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

Sheng-Chieh (Shawn) Chen, Min Tang, Drew Thompson,
Luying Liu, David Pui,

VCU

Energy Consumption in Air Filtration

- Pressure drop increase during the loading: mainly from clogging (dendrite formation). Fan and air-conditioning system need to run longer to meet the same cooling load, resulting in annual increases in energy consumption 14% (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 (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

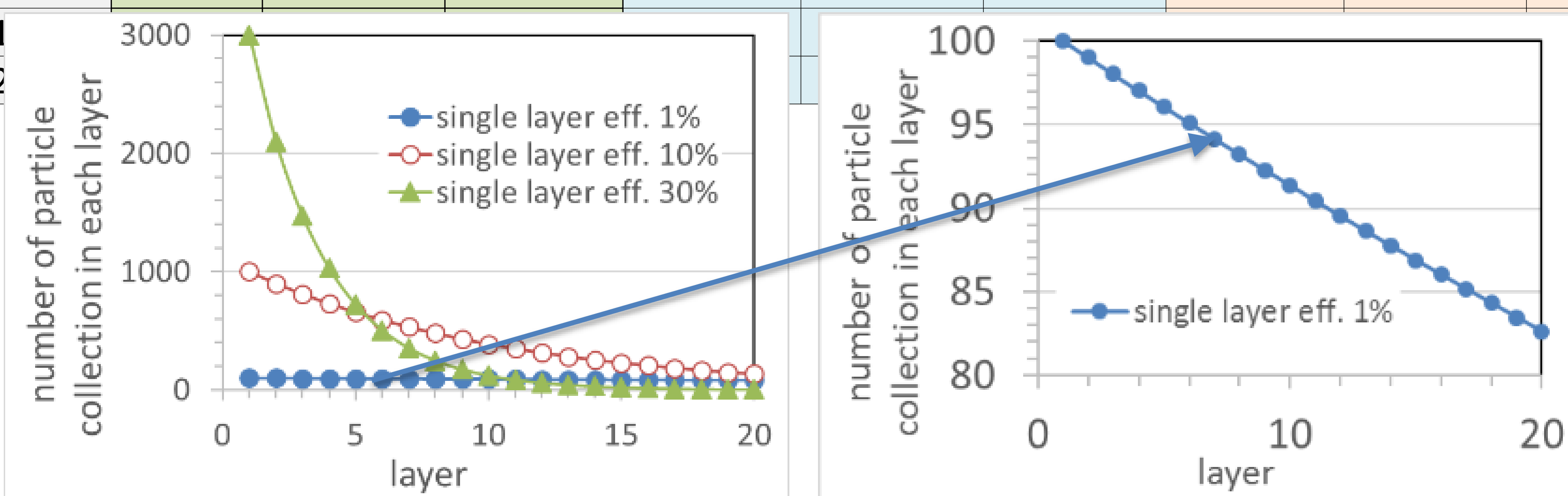
- Analyze particle depositions in different filter media in a microscopic point of view.
- Propose a composite media and conduct a series of experiments for initial efficiency and loading characteristics.
- Develop models to predict the filter efficiencies for both initial and in-use (or loaded) conditions and validate the models with data.
- Compare the data and investigate how to achieve the design of a filter with high efficiency and low pressure drop.
- Develop and optimize a composite media for the removal of high $PM_{2.5}$ concentration with low pressure drop and long service life.

Minimizing the Growth of Pressure Drop during the Loading (at the same efficiency)

- 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
- Deep 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 reduced packing density could have quadruple service life than the uniform packed media. No experimental data (what particle?) to support.
  - ❑ Layer efficiency influences clogging rate by affecting the deposition pattern within the filter. The higher efficiency, the particles are collected in a smaller volume-leading to a greater tendency of the filter to clog at the leading surface.
  - ❑ Analysis particle deposition in microscopic point of view is needed.

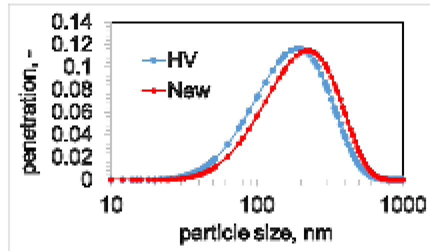
Effect of Single Layer Efficiency on Filter Loading Performance (Mechanical Media)

layer	Pene. at n layer	Inlet: 10000	Layer collection	Pene. at n layer	Inlet: 10000	Layer collection	Pene. at n layer	Inlet: 10000	Layer collection
1 (=equl.fiber diameter)	0.9900	9900	100	0.9000	9000	1000	0.7000	7000	3000
2	0.9801	9801	99	0.8100	8100	900	0.4900	4900	2100
3	0.9703	9703	98	0.7290	7290	810	0.3430	3430	1470
4	0.9606	9606	97	0.6561	6561	729	0.2401	2401	1029
10	0.9044	9044	91	0.3487	3487	387	0.0282	282	121
11	0.8953	8953	90	0.3138	3138	349	0.0198	198	85
12	0.8864	8864	90	0.2824	2824	314	0.0138	138	59
18	0.8345	8345	84	0.1501	1501	167	0.0016	16	7
1[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5
2[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3



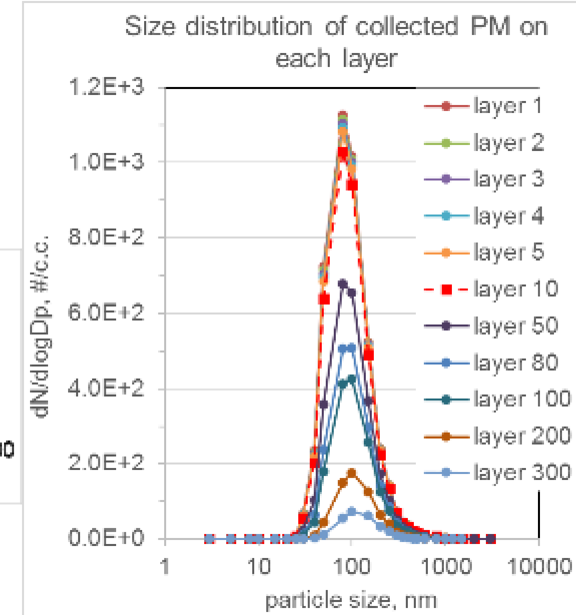
Required Thickness to Collect 60-70% of the Total Collected PM (mechanical media)

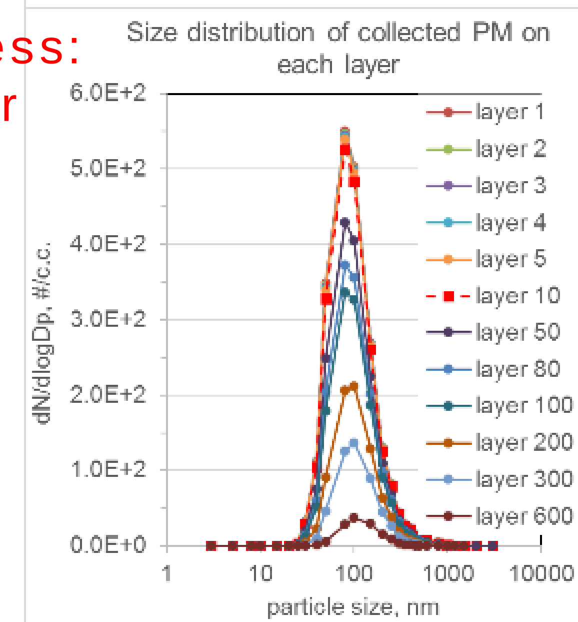
Fiberglass- D_f=2 μm, α=0.056, t=0.6 mm, face velocity=5 cm/s, Δp=130 Pa



- **Overall efficiency**
  - In number: 93%
  - In mass: 93%
- **% to overall efficiency in number:**
  - Collected in first 100 layer: 65%
  - Collected 101-200 layers: 25%
  - Collected 201-300 layers: 10%
- **% to overall efficiency in mass:**
  - Collected in first 100 layer: 65%
  - Collected 101-200 layers: 25%
  - Collected 201-300 layers: 10%

Layer thickness: fiber diameter



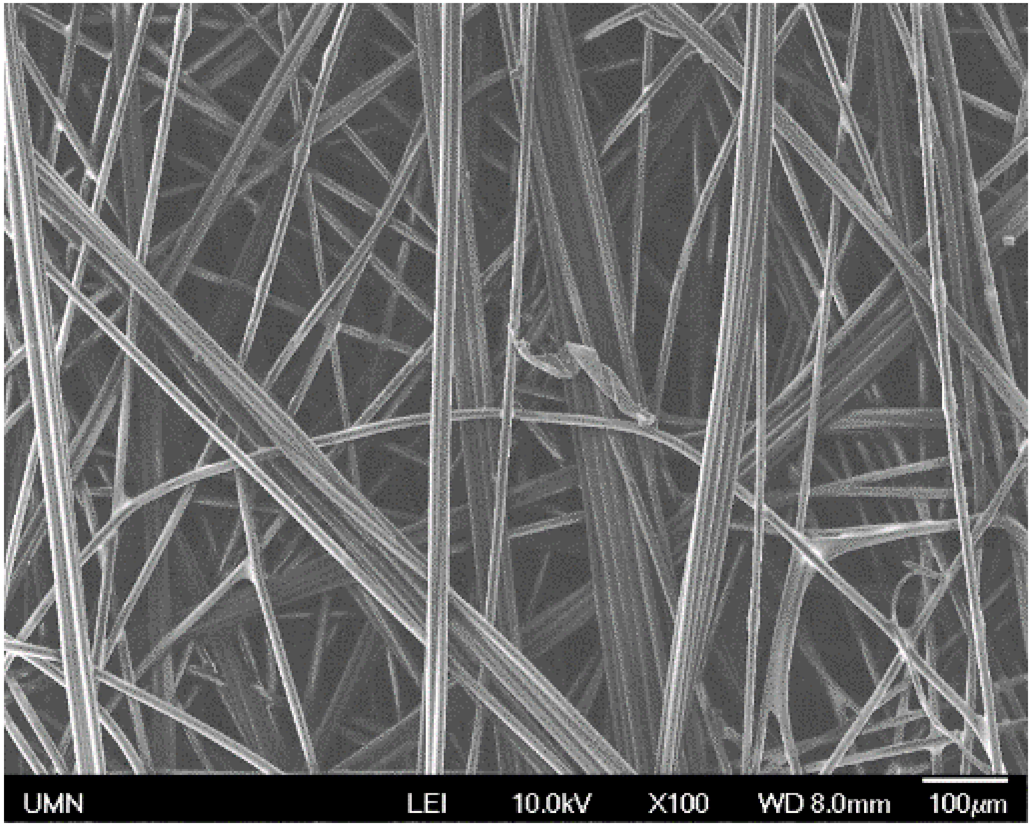


Fiberglass- D_f=1 μm, α=0.02, t=0.6 mm, face velocity=5 cm/s, Δp=100 Pa

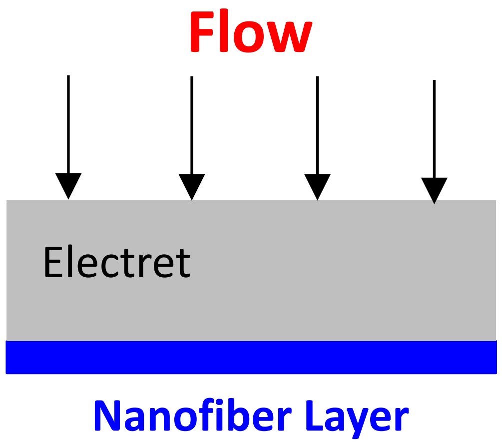
Proposed Media: Electret (#A)+ Nanofiber Layer (#B)

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

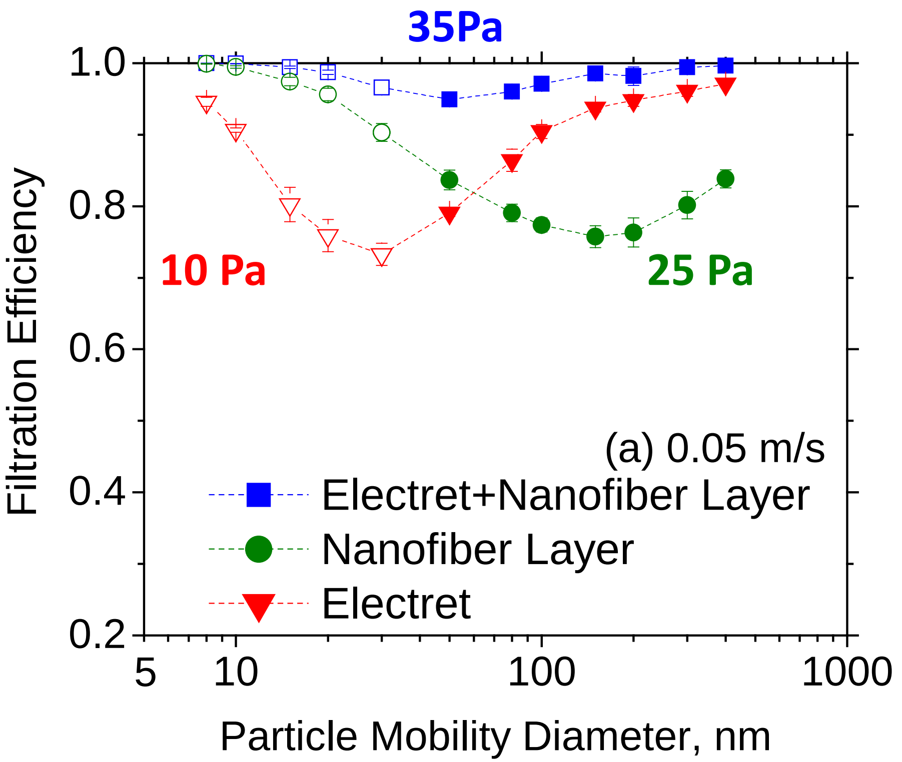
Electret (highly charged: 75 μC/m²)



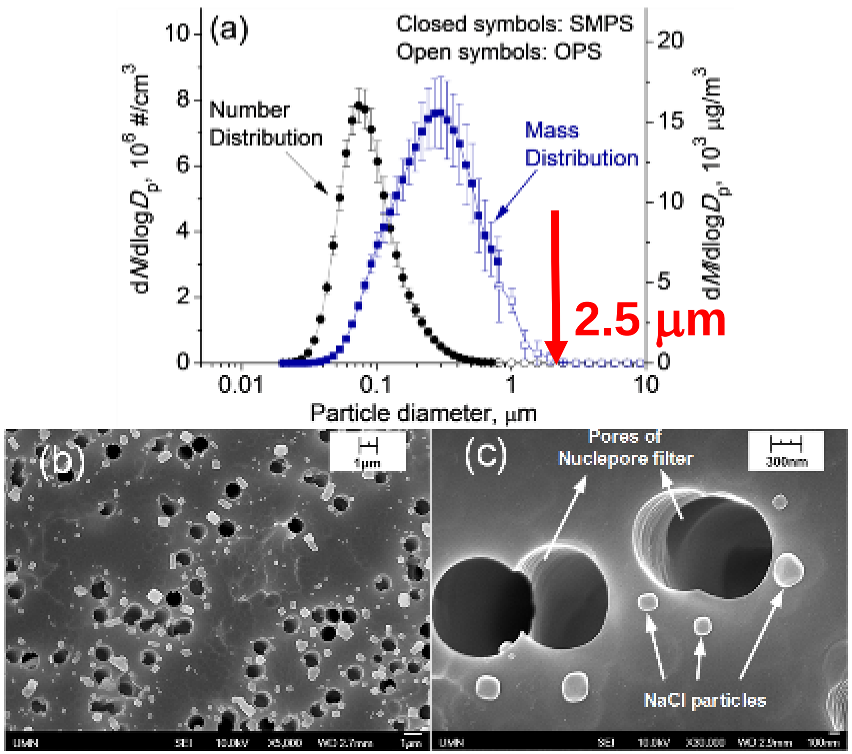
Types	Electret+ Nanofiber
Fiber diameter (μm)	16/0.3
Thickness (μm)	800/100
Efficiency (%) for 0.3 um @ 5 cm/s	≥ 95
Pressure drop (Pa)	~25-40
Mechanism (cross-section)	Depth Filtration



Initial Filtration Efficiency of the Composite Media



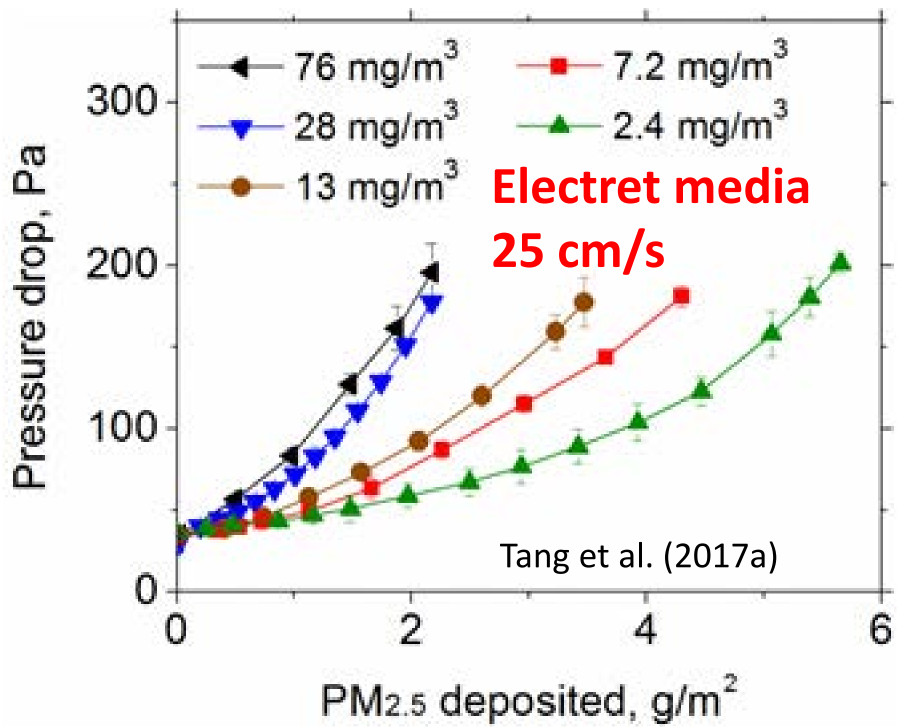
Face Velocity: 5 cm/s

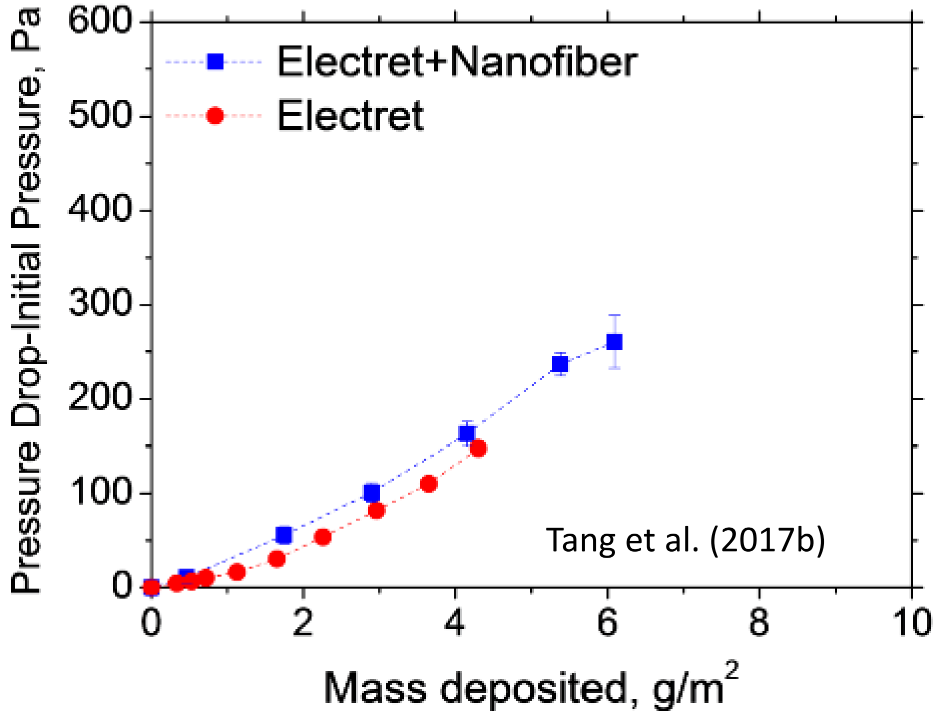


Electret + Nanofiber layer increases the minimum filtration efficiency and enhances nanoparticle removal compared to that of electret media.

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

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



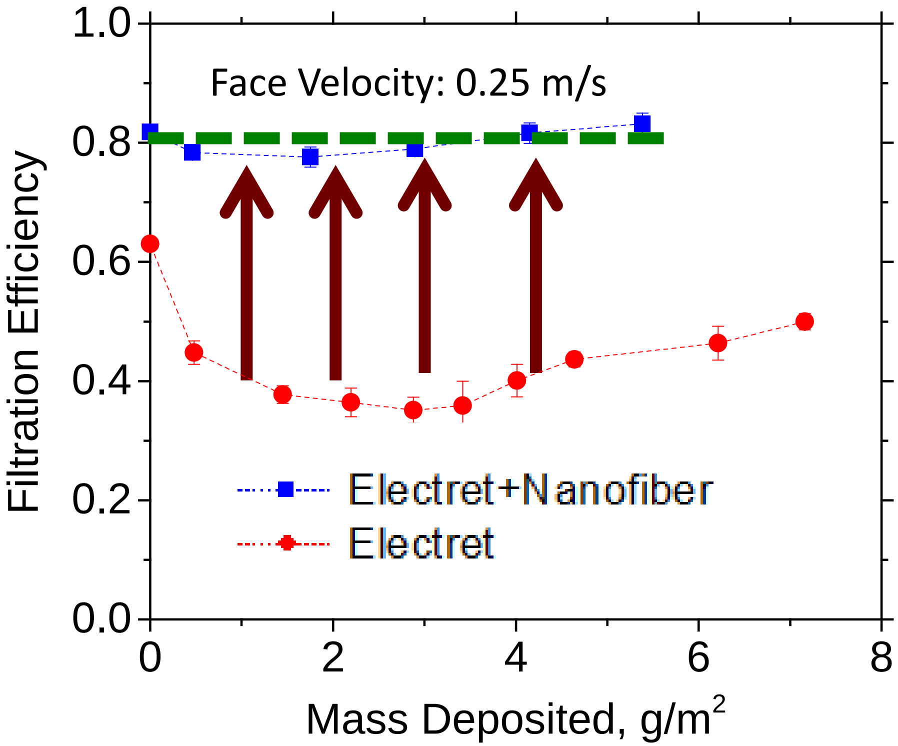


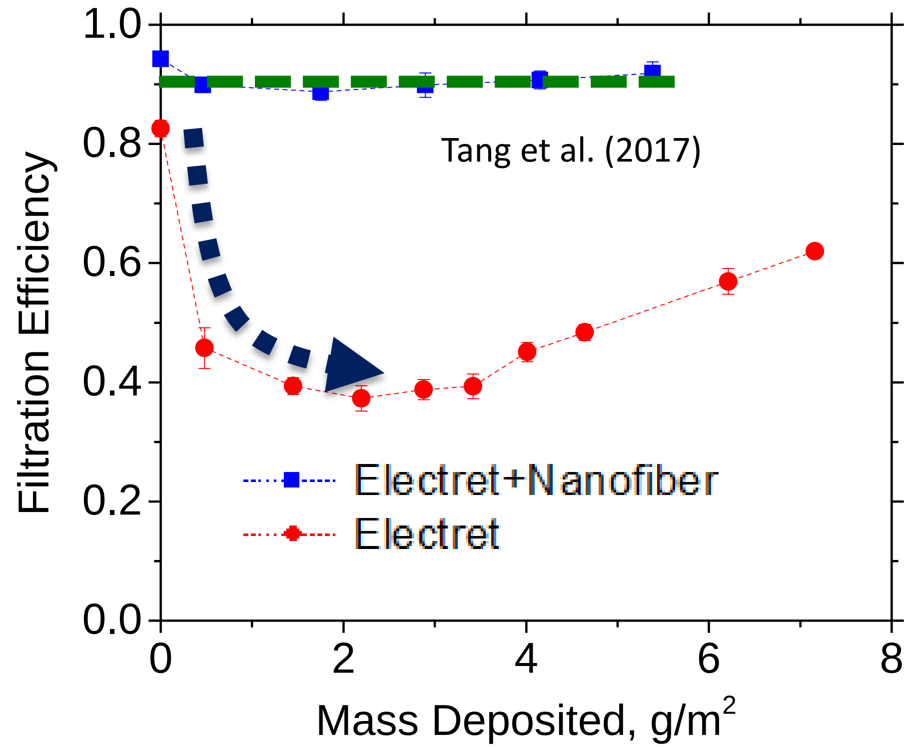
The trend of pressure drop growth is similar with Fiberglass filter. They both are depth filtration filters.

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, revision (2017b)

Filtration Efficiency of Electret (#A) and (#A+#B) 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)

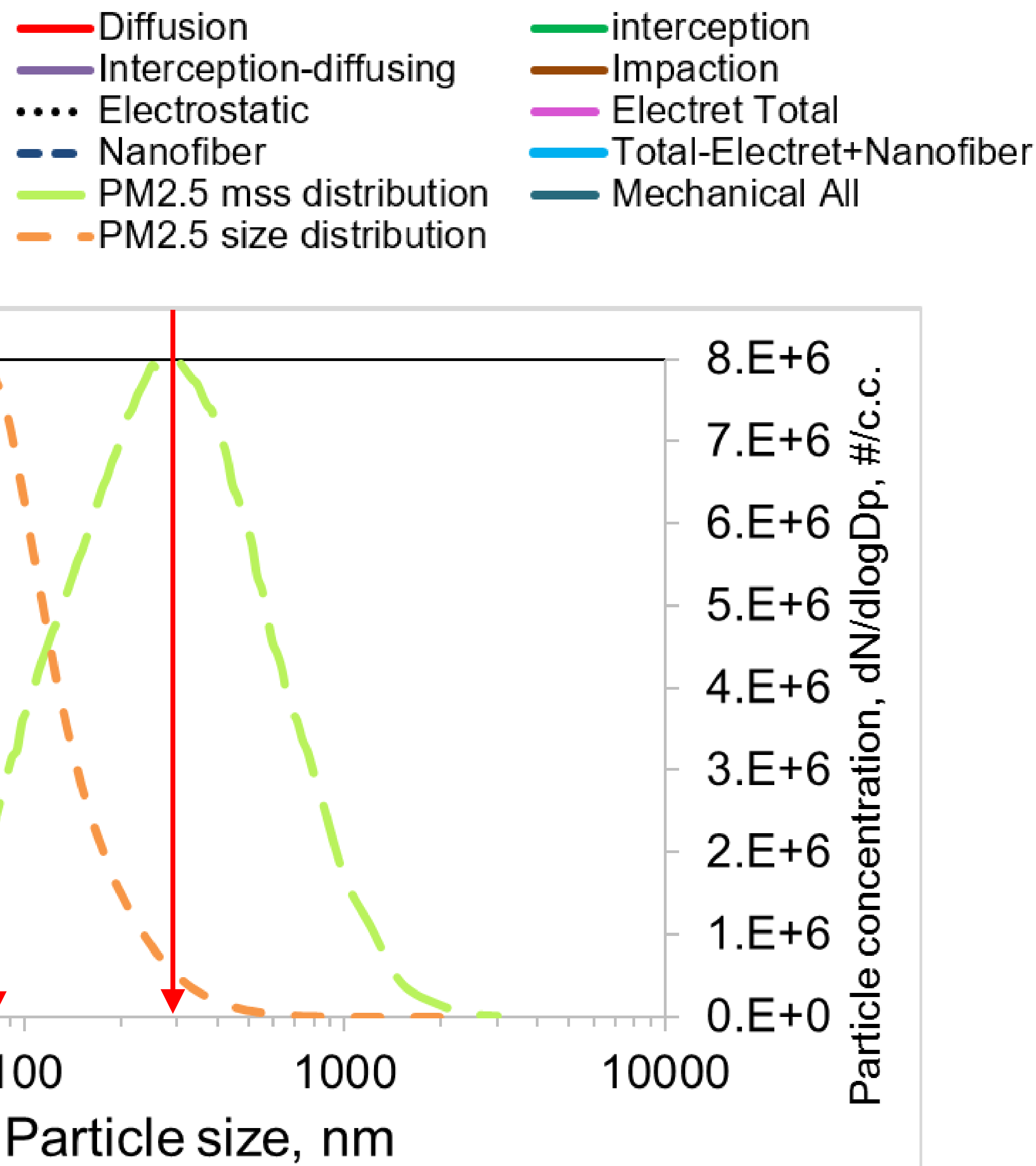
- Detailed analysis for the data has not been made

- From the microscopic point of view, the crucial parameters should be found for the optimal design of filter media

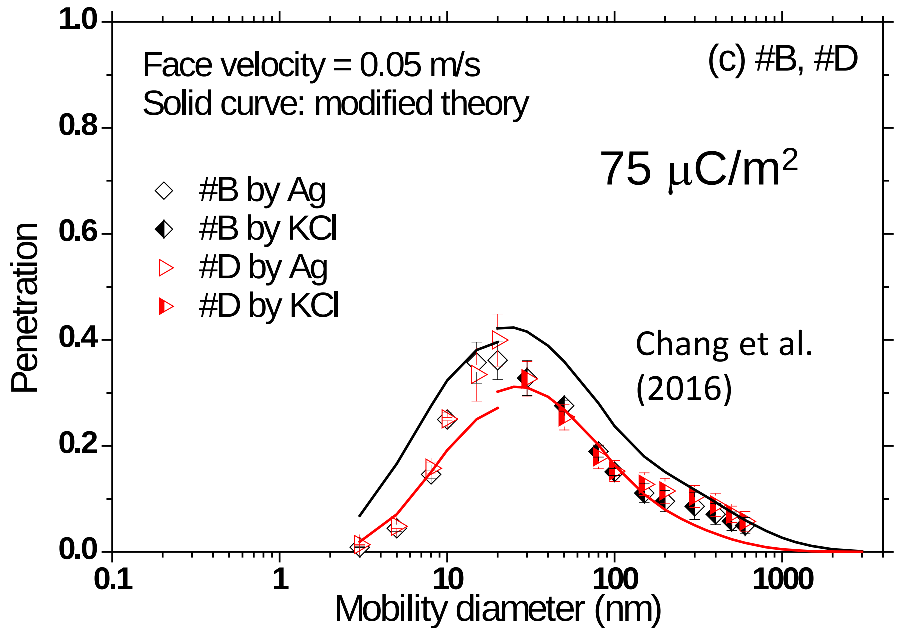
- Filtration models are needed to calculate the initial and loaded efficiency

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

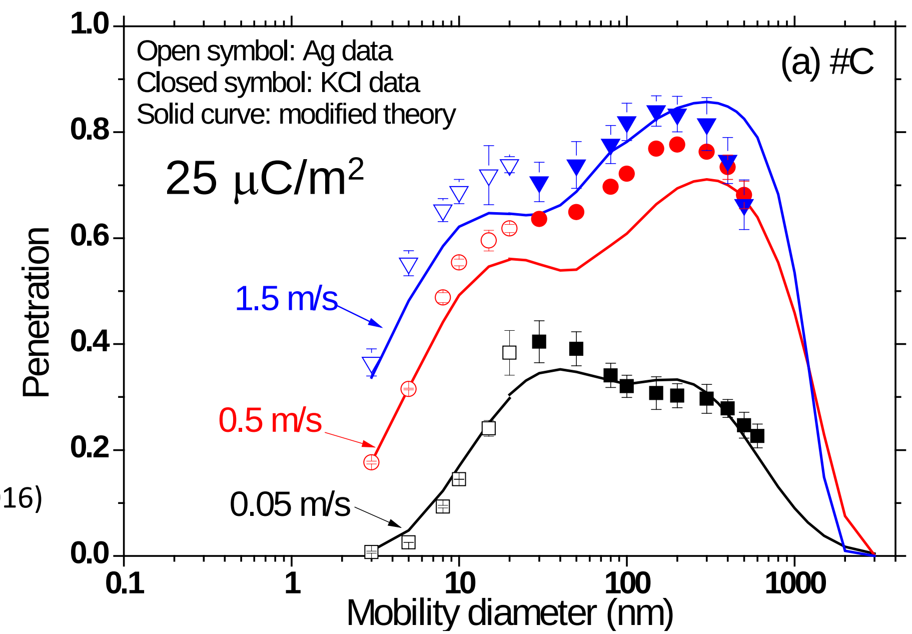
Electret (#A)
+
Nanofiber (#B)



Modeling of Initial Penetration for Electret media



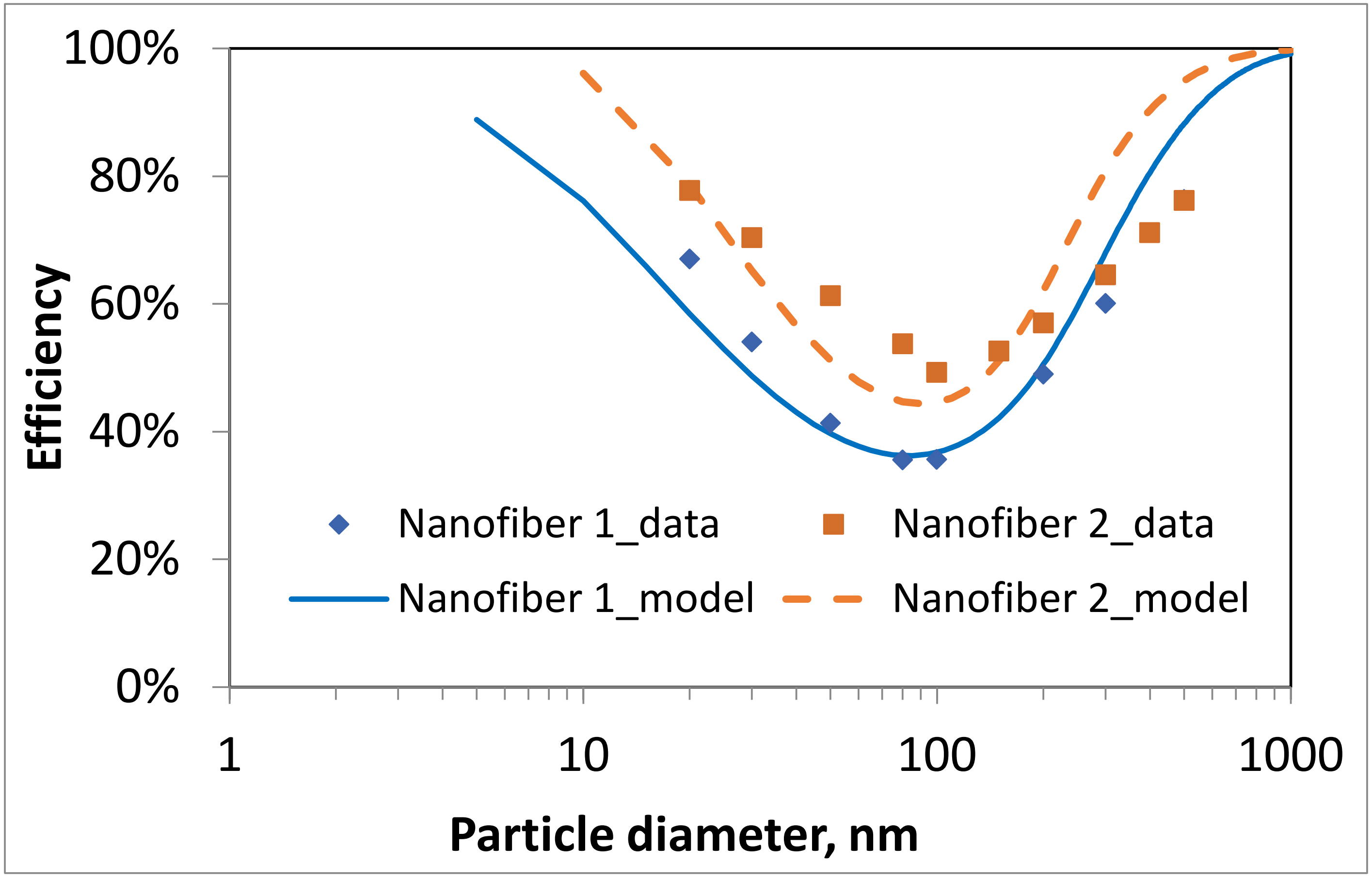
Good agreement between data and modified model is obtained.



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

Modeling of Initial Efficiency for Nanofiber

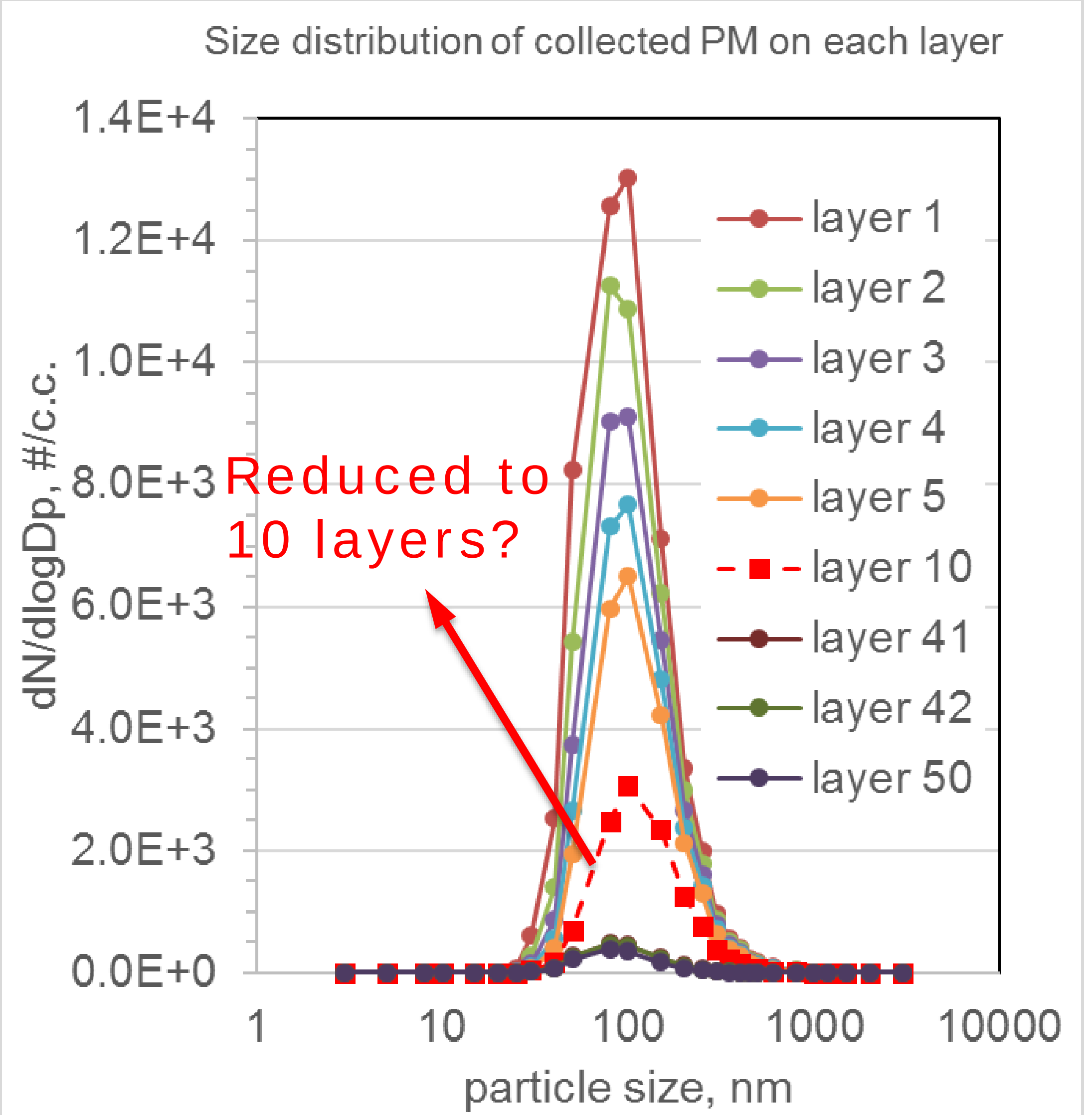
- Single fiber efficiency model was used to calculate the theoretical efficiency of nanofiber filter (Wang, Kim, Pui, 2008).
- Good agreement between data and model were observed.



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

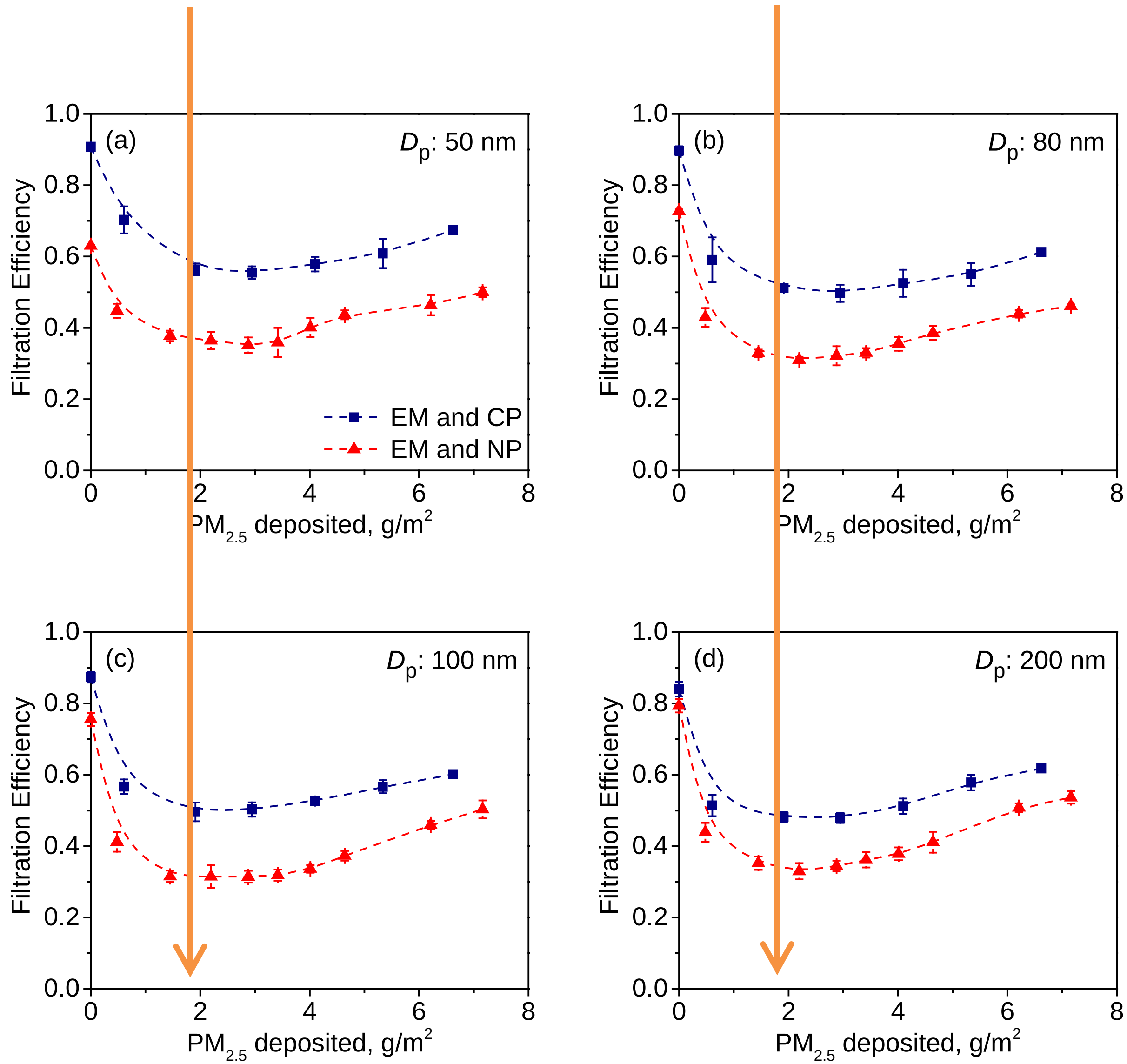
Required Thickness to Collect 70% of Total Collected $PM_{2.5}$ (Electret #A)

- **Efficiency (5 cm/s) of a commercial electret**
  - In number: 90%
  - In mass: 96%
- **In number:**
  - Collected in first 12 layer: 38524 (70%)
  - Collected from 13 to 52 layers: 16960 (30%)
- **In mass:**
  - Collected in first 12 layer: 80%
  - Collected from 13 to 52 layers: 20%



Holding Capacity of Composite Media

Examine the efficiency curve, **surface area** of deposited particles and pressure drop growth to derivate the deposition characteristics



Theoretical Modelling of Filter Efficiency during Loading Process- “mass/volume”

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

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

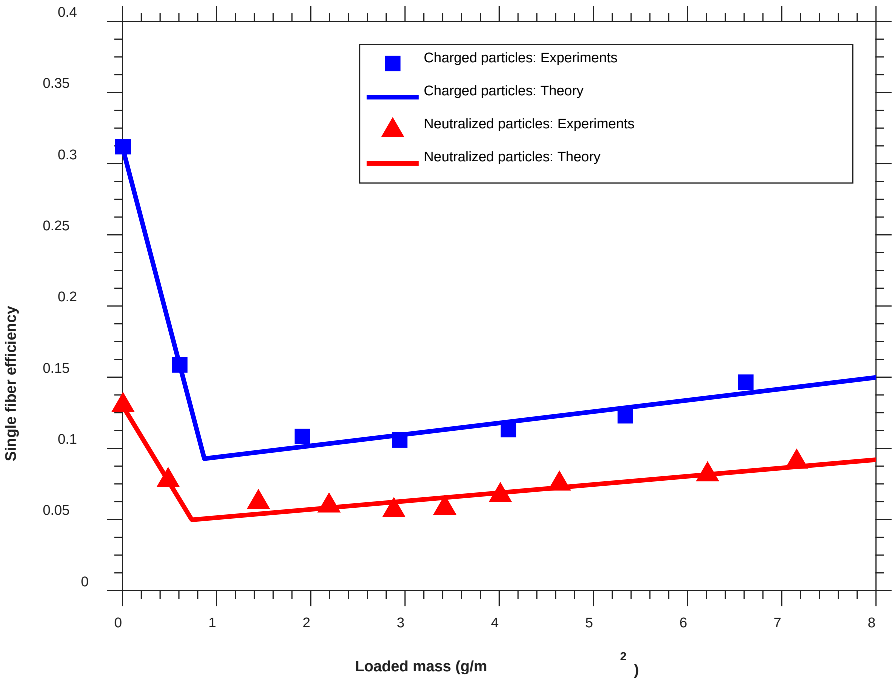
Brown et al. (1988) suggested the initial single fiber efficiency, h_0, decreases linearly with increasing local collected aerosol mass per unit volume, M (x,t), The parameter β gives an estimate of effectiveness of the loading aerosol in reducing the electrostatic filtration efficiency.

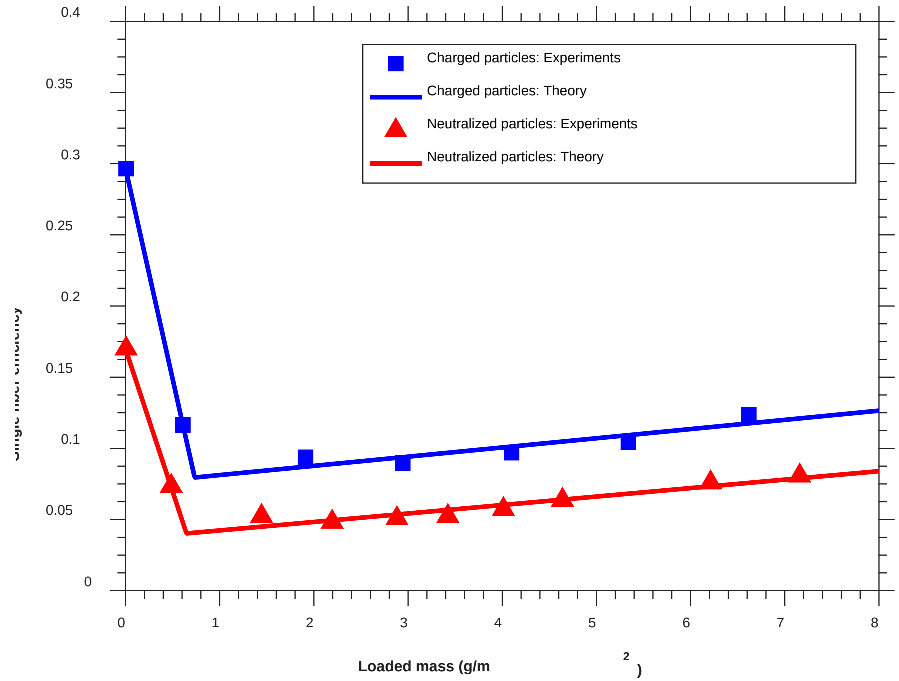
$$\eta(x,t) = \eta_{m0}\left[1 + \lambda M(x,t)\right]$$

Tang et al. (2017), Separation and Purification Technology, accepted

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.

Time for the Electret to Reach Minimum Efficiency-Method Based on the Mass of Deposited $PM_{2.5}$

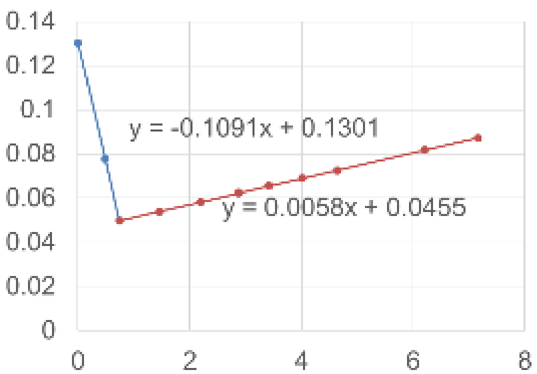
- Under initial efficiency, there is 6.4×10^{-6} mg/cm^3 of $PM_{2.5}$ collected by the Electret #E at 25 cm/s face velocity.
- However, the efficiency of #E is reducing during the loading process.
- The real time for the #E to reach minimum efficiency is 1.5 times of that calculated using initial efficiency: 31.2 mins (1.5x20.8)
- The real time for the #E to reach the end of loading from the point of minimum efficiency: 115.7 mins (173.6/1.5)
- Total operation time=147 mins
- Real operation time: 147x70x20x3=429 days=14 months

T1

dp (nm)	max	min	ave
50	0.602	0.297	0.449
80	0.699	0.248	0.474
100	0.728	0.215	0.472
200	0.768	0.239	0.503
300	0.801	0.257	0.529
500	0.875	0.307	0.591
max/ave	1.5	min/max	0.3

T2

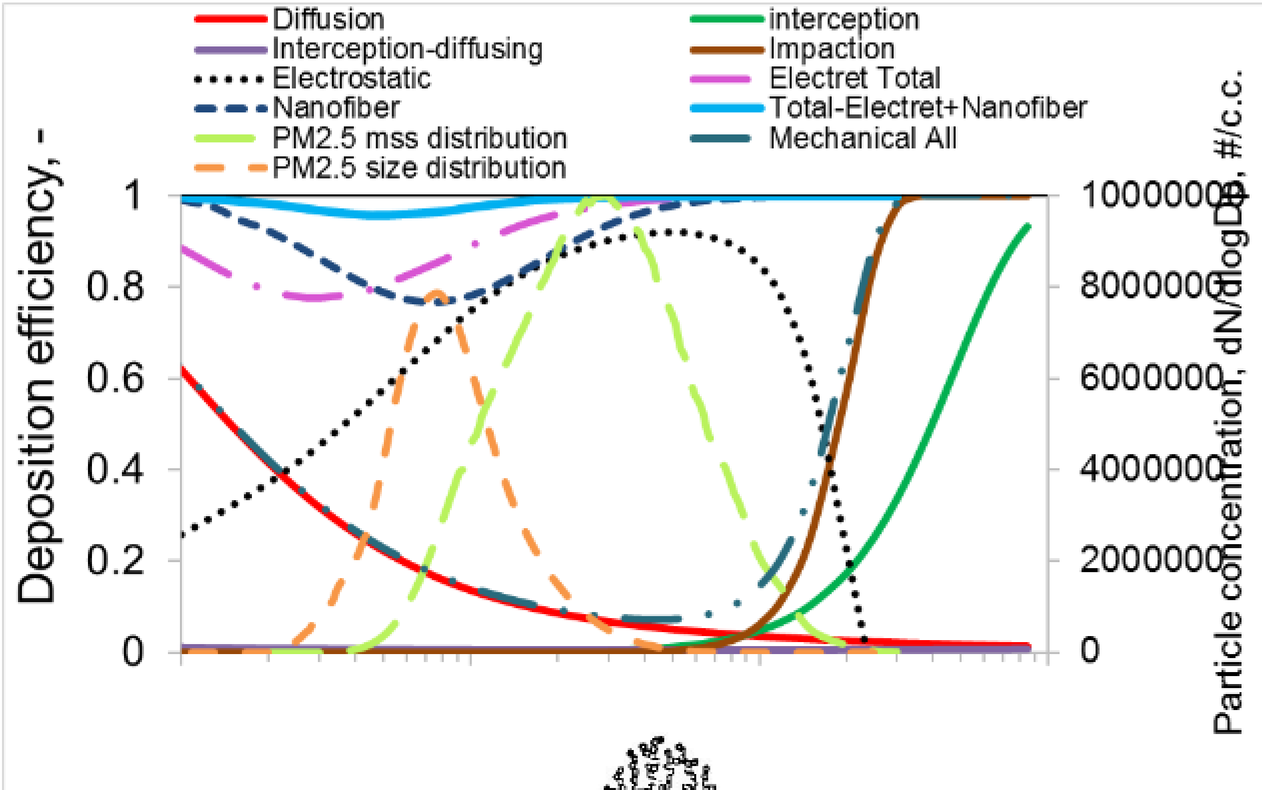
dp (nm)	min	max	ave
50	0.297	0.46	0.378
80	0.248	0.428	0.338
100	0.215	0.453	0.334
200	0.239	0.494	0.367
300	0.257	0.571	0.414
500	0.307	0.667	0.487
max/ave	1.3	ave/min	1.5



$$T1 = \frac{2\ g/m^2}{6.4\times10^{-6}\ mg/cm^3 \times 25/\sec} = 1250\ \sec = 20.8\ \min$$

$$T2 = \frac{(7-2)\ g/m^2}{(6.4\times10^{-6}\times0.3)\ mg/cm^3 \times 25/\sec} = 10417\ \sec = 173.6\ \min$$

$PM_{2.5}$ deposition pattern in the Electret #A



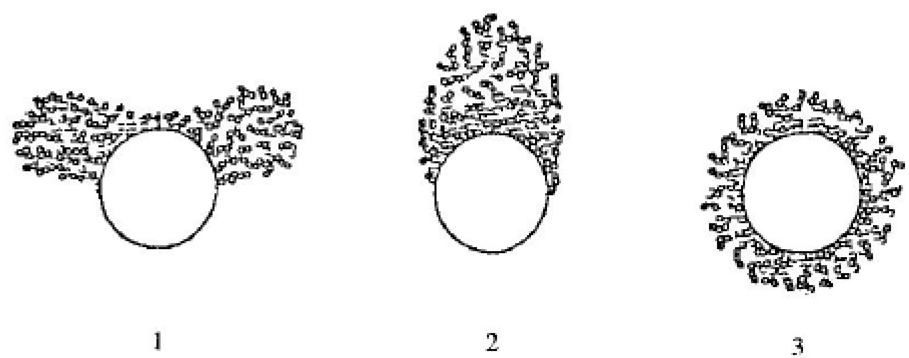
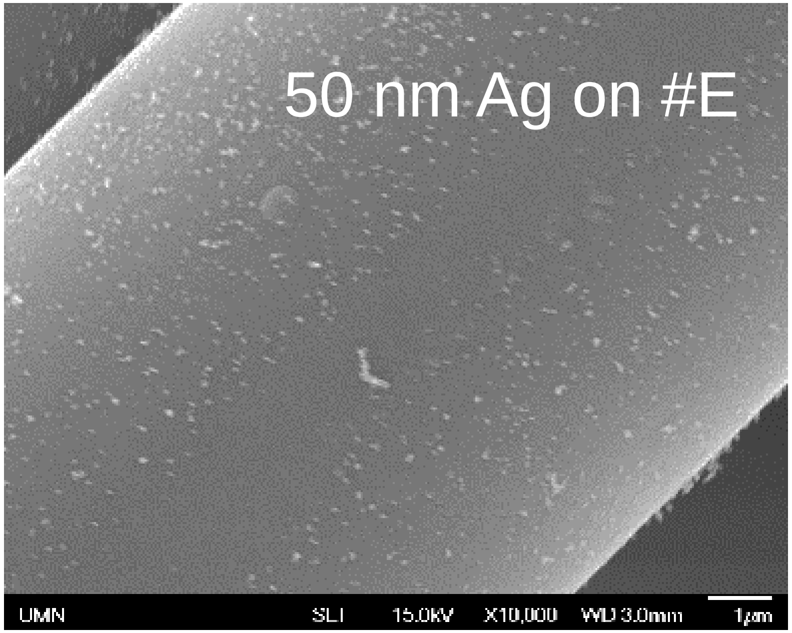


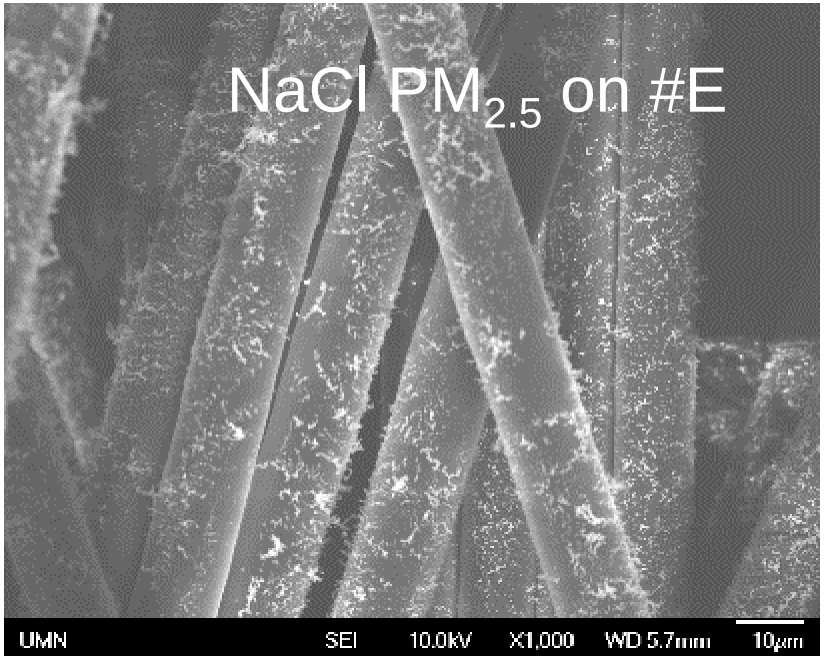
FIG. 8.2 Shape of aerosol deposits on fibres: (1) deposition by interception; (2) deposition by inertial impaction; (3) deposition by diffusion (6). (With permission from Pergamon Press Ltd, Headington Hill Hall, Oxford OX3 0BW, U.K.)

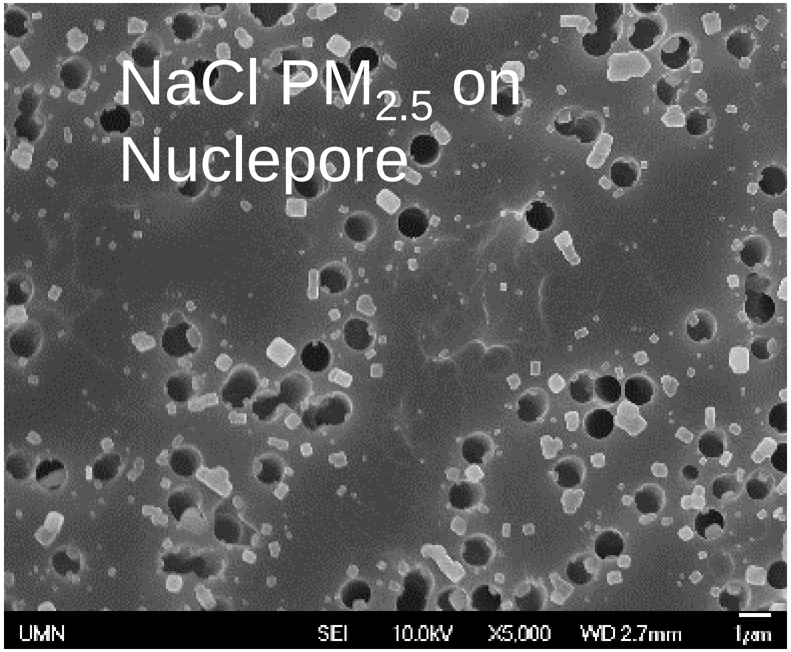
Brown (1993)

Loading with lower concentration particles - likely to occur in practice

Diffusion enhanced mechanism prefers a more uniform deposition

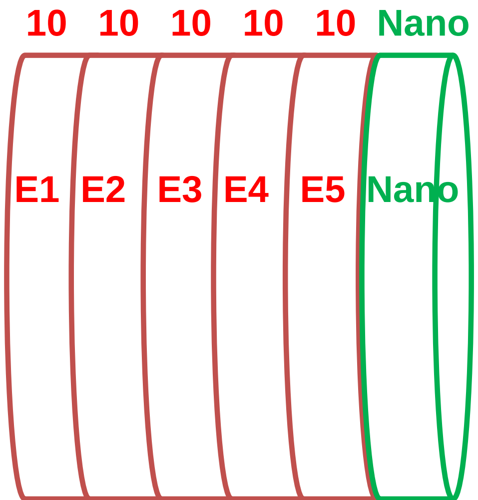






Description of analysis method

- $PM_{2.5}$ deposition was analyzed with layer by layer, each layer has a thickness of 160 μm (10 basic sub-layers).
- Penetration varied according to the given up of fiber charge—ratio of surface area of deposited PM2.5 to that of fiber.
- Number, surface and mass concentrations of deposited $PM_{2.5}$ in each layer were calculated.
- 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/m^2	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

Summary and Future Work

- Electret media perform perfectly on depth deposition. Uniform deposition pattern and equal amount depositions among layers are key points to have the optimal filter media—for removing high $PM_{2.5}$ concentration.
- To achieve low pressure drop while remaining high efficiency and long service life, electret+nanofiber filter media was proposed.
- Initial efficiency and efficiency during loading with simulated $PM_{2.5}$ 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 successfully well predicted not only initial efficiency but also efficiency during the loading compared with experimental data.
- The model could be applied in the web-based application for designing electret+nanofiber composite for cost-effectiveness removal for $PM_{2.5}$.

Thanks for you attention

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I would be happy to take any question

scchen@vcu.edu