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Designing and Optimizing Composite Filters for High Efficiency, Low Pressure Drop, and High Loading Capacity $PM_{2.5}$ Filtration

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Air Pollutions are Impacting Asian Cities

Image from South China Morning Post

Air Purifier and HVAC System: Clean Air Delivery Rate (CADR)

Indoor Air Cleaners

HVAC Systems

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

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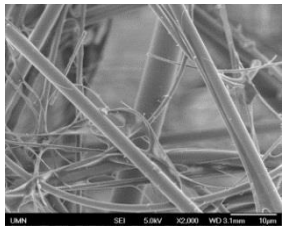
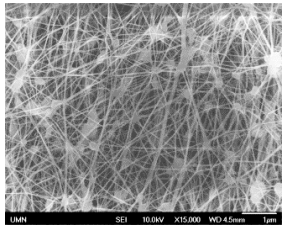
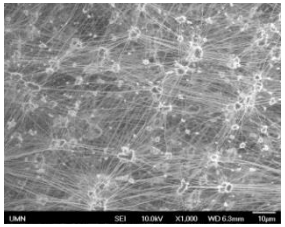
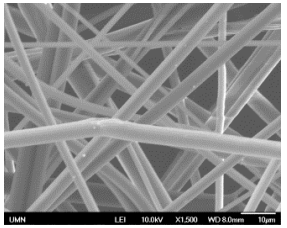
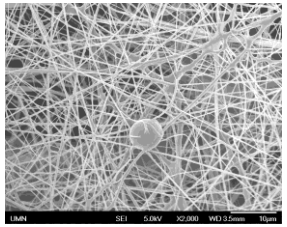
Energy Consumption in Air Filtration

- Pressure drop increase during loading: mainly from clogging (dendrite formation). Fan and cooling system need to run longer and consumes 14% more energy (Nassif 2012).
- Sustainability becomes more and more of global concern, ASHRAE as well as EUROVENT is developing classifications of energy efficiency for air filters (EUROVENT 2014; Sun and Woodman 2009).
- However, the current standards are using coarse dusts for loading. Energy consumption in real applications (finer particles) can increase significantly. Simulated $PM_{2.5}$ should be produced to load the filters (ASHRAE 2017; Brown 1993; Tang et al. 2017).
- For solving the energy issue, electret filter media, where charges added to the fibers increase the filtration efficiency without increasing pressure drop, are well-suited for HVAC and IAC applications (Chang et al. 2015; Chen et al. 2014).
- However, there are two major concerns: 1. significant efficiency reduction during the loading process 2. low efficiency for 10-30 nm particles at initial filtration condition, and due to the shielding of fiber charge (Tang et al. 2017).

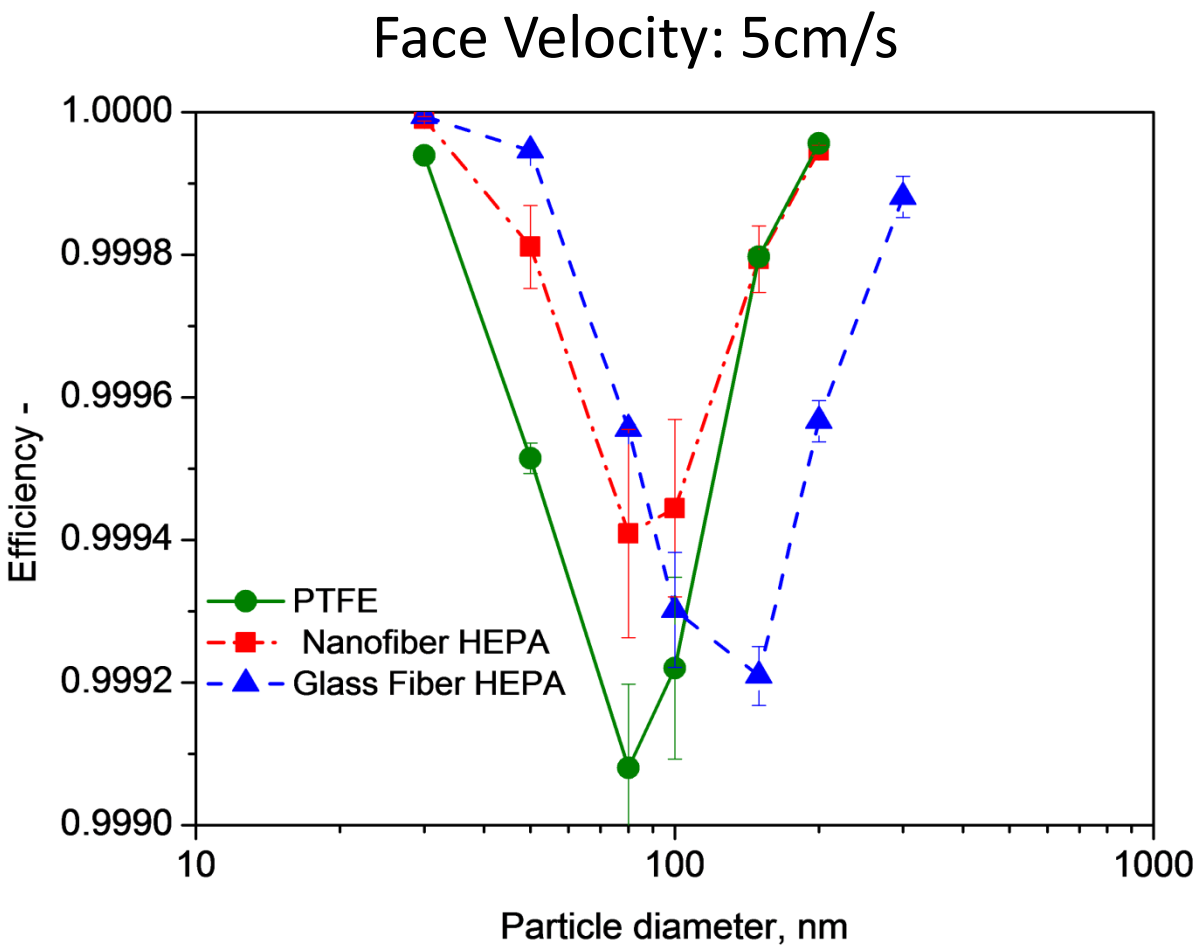
Objectives and Goal

- Propose a smart composite media and conduct systematic experiments for initial efficiency and loading characteristics using particles with $PM_{2.5}$ distribution.
- Compare models with efficiency data for both initial and in-use (or loaded) conditions.
- Analyze particle depositions in different filter media in a microscopic point of view: single fiber and single layer collection.
- Prove the smart composite media is an optimal design for removing high $PM_{2.5}$ with low pressure drop and long service life.

Comparison of Different Types of 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



Pressure Drop

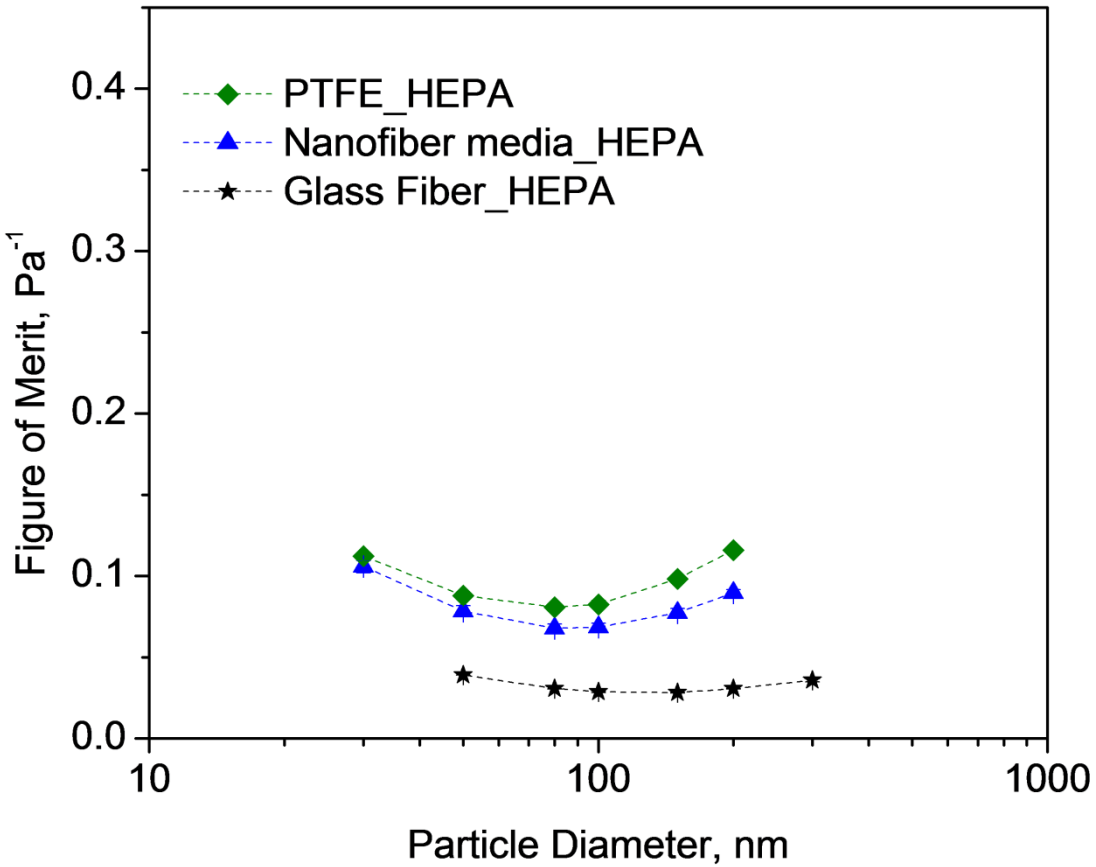
U-Nanofiber HEPA
115 Pa (0.46 in-H_2O)

PTFE
92 Pa (0.37 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.

Minimizing the Growth of Pressure Drop during the Loading (Key parameters)

- **Particle deposition pattern favors a lower increase of pressure drop (deposition site of particles is close to the forward stagnation point or cover the whole surface of fiber).**
- **Minimize and delay the formation of dendrites or increase the collapse rate of dendrites.**
- **Depth deposition is preferred.**

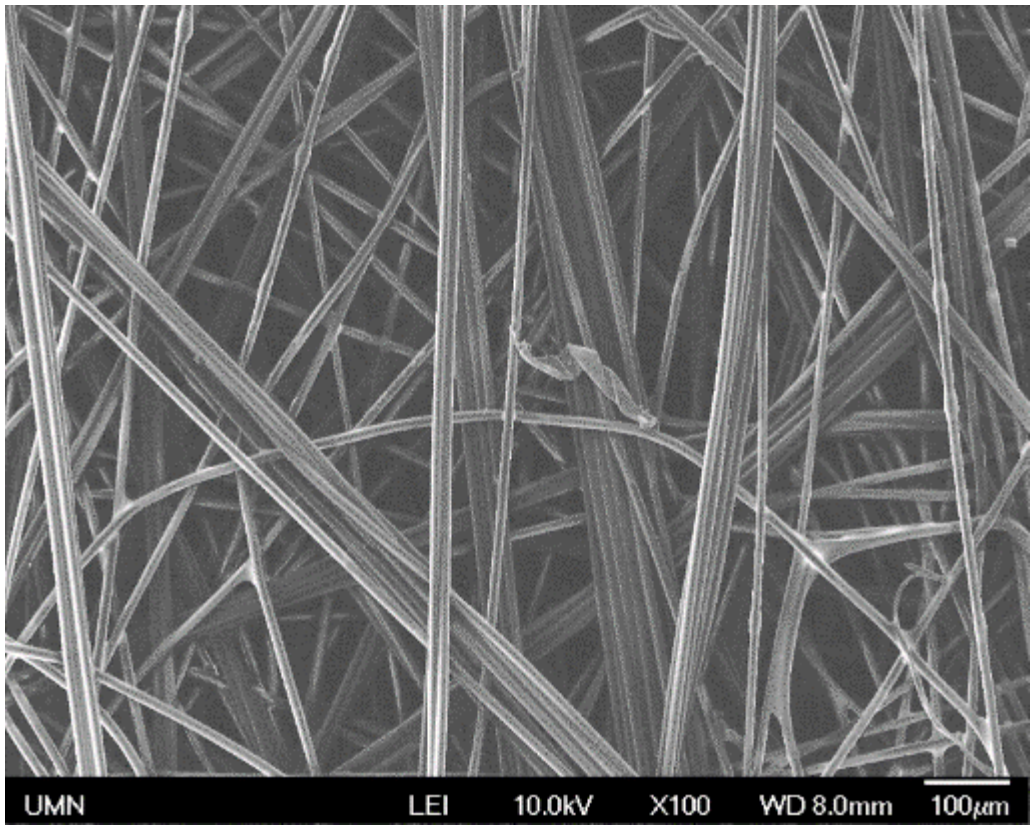
- **Open structure, low packing fraction** (0.07:0.32→3 times holding capacity, Brown, 1993).

- Sae-Lim et al. (2006) found that a media with reducing packing density along flow direction could have quadruple service life than the uniform packed media. No experimental data to support.

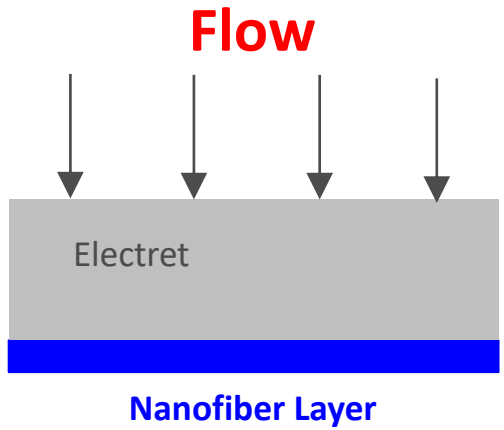
Proposed Media: Electret (#A)+ Nanofiber Layer (#B)

- Electret media used in commercial HVAC filter (#A)
- 300 nm mean fiber diameter nanofiber (#B)
- Composite media #A+#B

Electret (highly charged: 75 μC/m²)

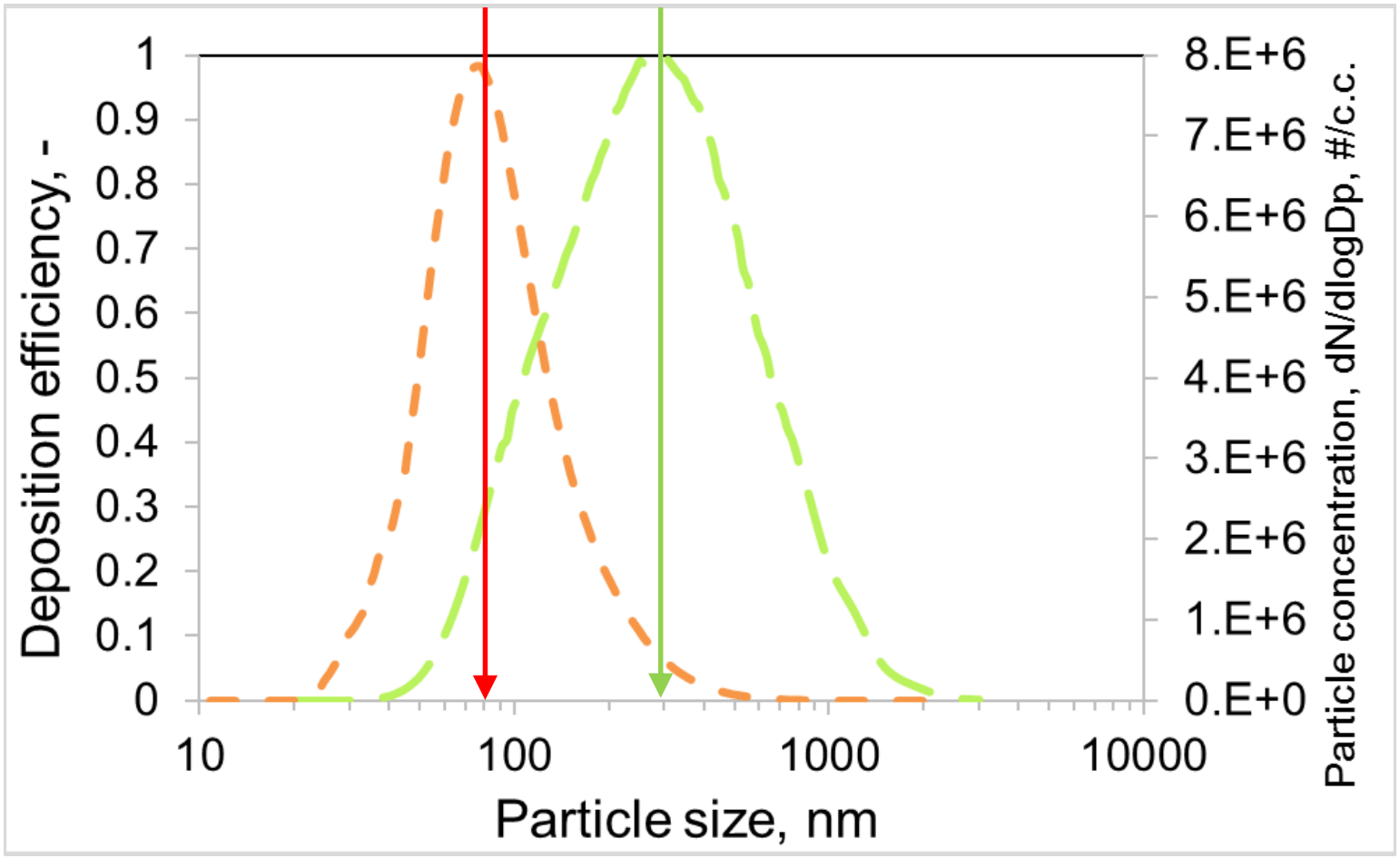


Types	Electret+ Nanofiber
Fiber diameter (μm)	16/0.3
Thickness (μm)	800/100
Efficiency (%) for 0.3 um @ 5 cm/s	≥ 95
Pressure drop (Pa)	~25-40
Mechanism (cross-section)	Depth Filtration

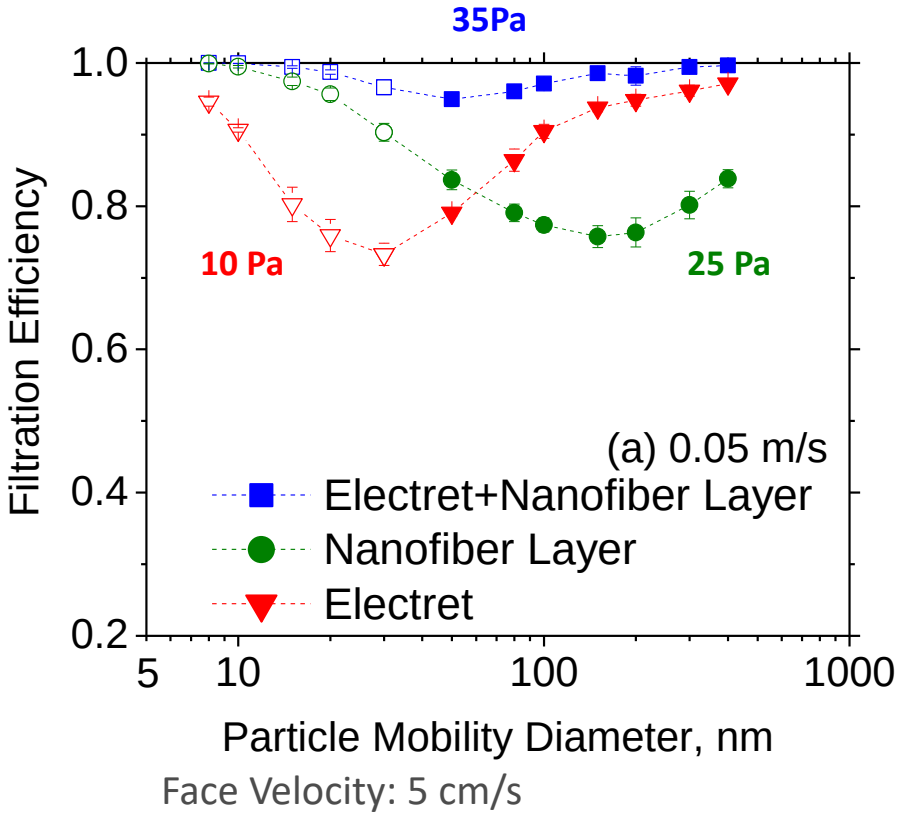


Deposition Characteristics of $PM_{2.5}$ in the Proposed Composite Media

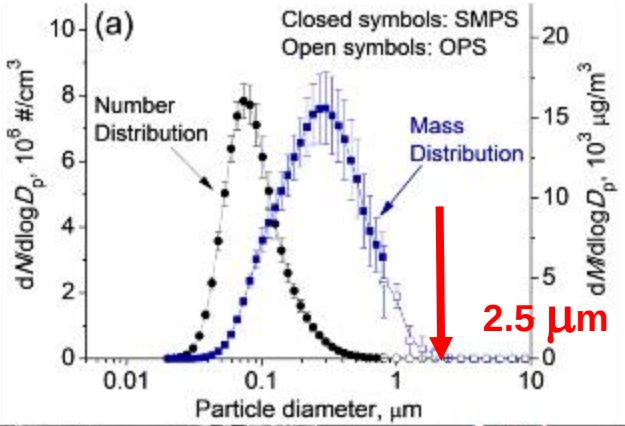
Electret (#A)
+
Nanofiber (#B)

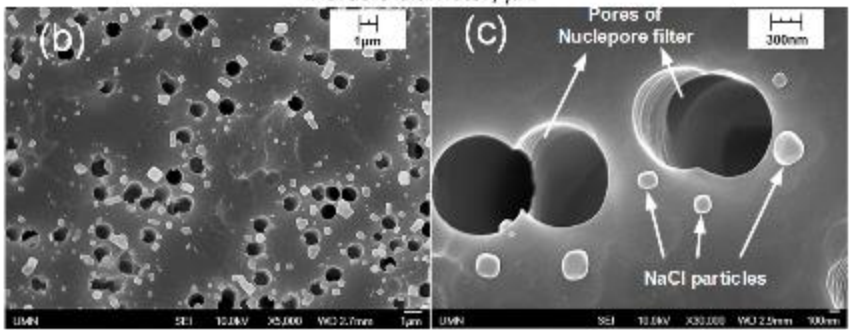


Initial Filtration Efficiency of the Composite Media



Face Velocity: 5 cm/s

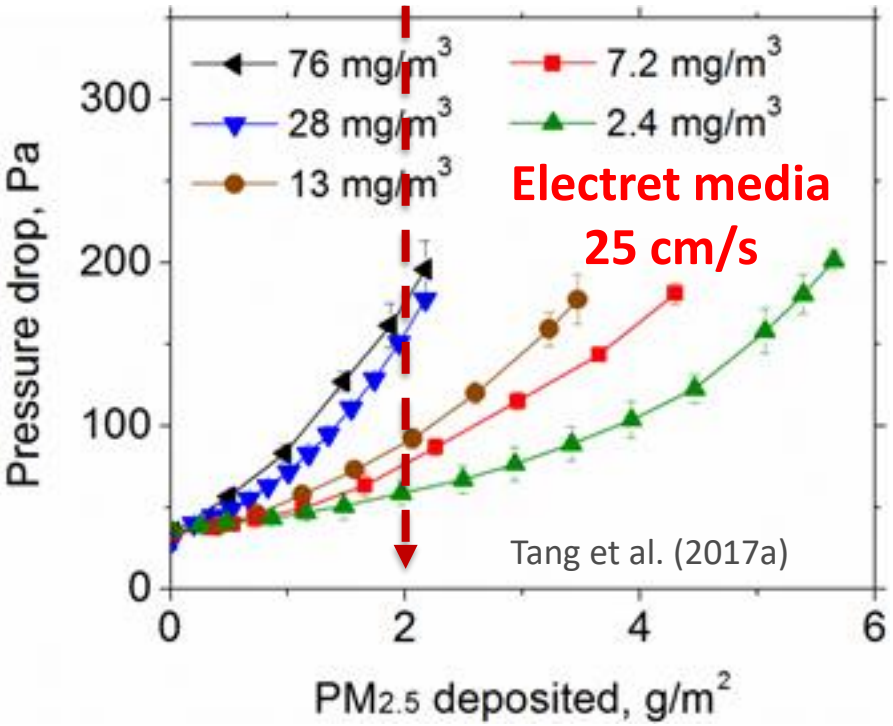


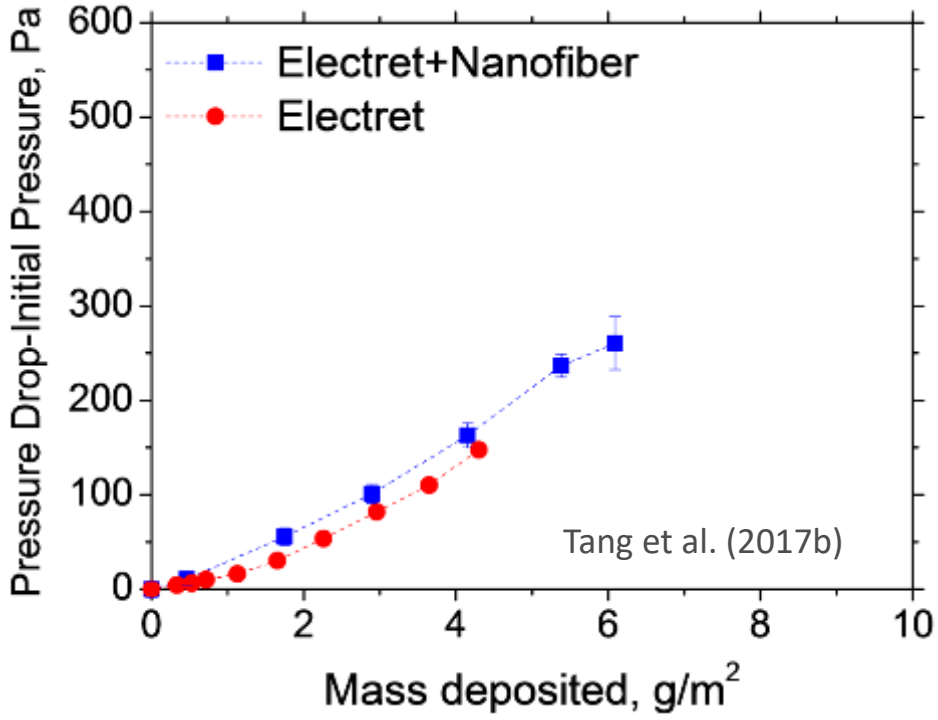


Electret + Nanofiber layer increases the minimum filtration efficiency and enhances nanoparticle removal compared to that of electret media.

Tang et al. (2018) Separation and Purification Technology

Effect of $PM_{2.5}$ Conc. on Loading Characteristics for Electret and Composite Media



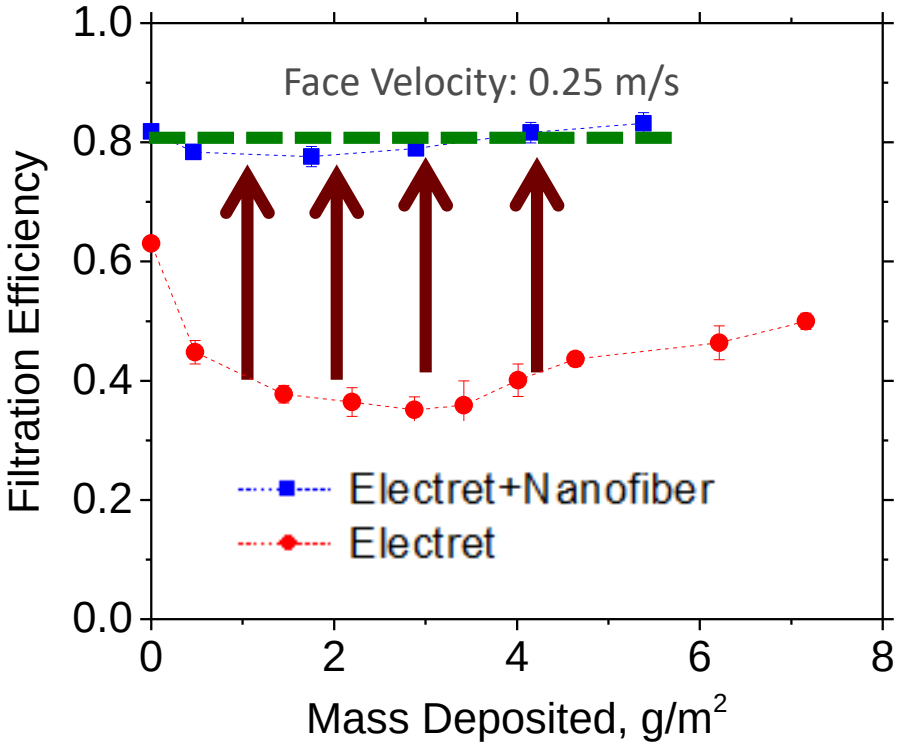


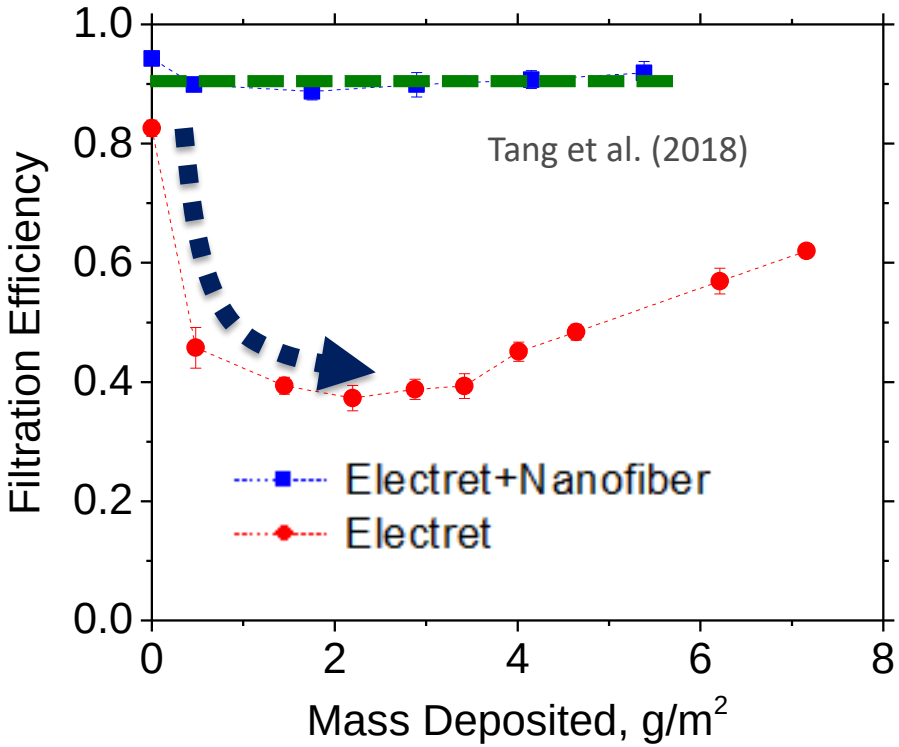
The trend of pressure drop growth is similar with Fiberglass filter. They both are depth filtration filters.

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

Tang et al. (2017) Separation and Purification Technology
Tang et al. (2018) Separation and Purification Technology

Filtration Efficiency of Electret and Composite Media along Loading





- The filtration efficiency of Electret decreased dramatically with an overall efficiency reduction 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.

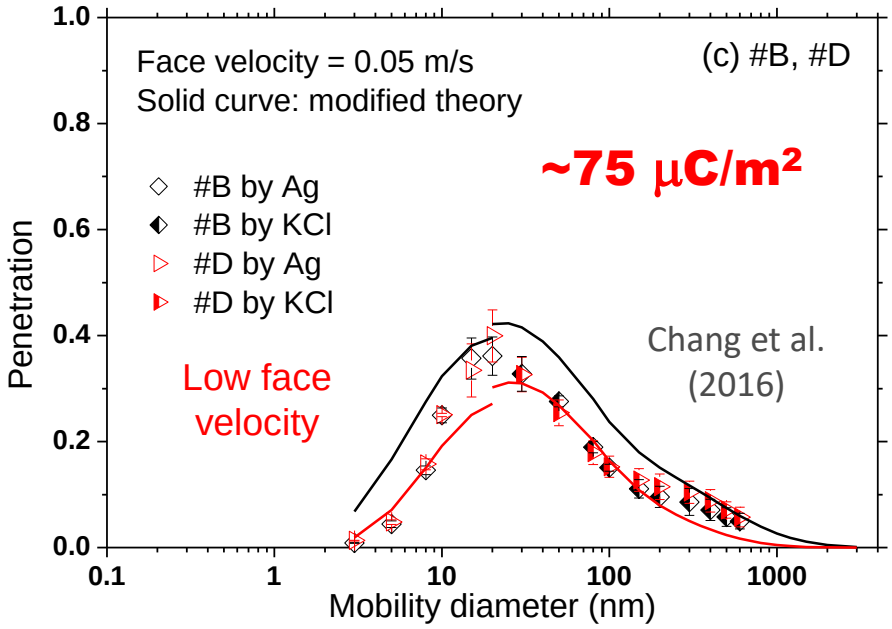
Tang et al. (2018) Separation and Purification Technology

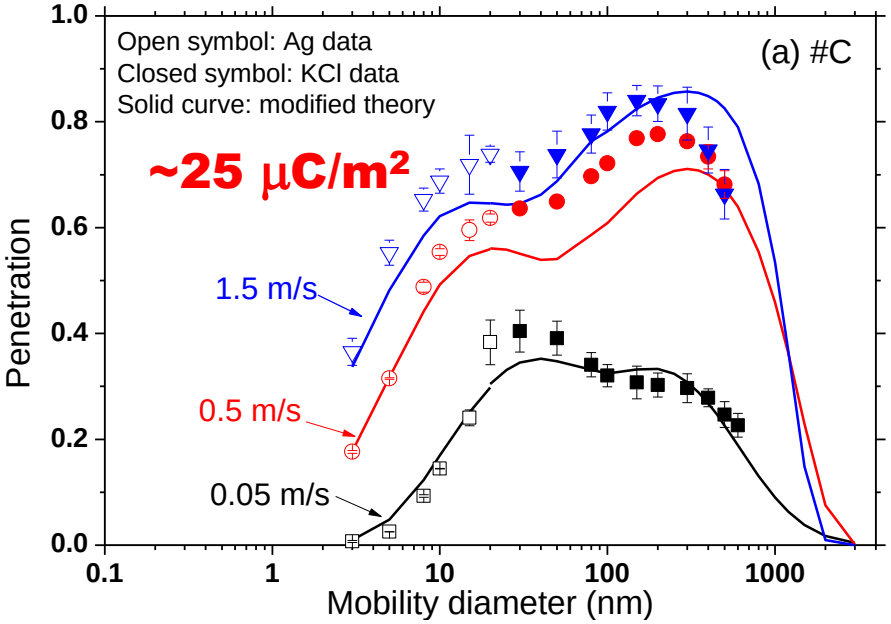
Experiments and Modeling of Initial Penetration for Electret Media

Good agreement between data and modified model is obtained.

Different media, different charging density and face velocity

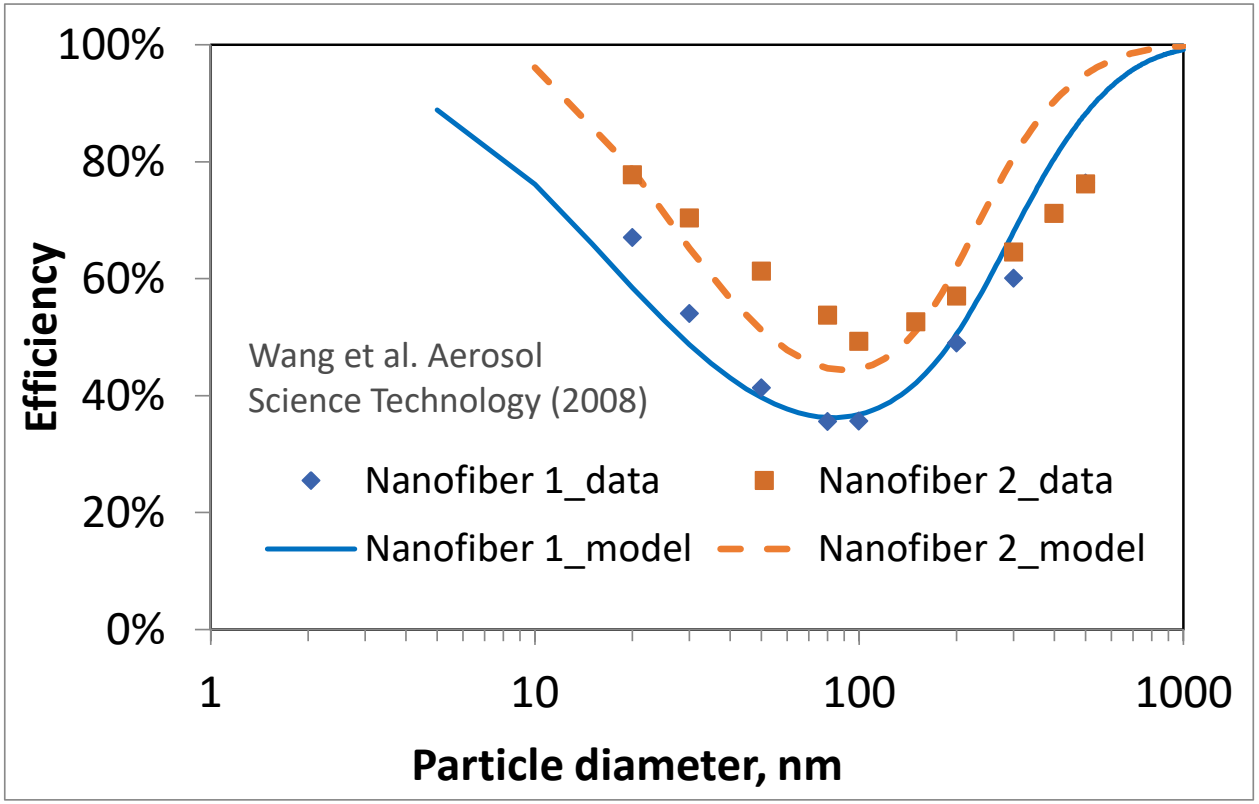
Chang et al. (2016) Aerosol Air Quality Research



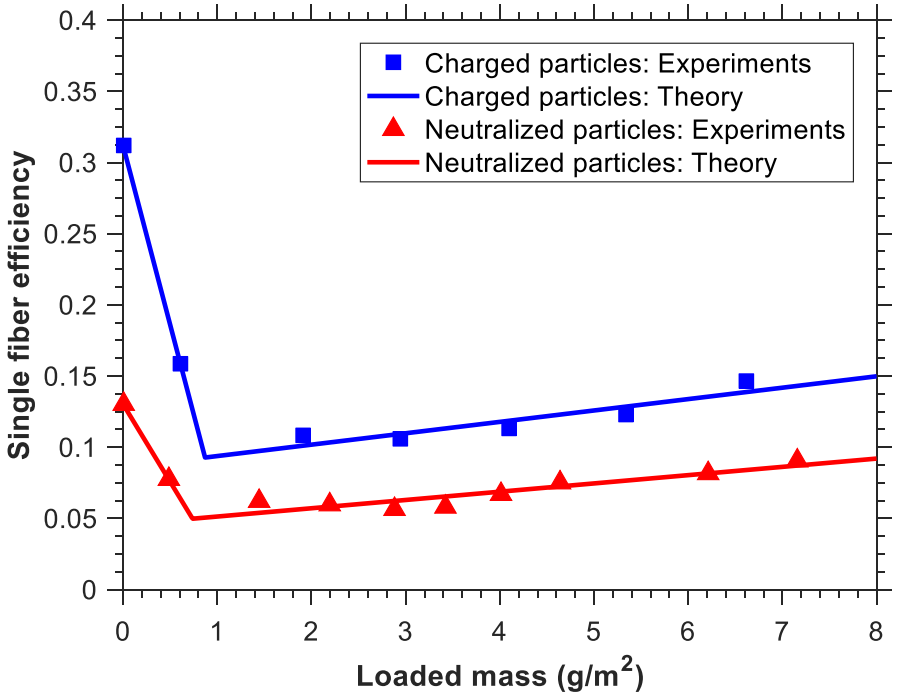


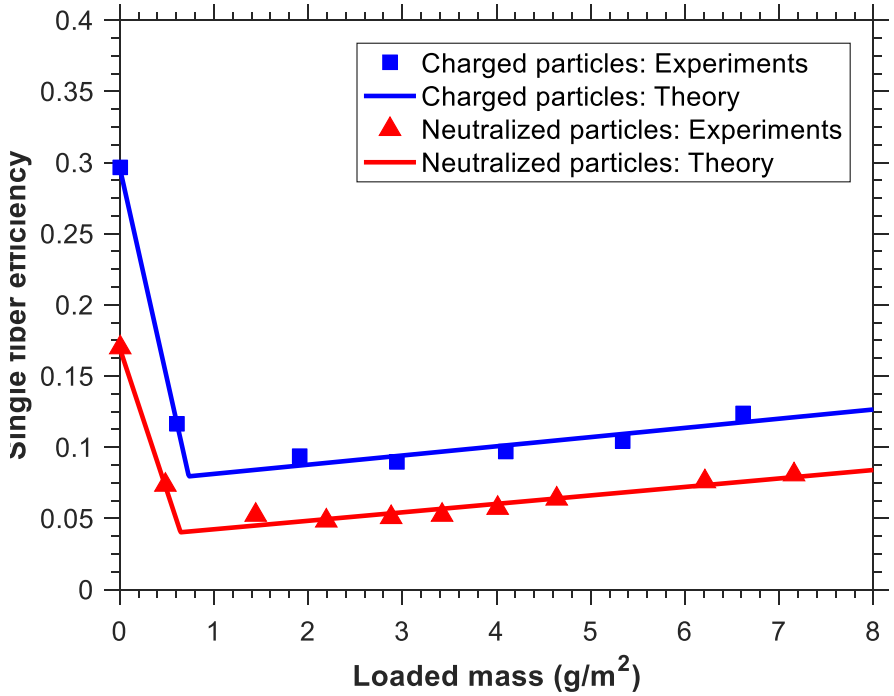
Modeling of Initial Efficiency for Nanofiber

- Single fiber efficiency model was used to calculate the theoretical efficiency of nanofiber filter (Wang et al. 2008).
- Good agreement between data and model were observed.



Modeling of Filtration Efficiency of Electret Media during the Loading Process

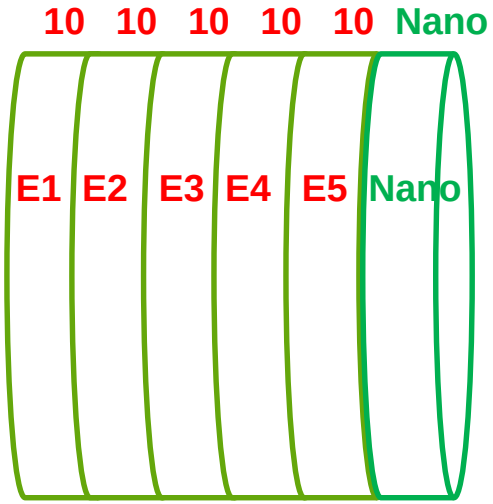


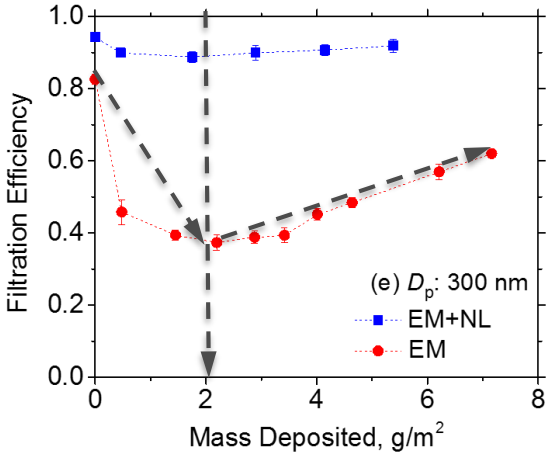


- The proposed model caught the evolution trend of filtration efficiency during the loading very well.
- These results are not easy to be used to analyze the particle deposition and loading in the microscopic point of view.

Analysis Method Based on Surface Area of Fibers and Deposited $PM_{2.5}$

- $PM_{2.5}$ deposition was analyzed with layer by layer, each layer has a thickness of 160 μm (Sum of 10 basic layers).
- Penetration varied according to the given up of fiber charge—ratio of surface area of deposited $PM_{2.5}$ to that of fiber.
- The layer efficiency curves were updated accordingly as the ratio of surface area of deposited $PM_{2.5}$ to fiber was 1/3, 2/3 and 1.
- Number, surface and mass concentrations of deposited $PM_{2.5}$ in each layer were obtained.
- Compare with loading data in Tang et al. (2017)



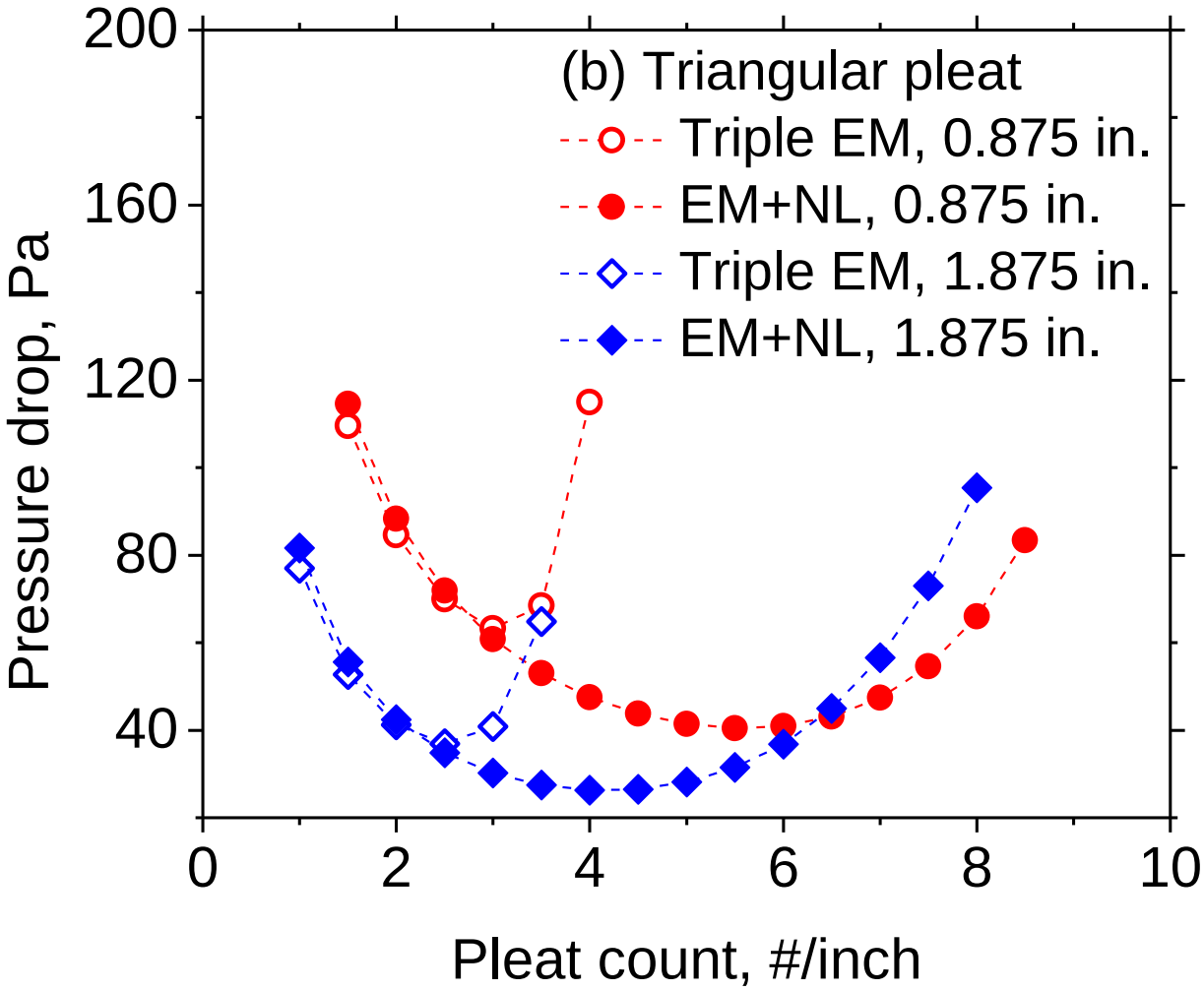


Deposition Characteristics of Electret (#A) and (#A+#B)-Layer by Layer Analysis

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
period 1	19.50%	14.80%	9.82%	6.93%	4.87%
period 2	17.20%	11.50%	7.87%	4.94%	3.59%
period 3	13.30%	6.23%	4.15%	3.27%	2.34%
period 4	9.88%	17.53%	11.75%	8.13%	5.79%
period 5	11.52%	9.73%	16.46%	11.37%	8.08%
period 6	13.25%	11.19%	9.40%	15.44%	10.95%
period 7	14.90%	12.58%	10.56%	8.93%	14.35%
period 8	2.21%	12.70%	10.72%	9.01%	7.62%
period 9	3.84%	3.74%	21.52%	18.17%	15.27%
period 10	2.52%	2.46%	2.40%	13.83%	11.69%
period 11	2.89%	2.82%	2.75%	2.68%	15.50%
↓	↓	↓	↓	↓	↓
↓	↓	↓	↓	↓	↓
↓	↓	↓	↓	↓	↓
total	251.9%	222.3%	205.3%	185.1%	169.9%

g/m²	Experiments	Model calculation
In Electret	3.26±0.11 (55%)	3.16 (54%)
In Nanofiber layer	2.68±0.25 (45%)	2.71 (46%)
Total	5.94	5.87

Pleating Counts and Pressure Drop of Composite Media



Chen et al. (1995) Aerosol Science and Technology
Tang et al. (2018) Separation and Purification Technology

Summary and Future Work

- Electret media perform perfectly on depth deposition. Uniform deposition pattern and nearly equal amount of depositions of $PM_{2.5}$ mass among layers.
- Nanofiber acted as a safety guard to capture the penetrated $PM_{2.5}$ during its efficiency reduction period. Due to the effective use of every parts of filter media, the proposed electret+nanofiber filter media is a high energy and efficiency effectiveness media.
- Theoretical models successfully predicted not only initial efficiency but also efficiency during the loading.
- More works are needed to summarize all the key parameters of filter performance and to provide empirical equations to design optimal filters for $PM_{2.5}$ removal with energy effectiveness.

Thanks for you attention

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I would be happy to take any question

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