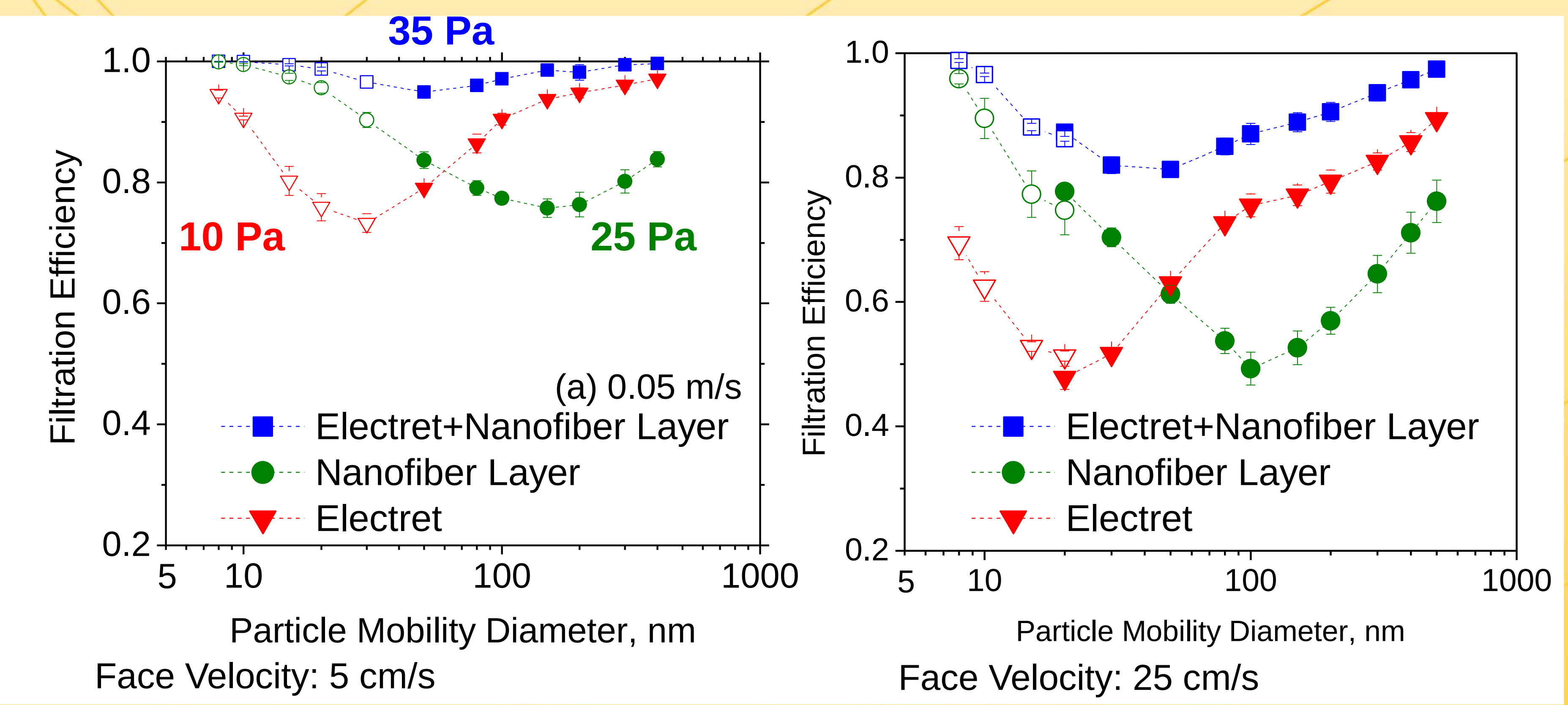
Initial Filtration Efficiency of the Composite Media



Electret + Nanofiber layer increases the minimum filtration efficiency and enhances nanoparticle removal compared to that of electret media.

Tang et al., Separation and Purification, in press (2017)

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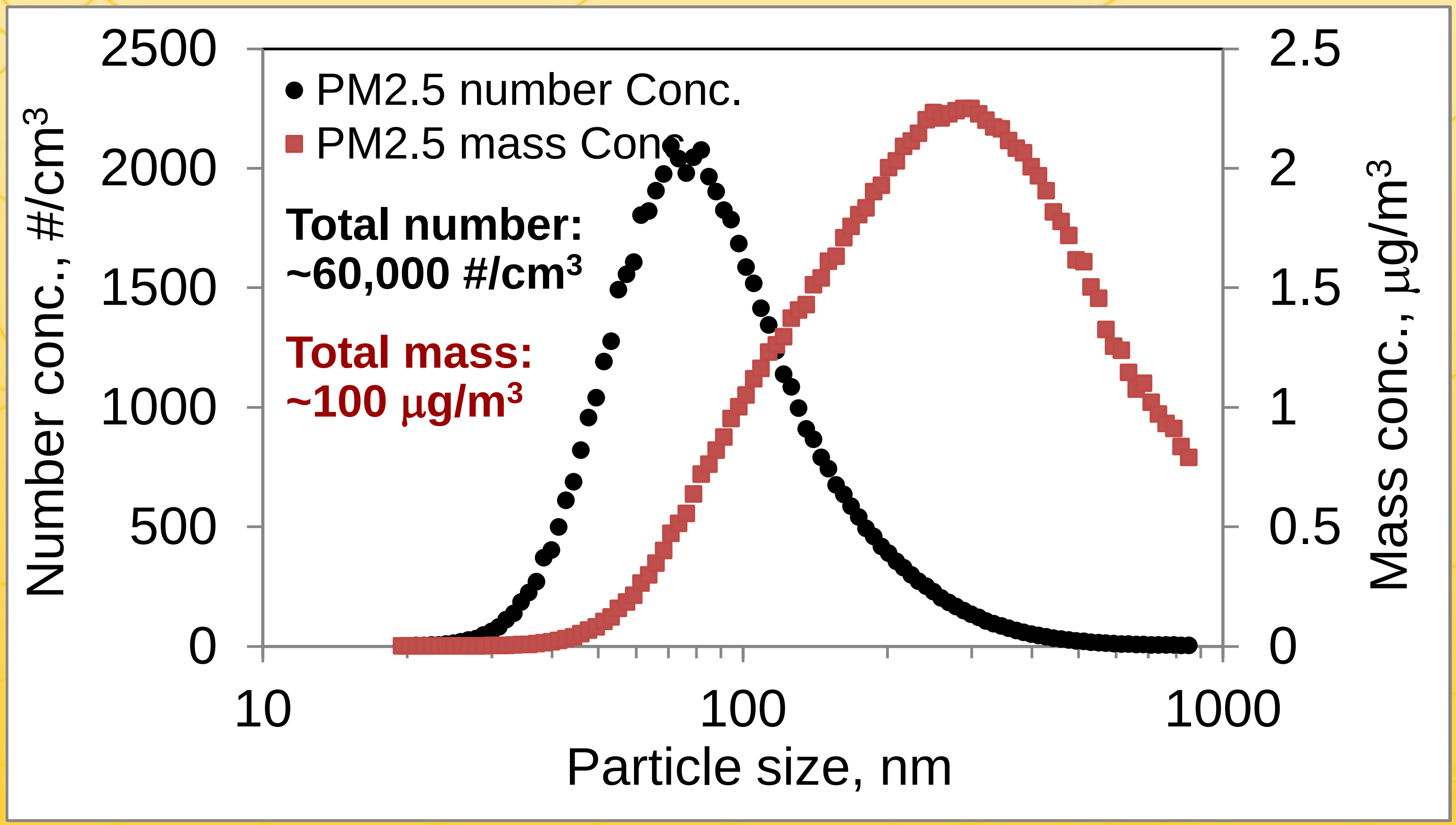
Change of Size Distribution of $PM_{2.5}$ after Passing through Typical Electret Media and Nanofiber Layer



Modeling of Initial Efficiency for Nanofiber Layer and Electret

- Single fiber theory (superposition of mechanical and electrostatic depositions)
  - Theoretical particle penetration

$$P_{theo} = \sum_{n=-10}^{n=10} f(n) \times \exp\left(-\frac{4\alpha E_T(n) t}{\pi d_f (1-\alpha)} \right)$$

- α: the solidity of the filter
- *t: the* thickness of the filter
- d_f: the fiber diameter

Interception of diffusing particles **Impaction**

$$E_T = 1 - (1 - E_D)(1 - E_R)(1 - E_{DR})(1 - E_I)(1 - E_q)$$

Diffusion **Interception** **Electrostatic attraction deposition**

$$E_q = 1 - (1 - E_{qC}(n))(1 - E_{qD})$$

$E_{qC}(n)$: depositions by the Coulombic force

E_{qD}: depositions by dielectric polarization force

$E_{qc}(n) \times E_{qD}$: Polarization force for charged particles were considered (Chang, Chen, Pui et al. 2016).

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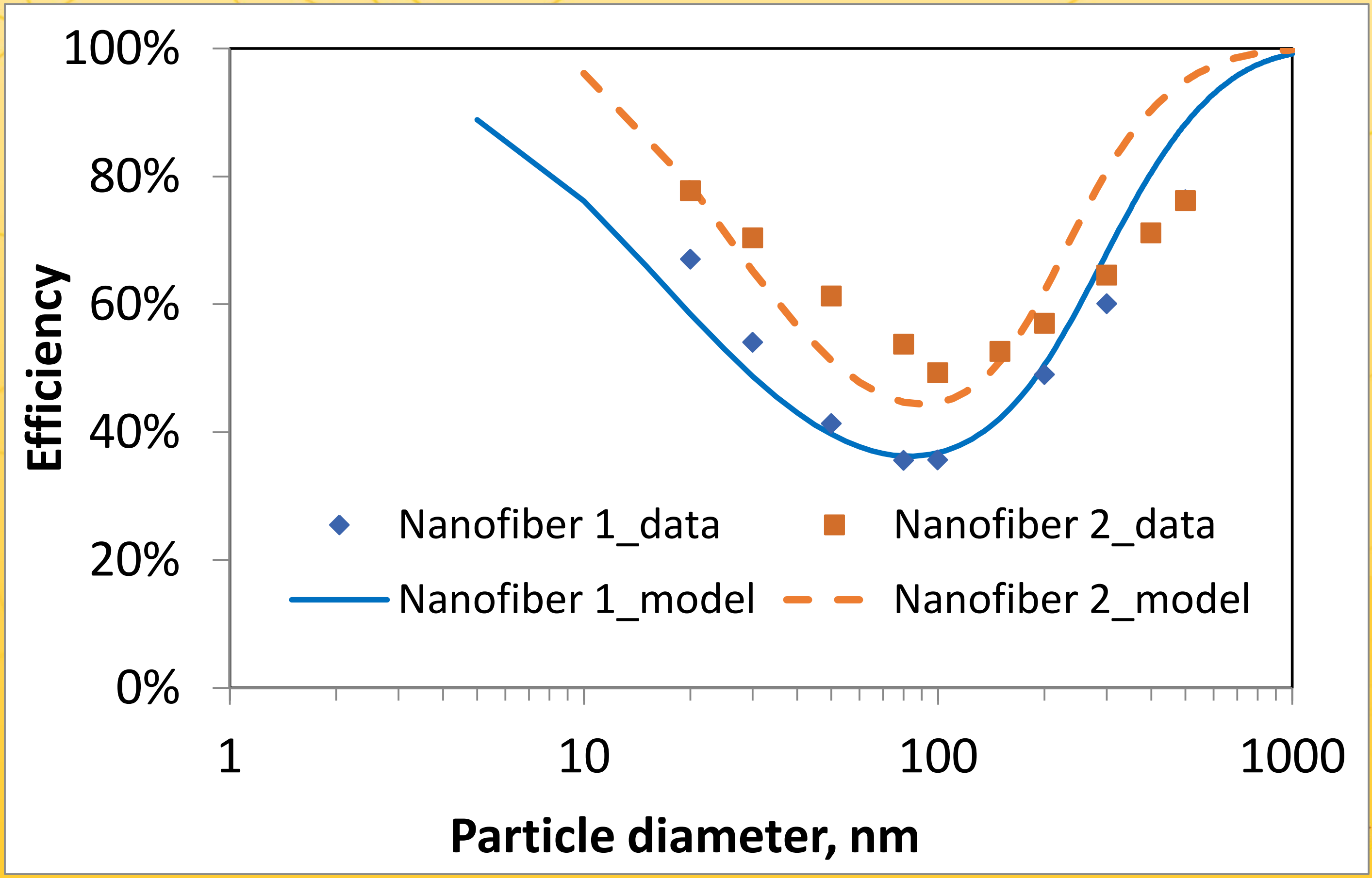
Chang et al., Aerosol Air Quality Research, 16: 3349-3357 (2016)

Modeling of Initial Efficiency for Nanofiber

- Single fiber efficiency model was used to calculate the theoretical efficiency of nanofiber filter (Wang, Kim, Pui, 2008).
- Fair agreement between data and model were observed.



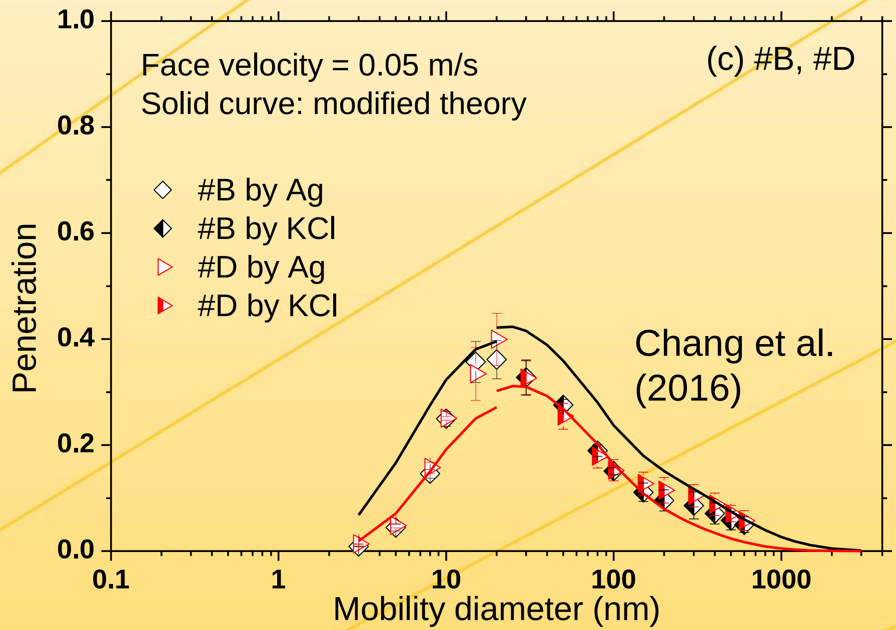
Wang et al. Aerosol Science Technology 42: 722-728 (2008)

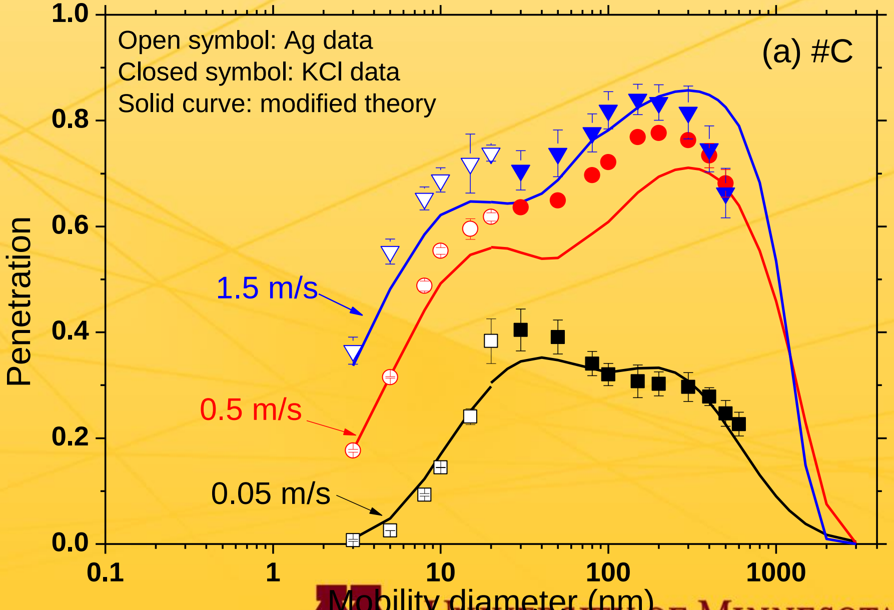
Modeling of Initial Penetration for Electret media

$$\frac{4De}{U_0 d_f^2 E_T^2} \geq 1$$

D, e, and U are diffusivity of the particles, half-layer spacing in fiber array, and face velocity.

Brown (1993) reported that the single fiber efficiency model may not be applicable if the diffusivity of the particles is not sufficiently great to distribute the incoming particles uniformly in concentration within an inter-layer spacing of the media.





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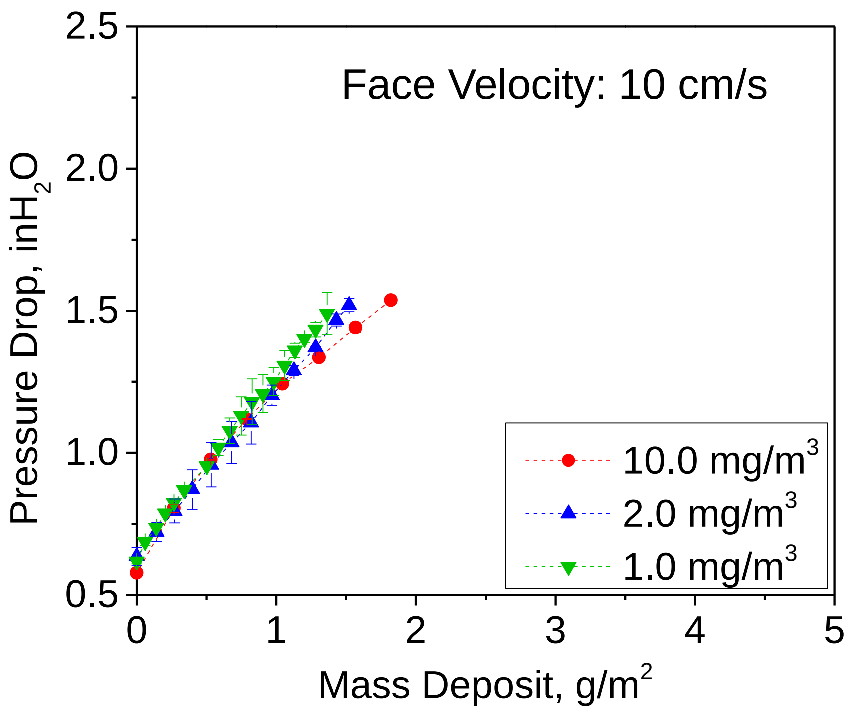
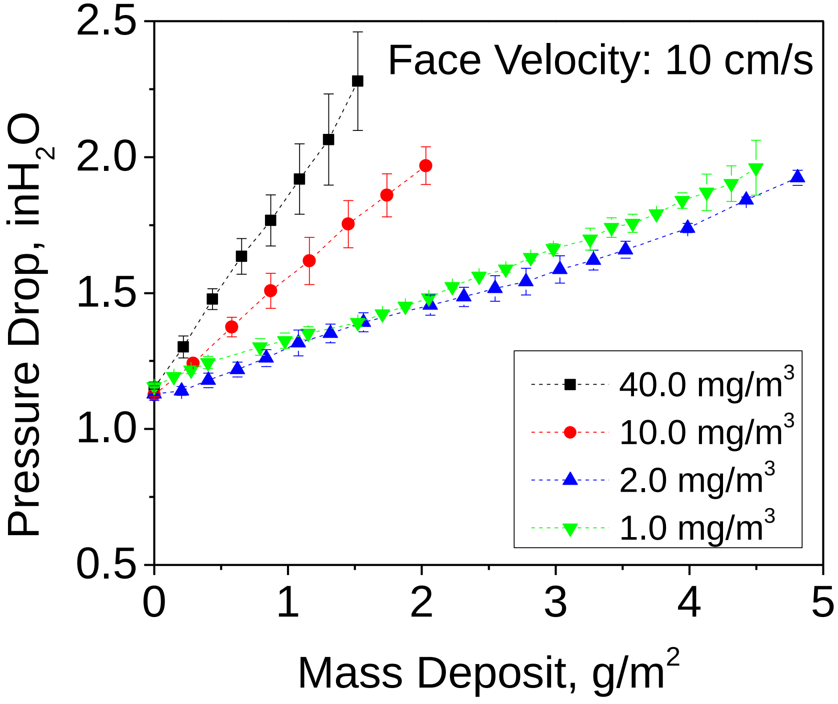
Chang, Chen and Pui, Aerosol Air Quality Research, 16: 3349-3357 (2016)

Effect of Particle Concentration on Loading Characteristics

PTFE Media Surface filtration

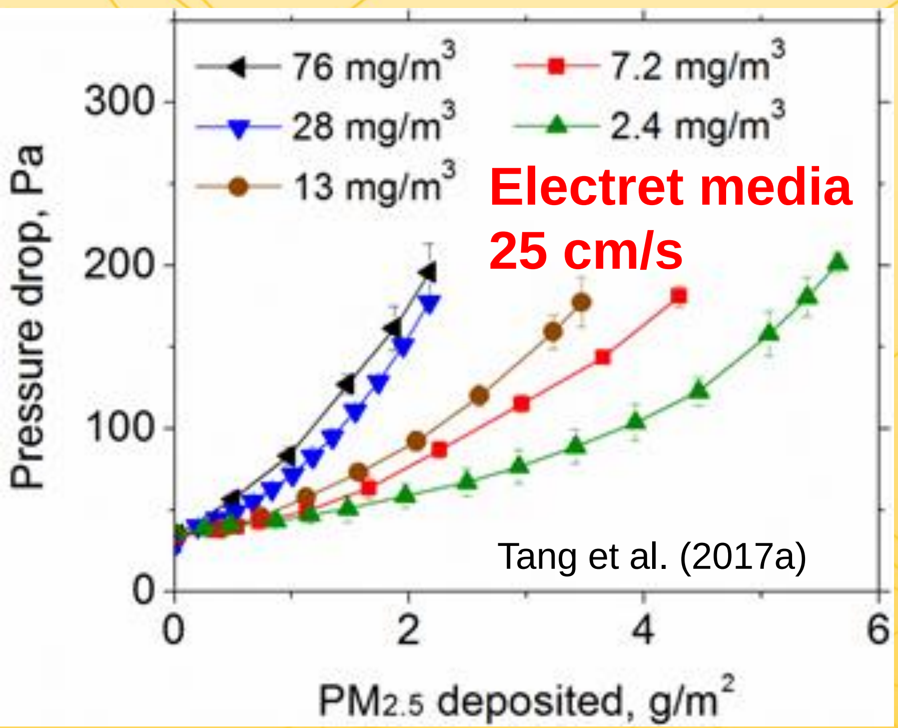


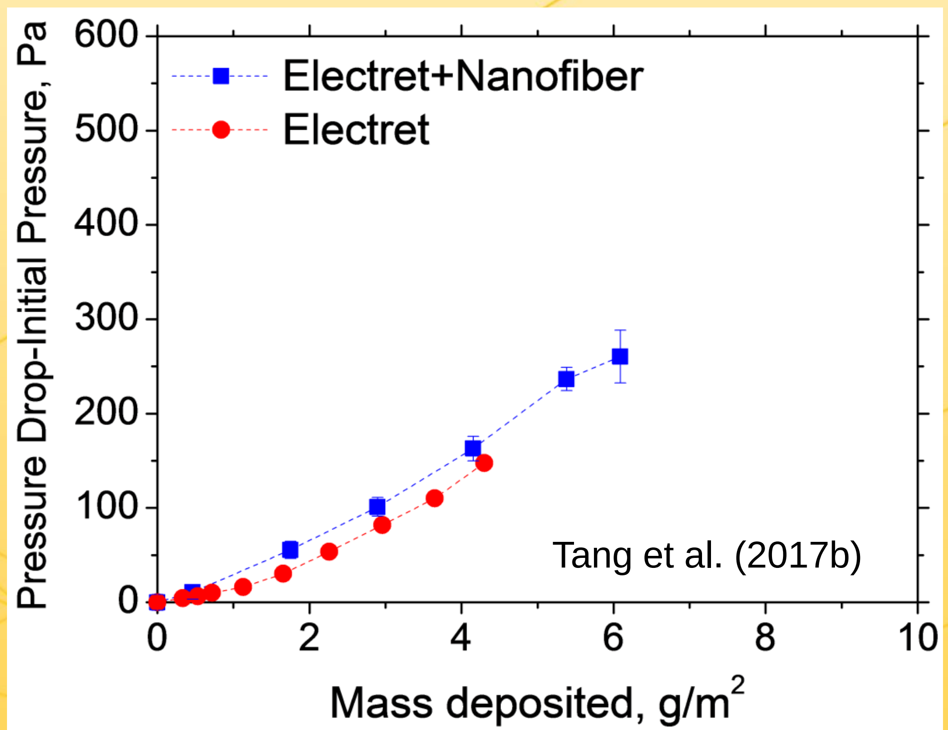
Glass Fiber Media Depth filtration



For depth filtration media, loading test should be under low particle concentration.

Effect of Particle Concentration on Loading Characteristics for Electret and Composite Media





The trend of pressure drop growth is similar with Fiberglass filter. They both are depth filtration filters.

Adding nanofiber in the bottom of electret media does not increase the slope of the pressure curve.

Tang, Chen et al. Separation and Purification, in press (2017a)
Tang, Chen et al., Aerosol Air Quality Research, accepted (2017b)

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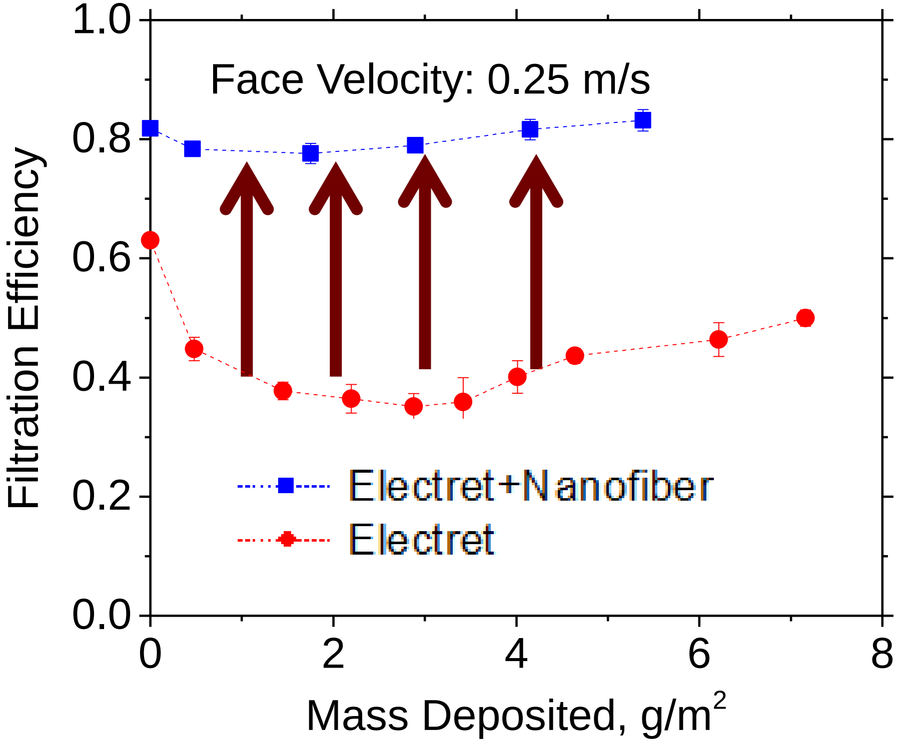
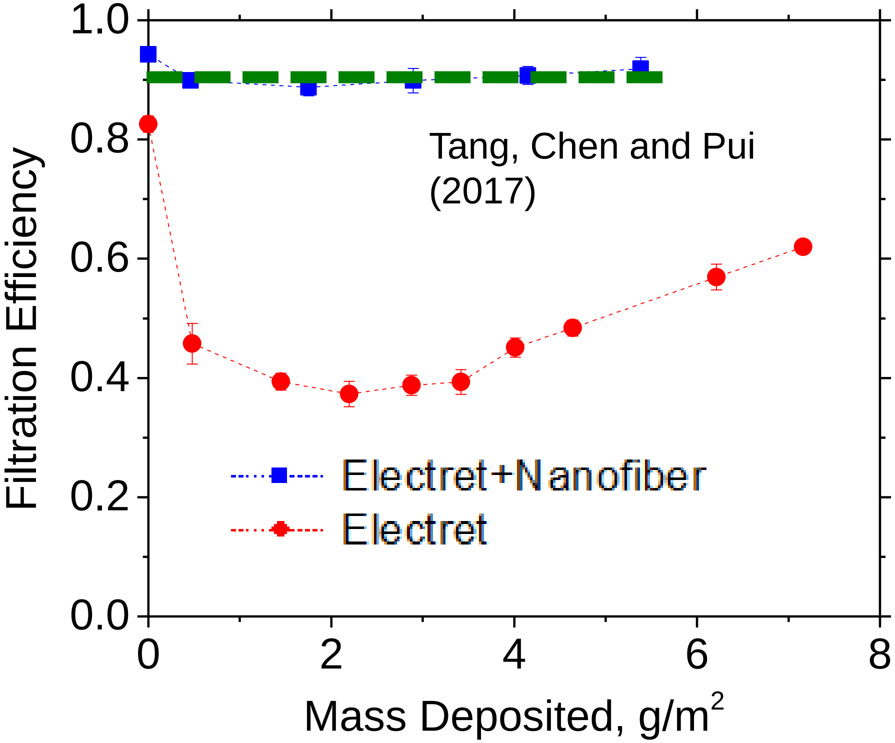
Filtration Efficiency of Electret Media and Electret+Nanofiber Layer along Loading





- The filtration efficiency of Electret decreased dramatically with an overall efficiency of 20-40% right after 0.5 g m^{-2} of loading for all particle sizes
- In comparison, the Electret + Nanofiber media have only a slight reduction of efficiency by 3-10% after 0.5 g m^{-2} of loading

Tang et al., Separation and Purification, in press (2017)

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Theoretical Modelling of Filter Efficiency during Loading Process

For homogenous fibrous filter media undergoing depth filtration, the single fiber efficiency will vary with time and depth during loading process as $\eta(x,t)$

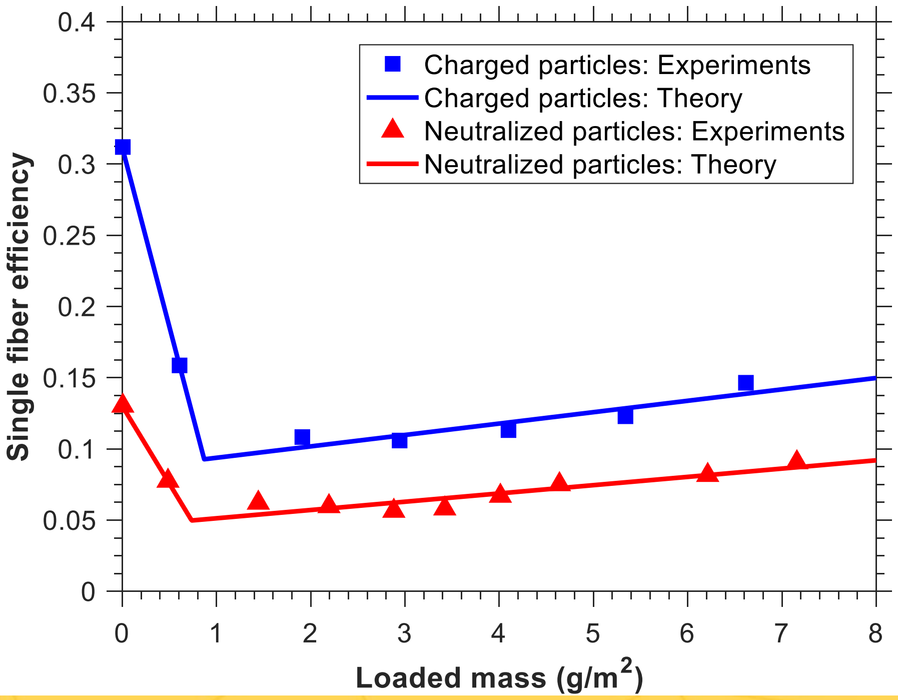
$$\eta(x,t) = \eta_0 - \frac{\pi(1-\alpha)d_f}{4\alpha}\beta M(x,t)$$

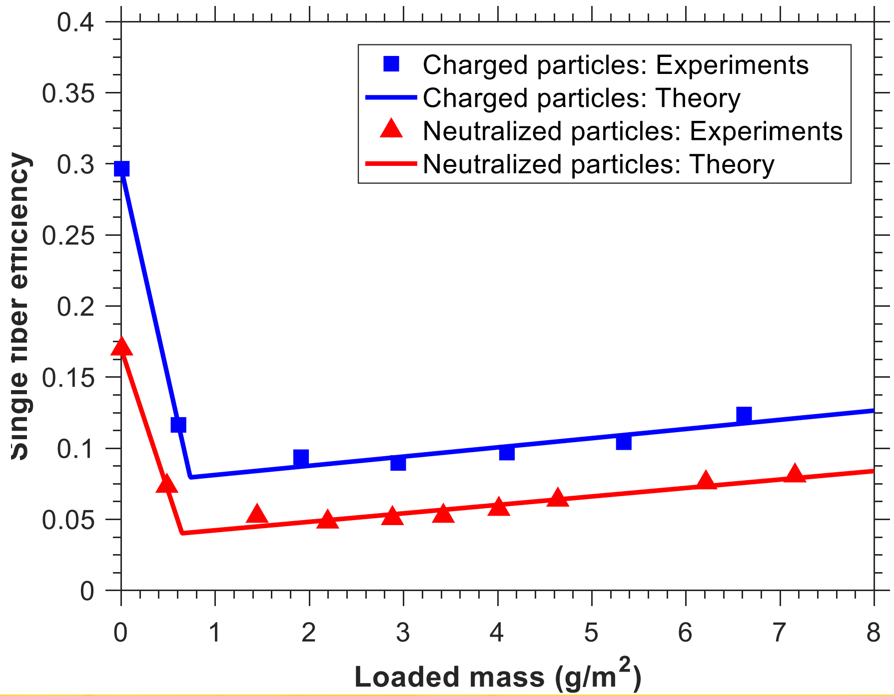
Brown et al. (1988) suggested the initial single fiber efficiency, η_0, decreases linearly with increasing local collected aerosol mass per unit volume, M (x,t), The parameter β gives an estimate of effectiveness of the loading aerosol in reducing the electrostatic filtration efficiency.

$$\eta(x,t) = \eta_{m0}\left[1 + \lambda M(x,t)\right]$$

In comparison, the theoretical and experimental work of Kanaoka et al. (1983) and Myojo et al. (1984), respectively, suggested that the initial single fiber efficiency of mechanical filter media will increase linearly with the increasing local collected aerosol mass concentration.

Modeling of Filtration Efficiency of Electret Media during the Loading Process





The proposed model caught the evolution trend of filtration efficiency during the loading very well.

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Summary and Future Work

- Characteristics of different types of filter media were compared and discussed. It is suggested to use lower grade of filter media to enhance the CADR.
- To achieve low pressure drop while remaining high efficiency, electret+nanofiber layer filter media was proposed.
- Initial efficiency and efficiency during loading with mimicked $PM_{2.5}$ of proposed electret+nanofiber media were investigated and discussed.
- The new composite media not only achieved the energy-effectiveness and efficient filtration but also minimized the efficiency reduction compared with using only electret media.
- Theoretical models were used to predict not only initial efficiency but also efficiency during the loading. Results were in good agreement with experimental data.
- The model could be applied in the web-based application to design a proper filters using the combination of electret+nanofiber for cost-effectiveness removal for $PM_{2.5}$.

Thanks for you attention

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I would be happy to take any question

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