Combined Effects of Aerosol Concentration and Testing Humidity on Laboratory Air Filter Loading Test using Sub-micrometer Hygroscopic Aerosols

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Introduction – Filter loading test

- **Why conducting filter loading test?**
  - Comparing performance
  - Predicting performance
- **Factors influencing loading characteristics:**
  - Media properties
  - *Filtration velocity / flowrate*
  - *Test aerosols (Size, Morphology, Concentration, Chemistry)*
  - *Other operation conditions (Humidity, Temperature, Pressure, etc.)*
- **Trade-offs have be to made, to conduct experiments at reasonable costs (hardware and time)**
  - Controlling **primary** factors;
  - Controlling **secondary** factors with reasonable cost if possible; otherwise recognizing their effects.

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Introduction – Literature summary

- **Research articles:**
  - In 59 journal articles with topic on filter loading test employing solid particles, the number of articles mentioning the following parameters are listed below:

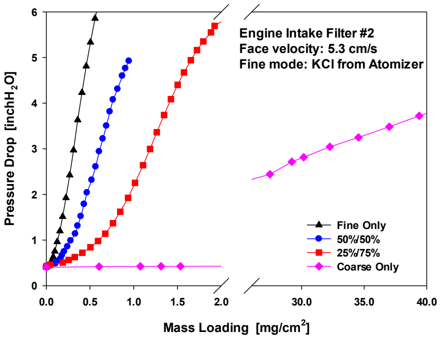
Testing parameter	Number of times being mentioned
Testing aerosol materials or size	59 (out of 59)
Filtration velocity (or flowrate)	58
Humidity	**9**
Testing aerosol concentration	**8**

- **Test standards:**

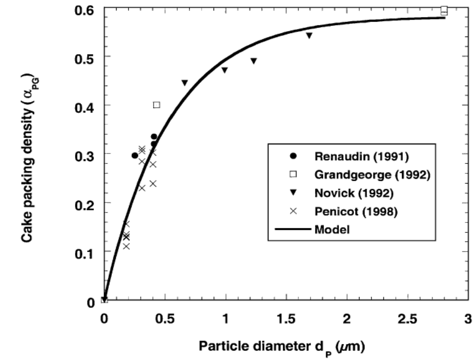
Standard	Test Aerosols	Relative Humidity	Concentration
ISO 5011:2014	ISO A2 & A4 dust	55±15%	1000 mg/m^3
ISO 16890:2016	Synthetic Loading Dust	45±10%	140±14 mg/m^3
EN 779:2012	Synthetic Loading Dust	<75%	70 mg/m^3
ASHRAE 52.2:2007	KCl / Synthetic Loading Dust	20% - 65%	70±7 mg/m^3

Introduction – Known primary factors

- **Testing Aerosol Size**
  - Mass ∝ Size^3, while Friction ∝ Size^2;
  - Affecting deposition profile and dendrite/cake porosity

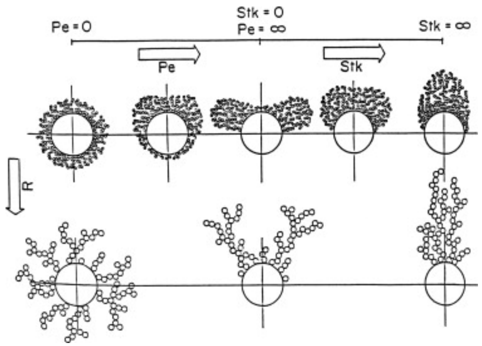


(Ou & Pui, CFR 2015)

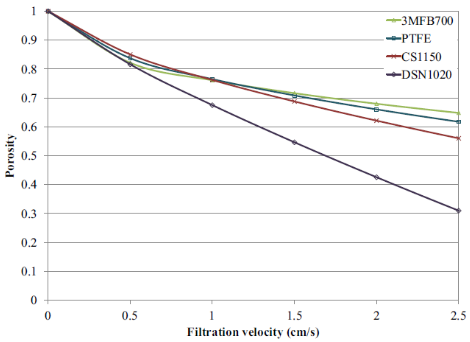


(Thomas et al., 2001)

- **Filtration Velocity**
  - Affecting deposition profile (depth and orientation);
  - Affecting compression.

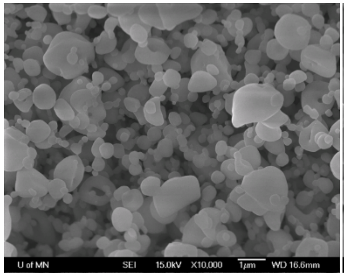


(Kasper et al., 2010)

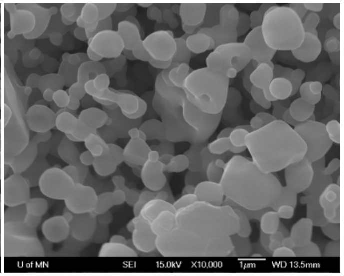


(Lupion et al., 2014)

- **Humidity**
  - Affecting particle size and necking between particles;
  - Affecting available solid surface for friction consequently.

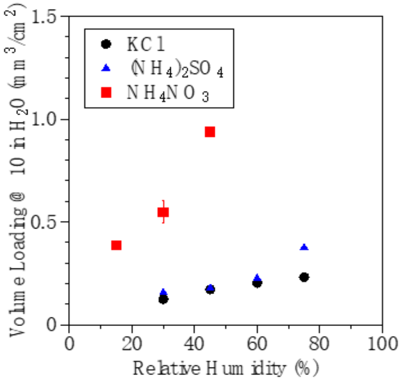


RH=30%



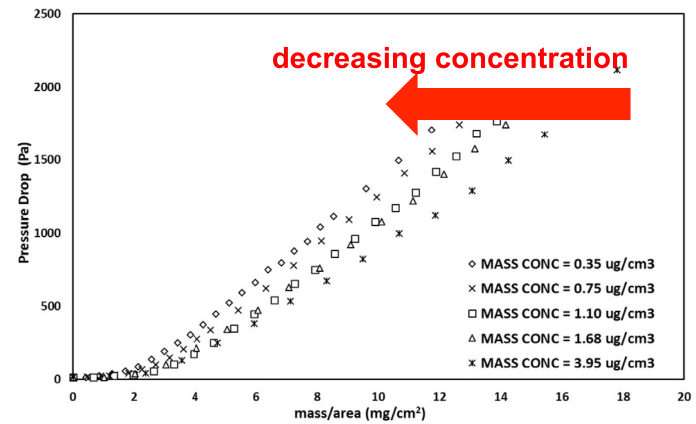
RH=75%

(Pei et al., CFR 2017)



Introduction – Is concentration a factor?

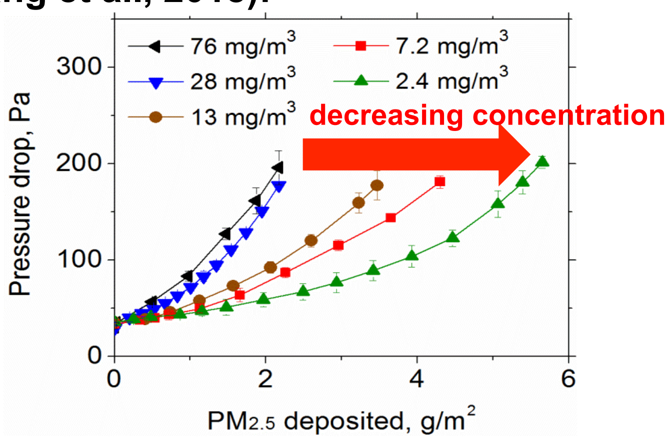
(Wang et al., 2016):



- Arizona Road Dust (ISO 12103-1, A3)
- Concentration range: 350 to 3950 mg/m³
- Lower concentration:
  → larger inter-particle spacing in flow
  → more space & time to rearrange in cake
  → denser cake
  → higher resistance

Cake collapse

(Tang et al., 2018):



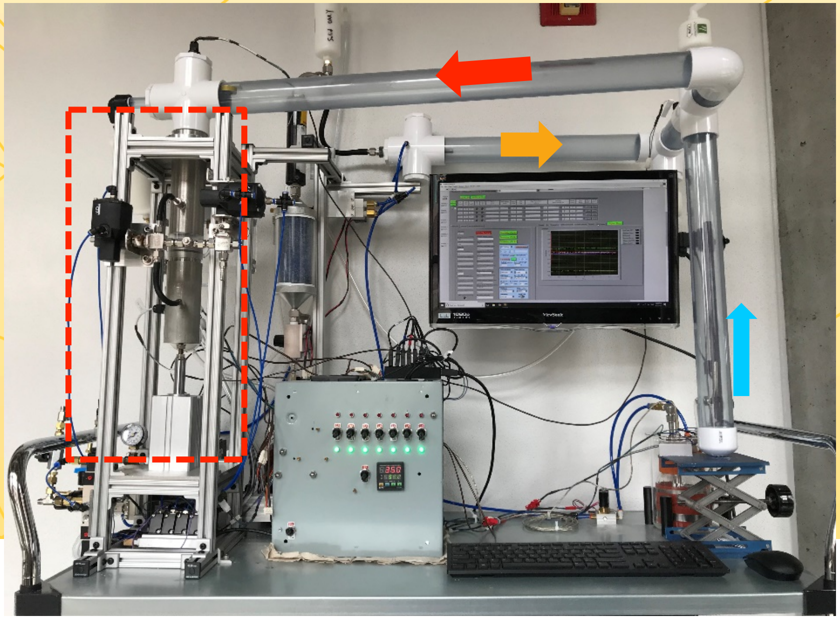
- Submicron NaCl particles on electret media
- Concentration range: 2.4 to 76 mg/m³
- Lower concentration:
  → larger inter-particle spacing in flow
  → more space & time to rearrange in dendrite
  → more collapsed dendrite
  → lower resistance

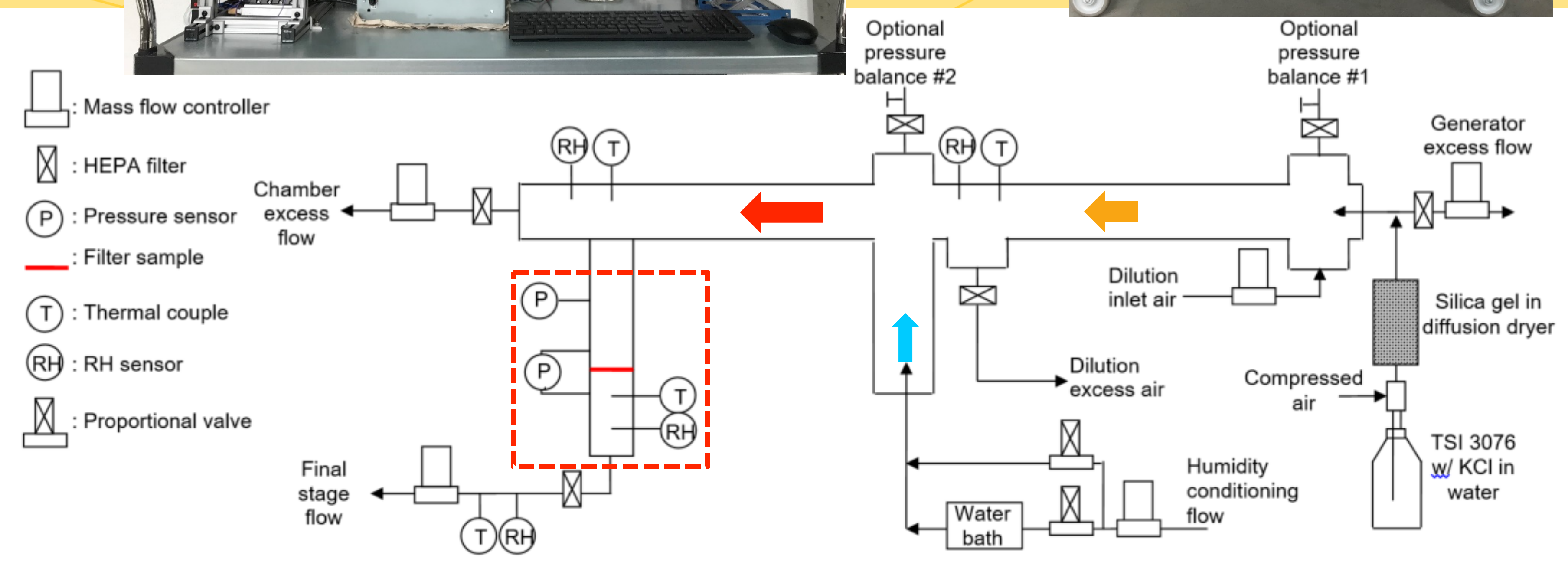
Dendrite collapse

- Is particle (cake/dendrite) collapse the **ONLY** explanation of concentration effect?
- Is concentration a **primary** factor or a **secondary** factor?

Test Methods – Loading-on-A-Cart Test Rig

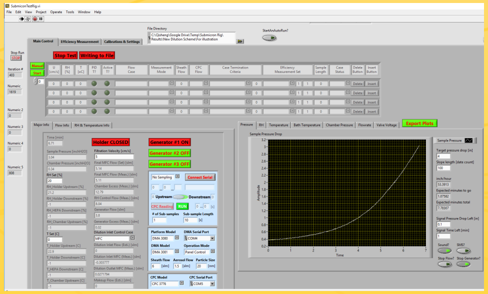
- "**Loading-on-A-Cart**" test rig: a filter loading test rig home-built on a movable utility cart.





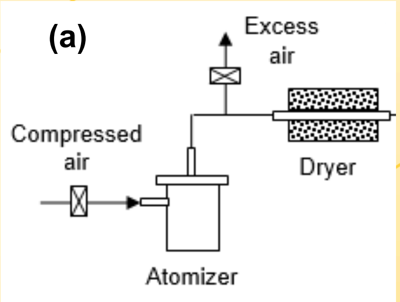
Test Methods – Loading-on-A-Cart Test Rig

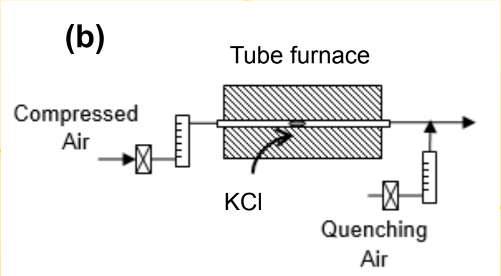
- Straight-through easy-feeding filter holder
- Flexible test aerosol selections:
  - having its built-in aerosol generator (TSI 3076 constant output atomizer);
  - being able to be attached to any other less-movable generators in the lab (e.g., furnace, soot burner in a hood, etc.)
- Fully automated:
  - Data logging of pressures, flowrates, humidities, temperatures, every 1 second;
  - Built-in two-stage dilution up to 1:100 dilution ratio;
  - Upstream/downstream sampling auto-switch;
  - Switchable between manual control and automated control;
  - Home-built LabVIEW program for automated control.



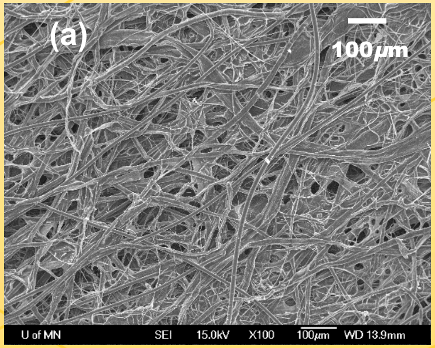
Test Methods – Test matrix

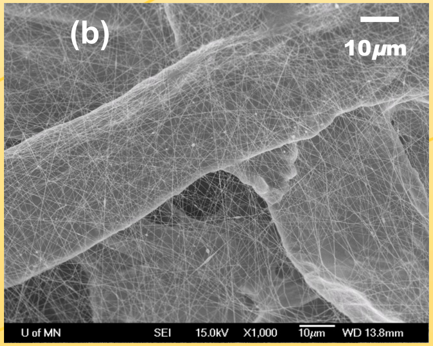
- **Testing aerosols**:
  - (a) KCl from **Collison atomizer** (mechanical aerosolization)
  - (b) KCl from **tube furnace** (evaporation-condensation)





- **Filter media** tested
  - (a) **Cellulose**
  - (b) Cellulose with **nano-fiber** coating



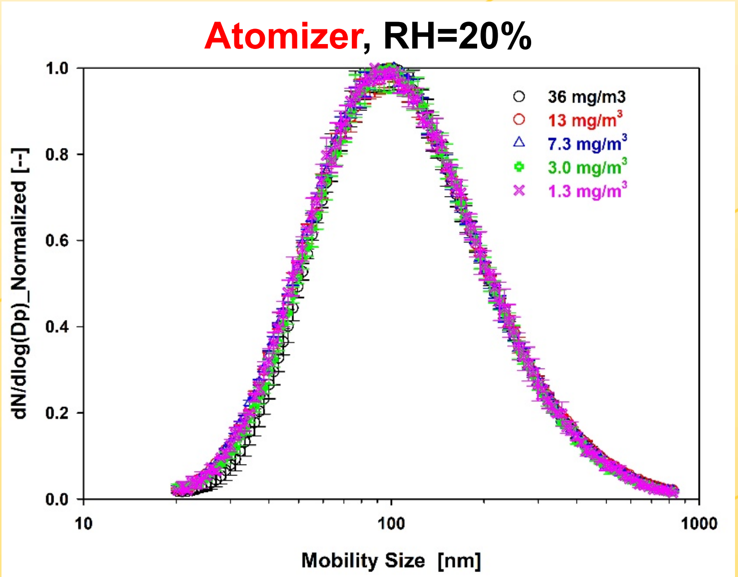


- **Relative humidity** level:
  - **Below 10%** (dry), **20%** (moderate), and **60%** (high)

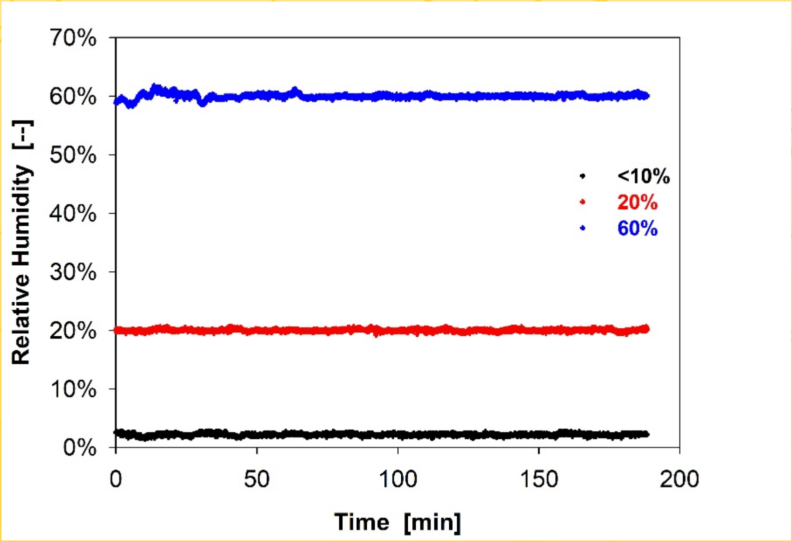
- **Aerosol concentration** levels:
  - From atomizer: 36, 13, 7.3, 3.0, and 1.3 mg/m^3;
  - From furnace: 11, 6.8, 3.0, and 1.2 mg/m^3;

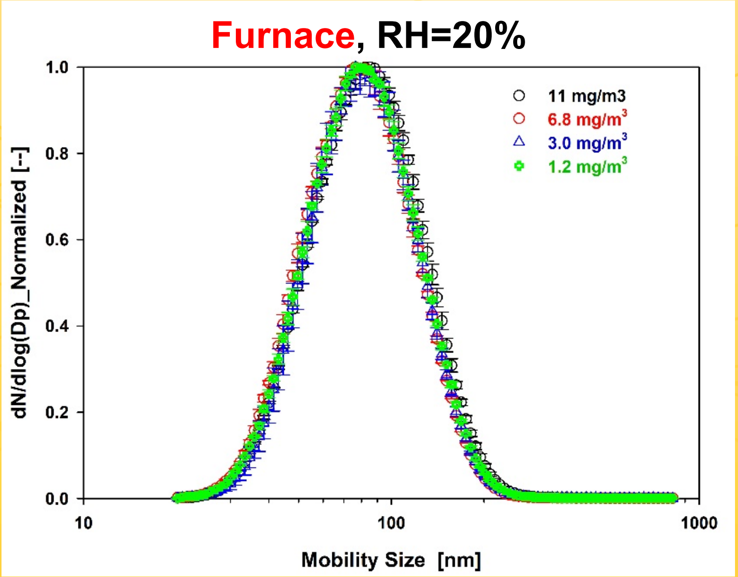
Test Methods – Size distribution & humidity

- **To study an unknown factor, all the known primary factors must be well controlled.**
  - ➢ Close size distributions at different dilution levels;
  - ➢ Stable humidity control within ±2%.



Typical RH curves during test





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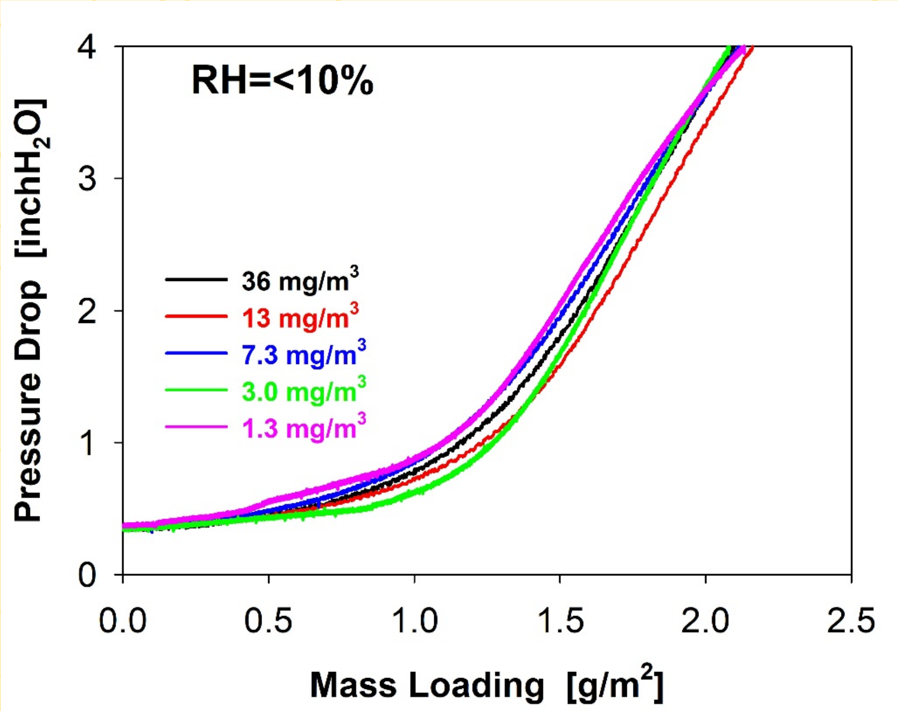
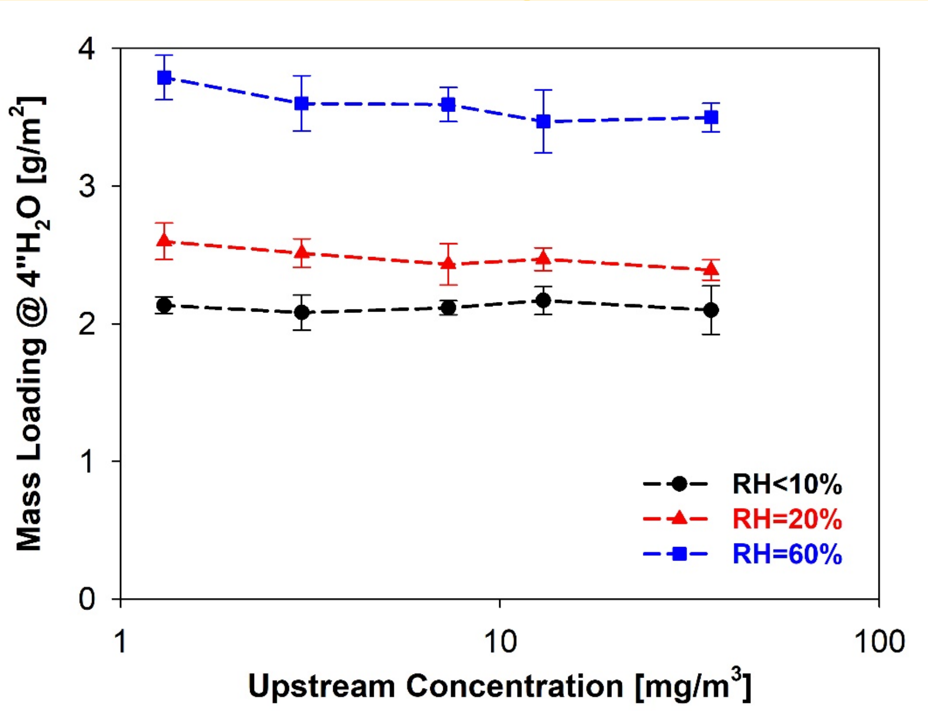
Results – Cellulose media (I)

- Loading cellulose media with KCl particles generated from **atomizer**:





- For **cellulose** media loaded with KCl particles generated from **atomizer**:
  – At **low RH** (20% or lower), **no effect** of aerosol concentration was observed;
  – At **high RH** (60%), mass loading increases **just slightly** with decreasing concentration.

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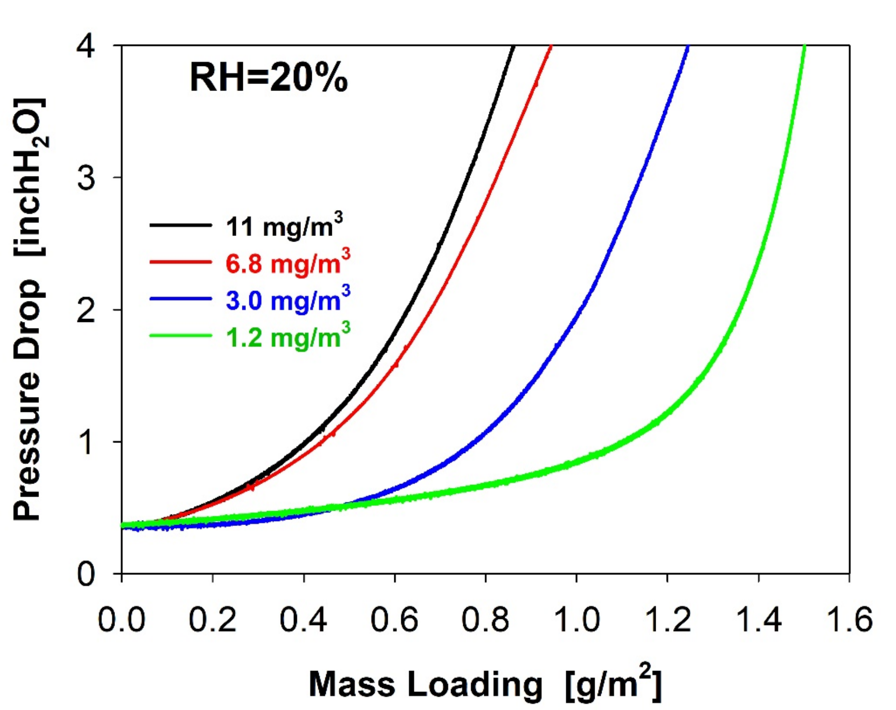
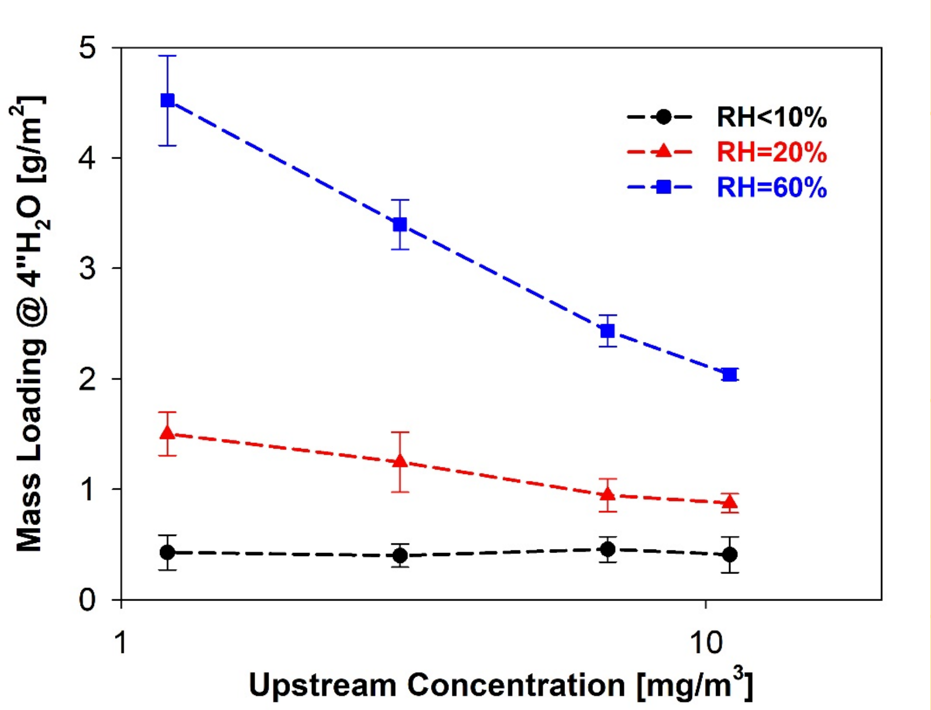
Results – Cellulose media (II)

- Loading cellulose media with KCl particles generated from **furnace**:





- For **cellulose** media loaded with KCl particles generated from **furnace**:
  - At **very low RH** (10% or lower), **no effect** of aerosol concentration was observed;
  - At **moderate RH** (20%), mass loading **increases** with decreasing concentration. This effect becomes more significant **at higher RH** (60%).

(See appendix 3 for more)

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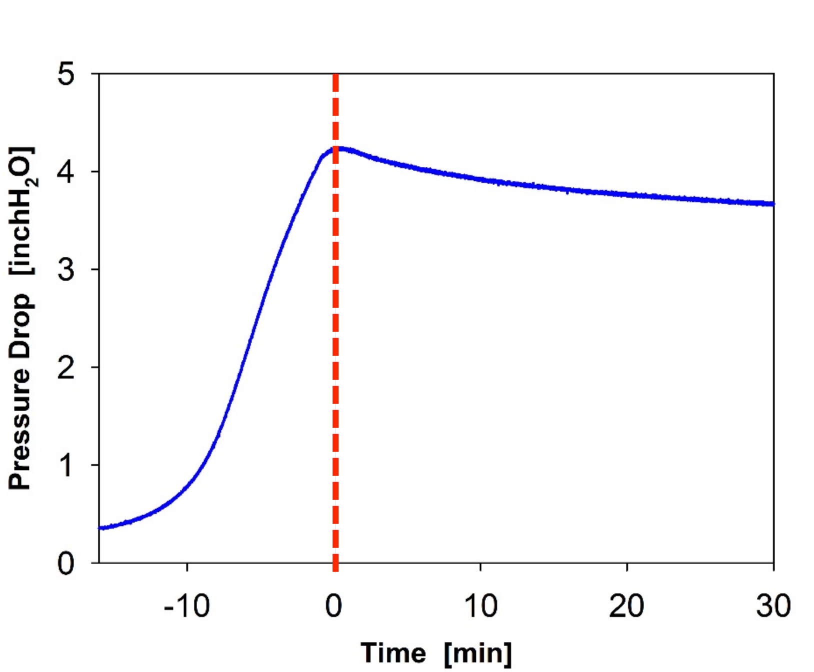
Results – What happens after loading?

- After reaching desired terminal pressure drop, aerosol feeding stops, while maintaining all flows and humidity.



(See appendix 1 for more)

- Particle dendrites (after depositing) may change their shape and/or structure, which leads to release of pressure drop.
  - This process takes time, and no instantaneous equilibrium reaches; therefore, loading rate (aerosol concentration) matters.
  - Pressure drop decaying is more pronounced at high RHs, implying restructuring of dendrite may be moisture induced.

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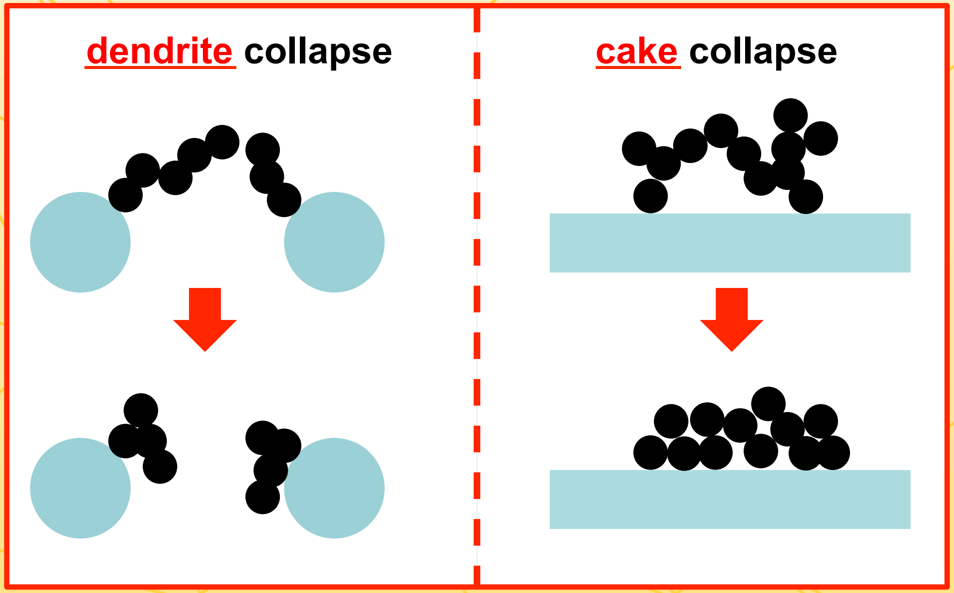
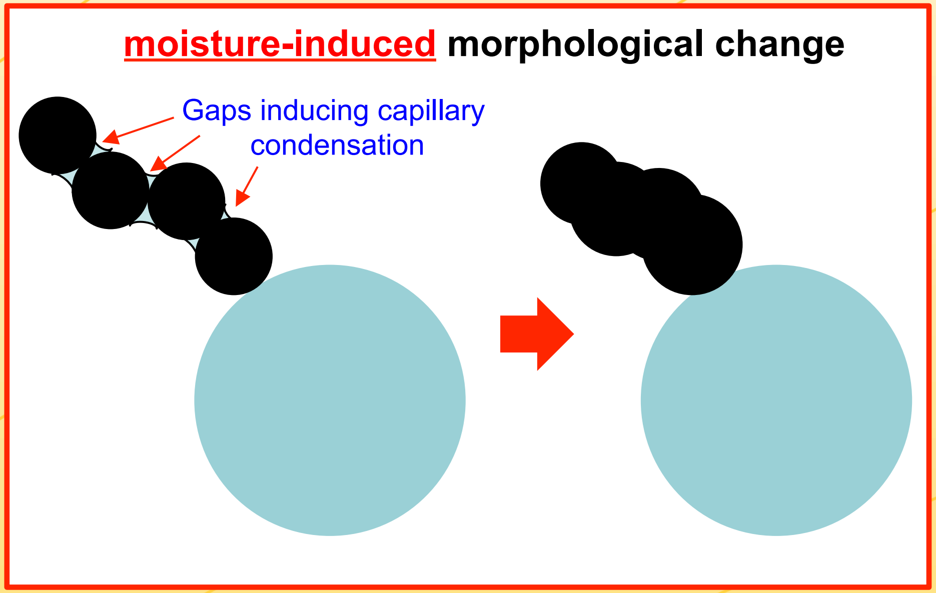
Results – What may cause ΔP to decay?



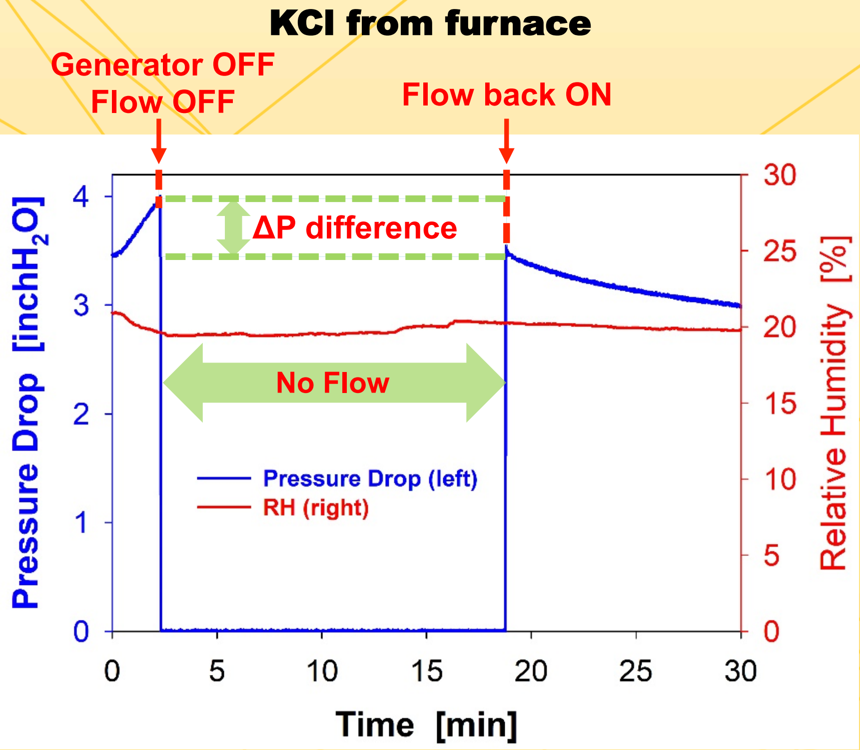


- Happening after particles deposit
  - **Rearranging position**
- **Concentration dependent**:
  - Inter-particle space
  - Time for particle relaxation
- Drag force vs. adhesion force

- Happening after particles deposit
  - **Forming gaps**
- **Concentration dependent**:
  - Time for water vapor diffusion
  - Time for salt molecules to relocate
- Strongly depending on **humidity**

Results – What may cause ΔP to decay?

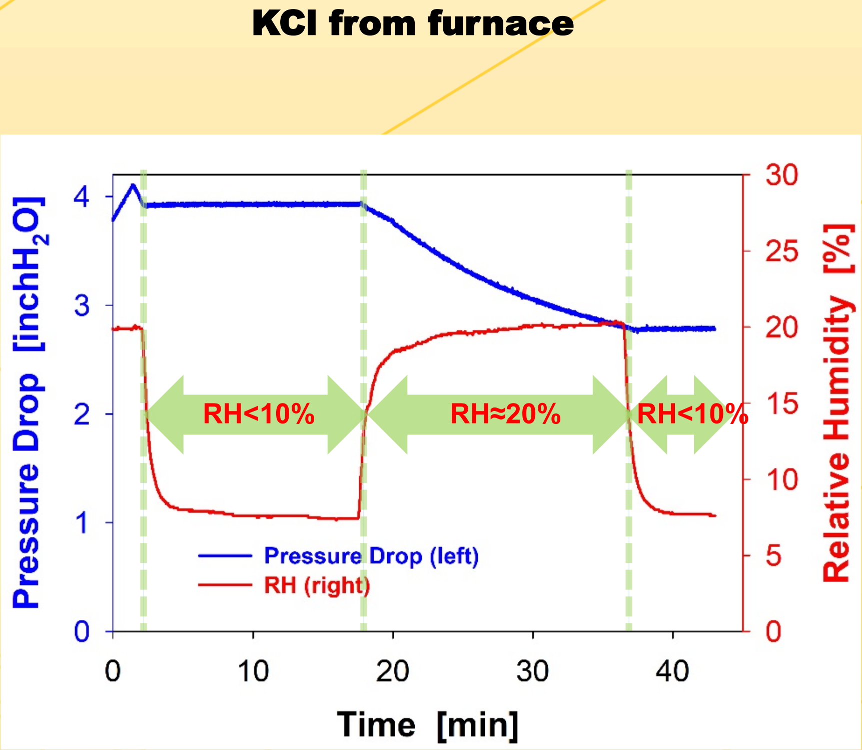
Special case 1: No-Flow decay



- ΔP continues to decay at moderate RH (20%) even without flow through media.
- Besides drag force by flow friction, which competes with adhesion force, there are other mechanisms causing ΔP to release.

(See appendix 2 for more)

Special case 2: Dry decay



- ΔP does not decay at dry condition (RH<10%), but resumes decaying when RH rises back to moderate level (20% or higher).
- Moisture-driven mechanism is a major contribution of ΔP release.

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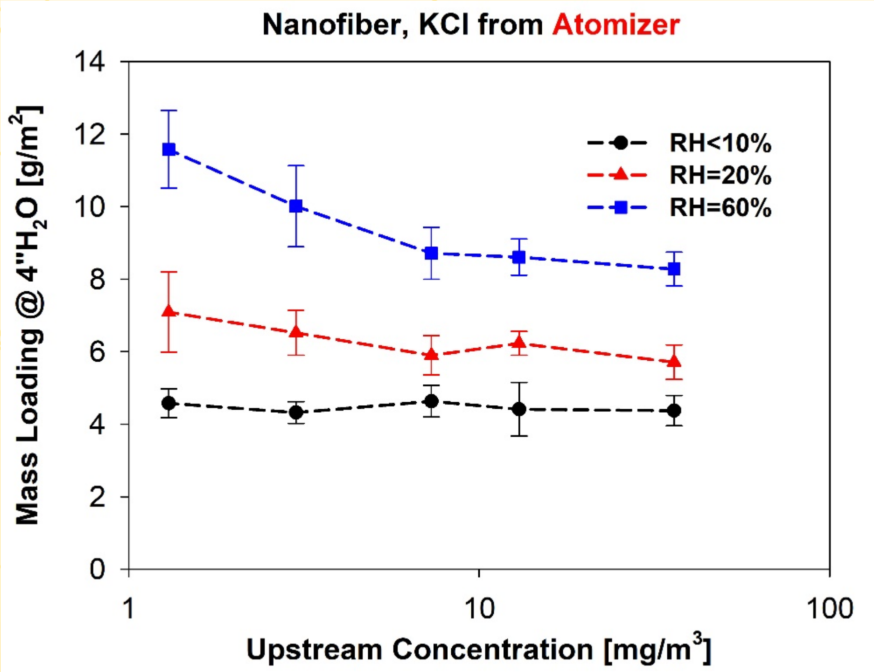
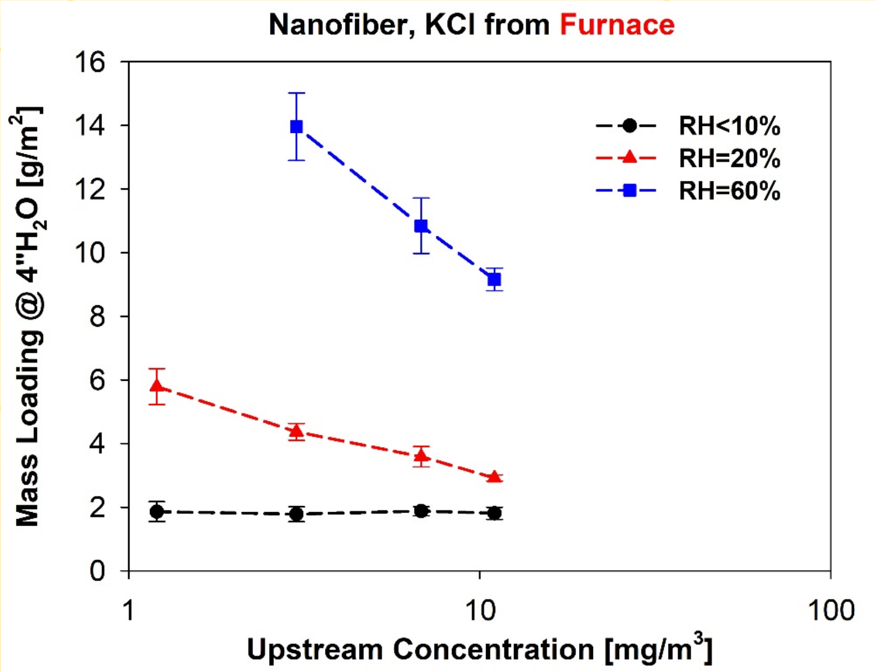
Results – Nanofiber media



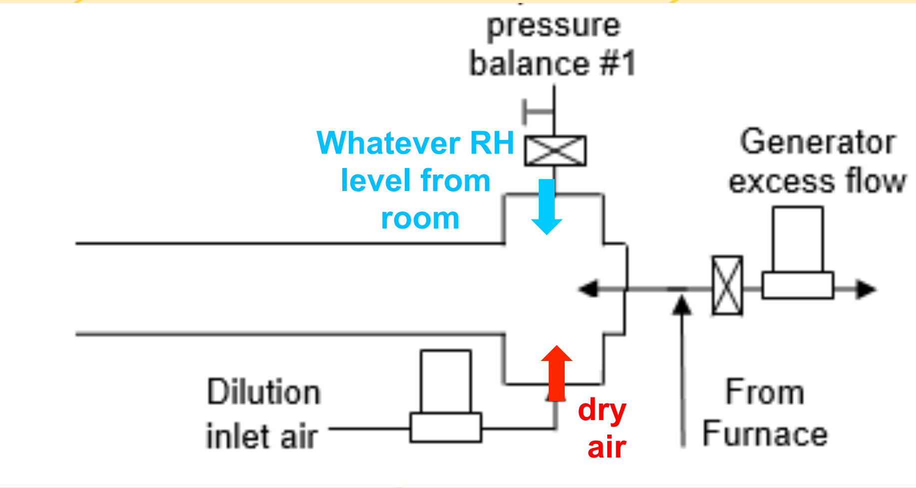


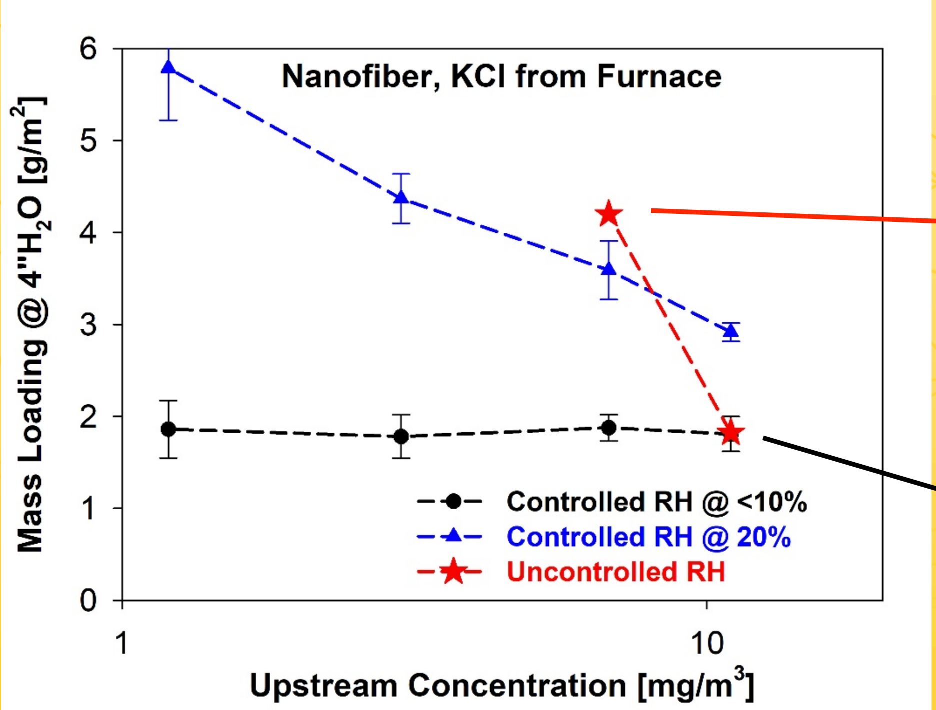
- Similar but more pronounced trend was observed for nano-fiber coated cellulose media, which is a **nearly surface loading** medium:
  - Growth in particle size and necking are the dominated mechanism for pressure drop decay, rather than the collapse of cake itself without size change.
  - If the particle cake collapsed without individual particle size change or necking, ΔP would increase because of reduced porosity in cake, which would lead to lower mass loading with decreasing concentration.

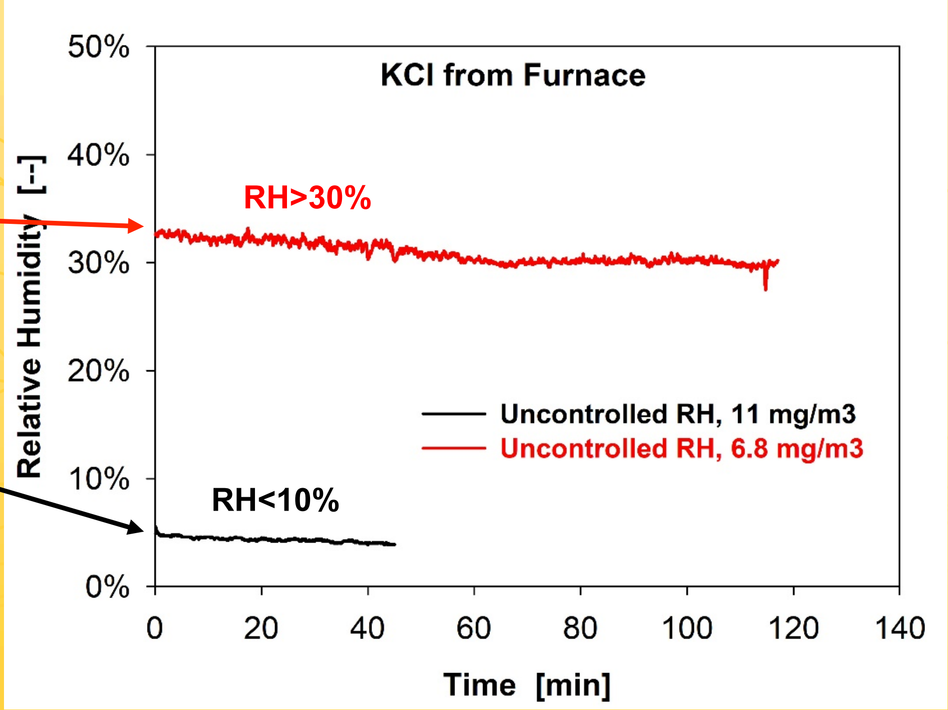
(See appendix 3 for more)

Results – What if without RH control?

- If RH is not actively controlled, depending on flow system design and humidity level in the room, diluting aerosol concentration without monitoring RH could unnoticeably affect humidity level in the test system, which further leads to significant difference on mass loadings.







Summary

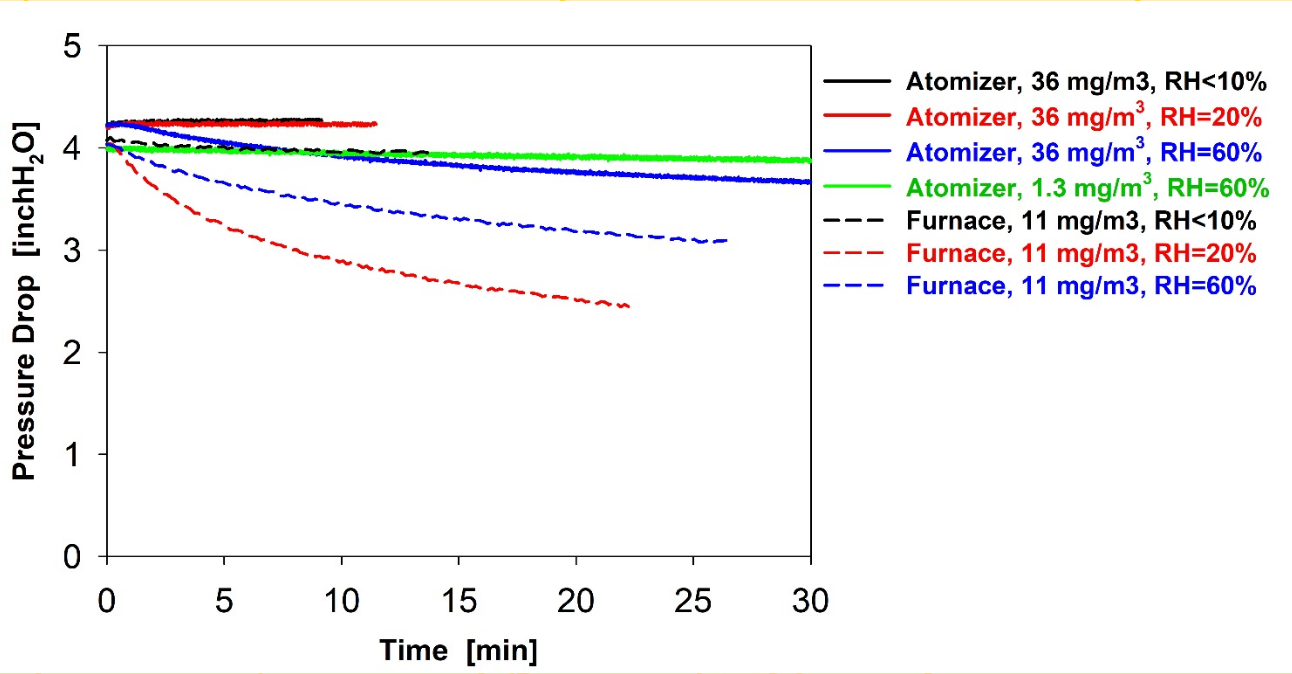
- Both aerosol concentration and testing humidity can influence laboratory filter loading test performance with sub-micrometer hygroscopic aerosols:
  - Moisture-induced structure change helps to release pressure drop of a hygroscopic-aerosol-loaded filter;
  - This process happens after particles deposit, and takes time. Therefore, test aerosol concentration can influence loading performance indirectly, depending on the competition between loading rate and releasing rate;
  - Comparing to particle size and humidity (which are primary factors), testing concentration is a secondary factor for normal test scenario, but needs attention at high RH levels.
  - Relative humidity in a loading experiment needs to be well monitored and controlled, before studying any unknown factors is possible.
  - Attention needs to be paid when designing flow and dilution system for filter loading test, as it can inconspicuously affect humidity level in test system.

Summary

- Filters are seldom used under very dry environments, especially when hygroscopic salt particles are the major pollutants:
  - Filter loading test at very dry condition does not have equally-important implication to practice, comparing to its counterparts at moderate or high humidities.
  - Filter loading test using dry salts generated from evaporation-condensation method may not be good candidates of testing aerosols, even if testing RH is maintained at higher level.
  - More systematic study is needed to compare the difference of hygroscopic salt particles generated from mechanical-atomization and evaporation-condensation methods, in terms of their suitability in mimicking inorganic hygroscopic fraction in $PM_{2.5}$ for laboratory filter loading tests.

Appendix 1 – What happens after loading?

- After reaching desired terminal pressure drop, aerosol feeding stops, while maintaining all flows and humidity.



- Particle dendrites (after depositing) may change their shape and/or structure, which leads to release of pressure drop. This phenomenon is more pronounced:
  - At **higher** RH – (larger difference between fresh dendrite and equilibrium);
  - At **higher** loading concentration – (less time to reach equilibrium during loading);
  - When loaded with KCl from **furnace**, comparing to counterparts from atomizer.

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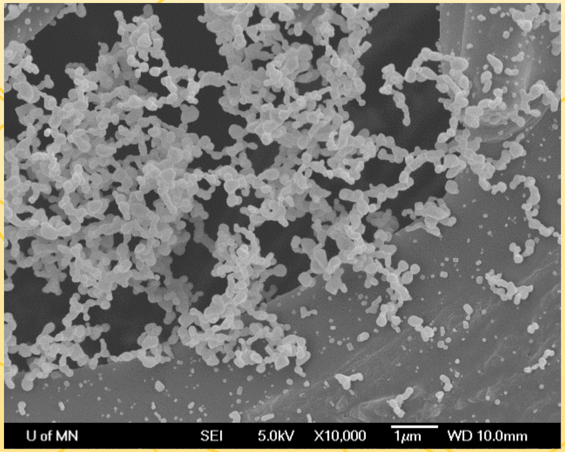
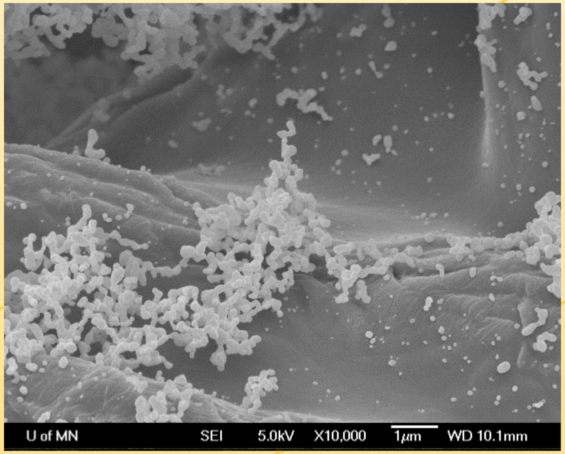
Appendix 2 – SEMs of loaded cellulose media

- SEMs of cellulose media loaded with KCl particles generated from furnace.

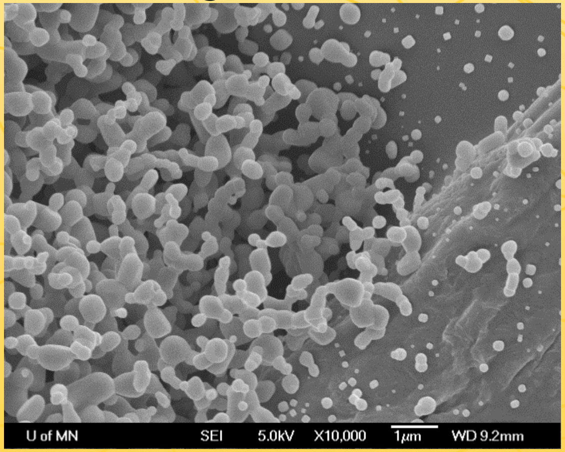
11 mg/m^3, RH<10%



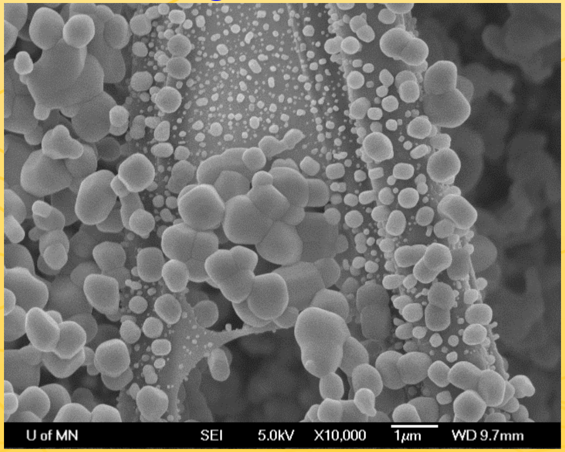
1.2 mg/m^3, RH<10%



11 mg/m^3, RH=60%



1.2 mg/m^3, RH=60%



- KCl particles grow in size at high RH (60%). This growth is more pronounced at low loading concentration, as more time is allowed for interaction with moisture to happen.

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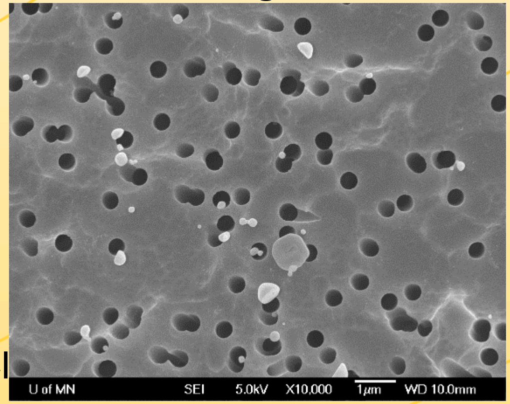
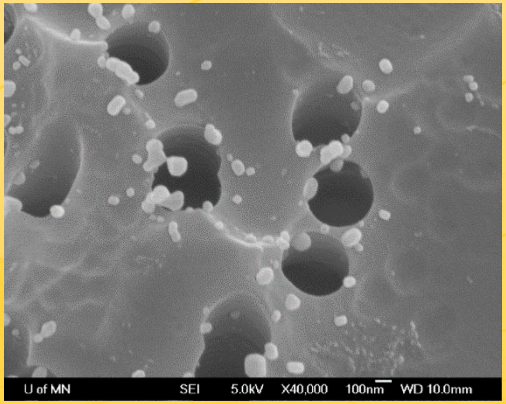
Appendix 3 – Atomizer vs. Furnace

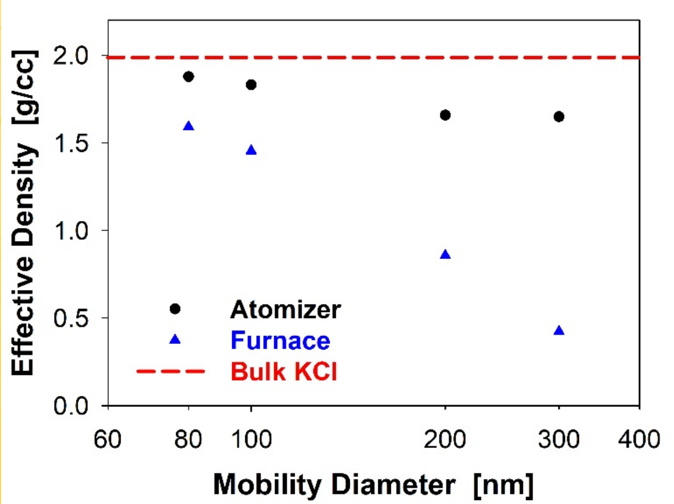
- Possible explanations of why furnace-generated KCl particles are more sensitive to RH, comparing to atomizer-generated counterparts:
  - Individual particles are generated from both generators, without severe agglomeration, as shown in SEMs. (doublets and triplets were found.)
  - Tandem DMA-APM measurement indicates lower effective density of furnace-generated KCl particles at same mobility size.
  - Size shift is observed for furnace-generated KCl particles at elevated RHs (60%).
  - Above findings indicate hollow structures may exist in furnace-generated KCl particles, which was observed in literature. (Park et al., JNR, 2009)
  - More systematic investigation is needed in terms of their (atomizer vs. furnace) suitability for filter loading test.

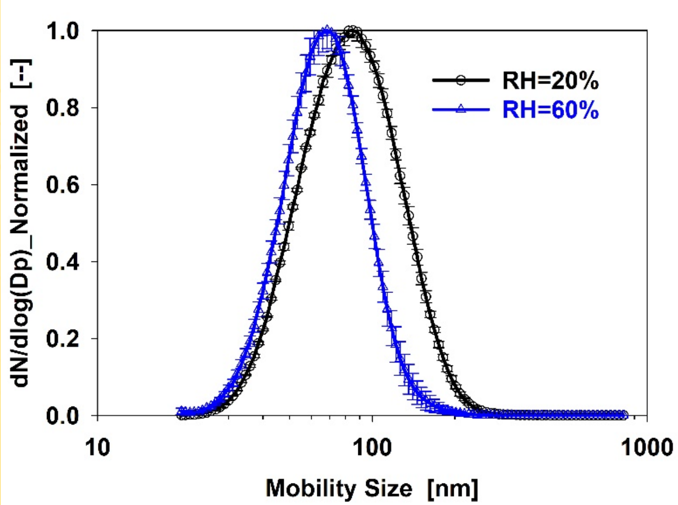
Atomizer-generated



Furnace-generated







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