Particle Loading Characteristics of Two-stage Filtration System

Xinjiao Tian[1], Qisheng Ou[1], Yun Liang[2], and David Y.H. Pui[1]

1Particle Technology Laboratory, University of Minnesota
2 South China University of Technology

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Center for Filtration Research

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Introduction

- pre-filters used in two-stage filtration systems

Pre-filter wrap

Pre-filter panel

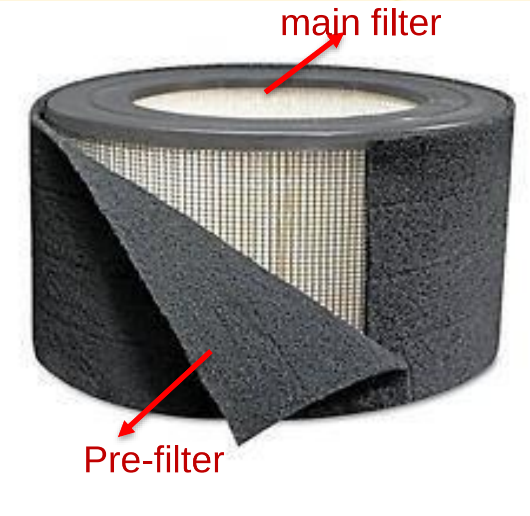
Pre-filter bag

Introduction

- Issues with main intake air filters:
  - pressure drop often increases rapidly
  - dust holding capacity is often low
  - relatively expensive

Why we want to use the two-s filter on the filtration system?

- Solutions with pre-filters:
  - slows down pressure drop increase of main filters
  - extra dust holding capacity
  - inexpensive
  - easy to change



Installing a pre-filter in front of the main filter, is a cost-effective way to extend the service life of the main filter.

- Factors influencing a two-stage filtration system performance:

  incoming aerosol distribution, face velocity of each stage, filter combinations, and others.

Introduction

Ratios of fine and coarse particles in atmospheric environment

Category	Total Conc. (μm/cm)^3	Fine/Coarse by Volume
BK& aged urban plume	71.4	62%/38%
Urban Average	69.8	55%/45%
Urban and freeway	89.4	42%/58%
Clean continental BK	6.5	23%/77%
Average BK	30.4	15%/85%
BK& local sources	42.7	7 %/93%
Marine surface background	12.1	1 %/99%

BK- Back ground

(WS Poon, BYH Liu 1997)

- The ratio of fine and coarse particles varies greatly among ambient environments.
- Filters are evaluated in *laboratories* using *either 100% fine or 100% coarse particles*, which *does not represent* the environment where filters are used.

> - *How does the particles size distribution in the environment affect the loading characteristics of a two-stage filter system?*

Objective

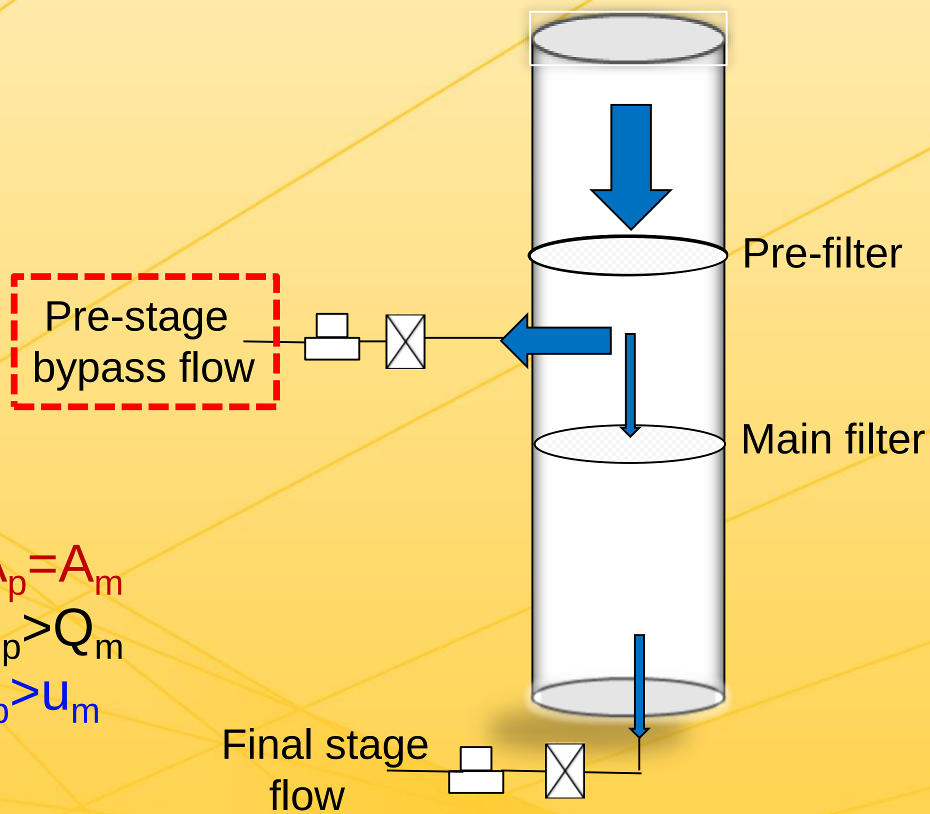
- To investigate the influence of installing a pre-filter on the loading characteristics of main filter.
- To compare loading characteristics of two-stage systems under different fine-coarse aerosol ratios and face velocity combinations of the two stages.
- To find the best scheme and to optimize the two-stage filtration system design.

Methodology – simulating a two-stage filter

Practical application

$A_p < A_m$
$Q_p = Q_m$
$u_p > u_m$

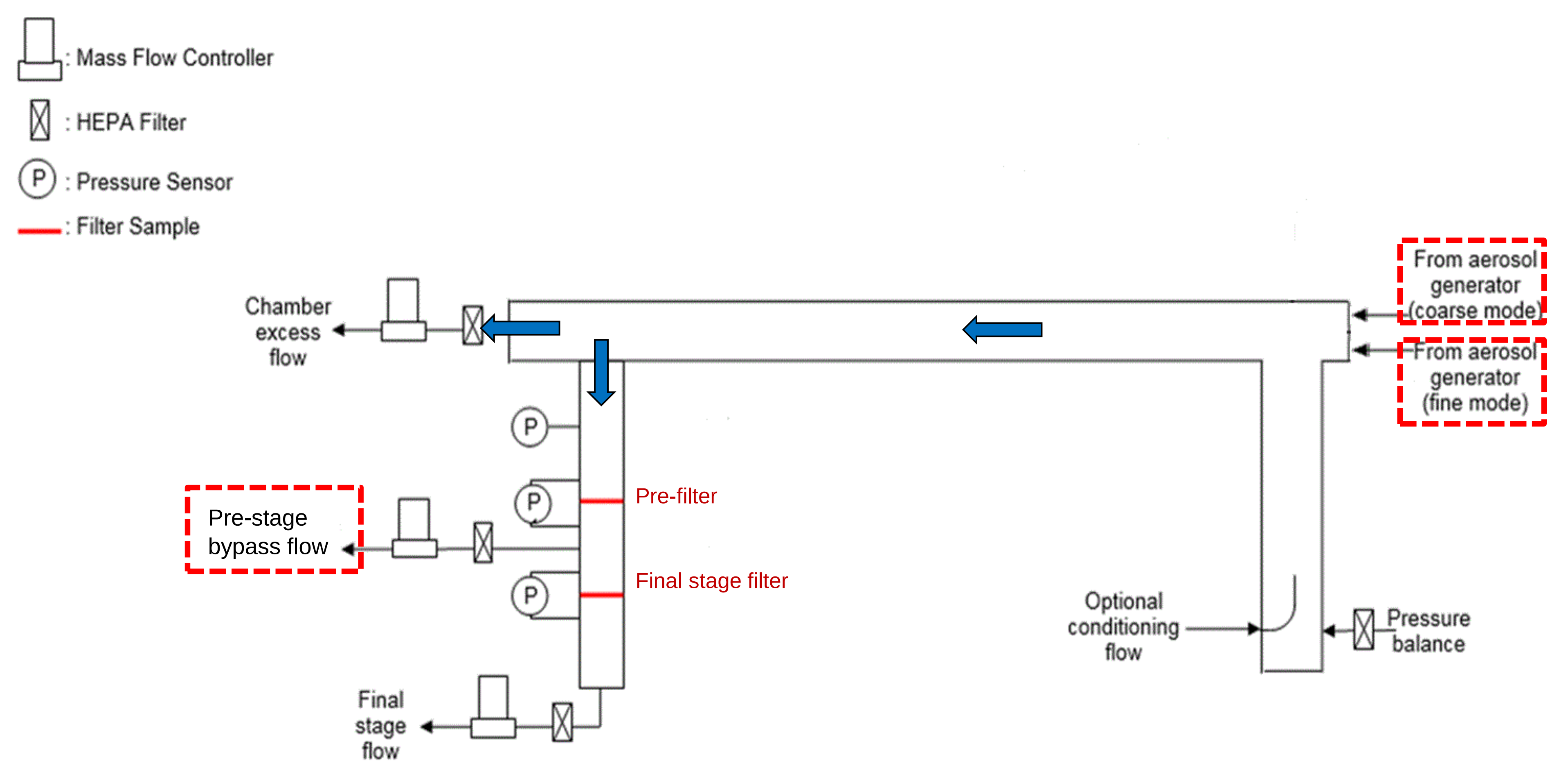
Experiment scenario



$A_p = A_m$
$Q_p > Q_m$
$u_p > u_m$

p: pre-filter
m: main filter

Schematic of test system

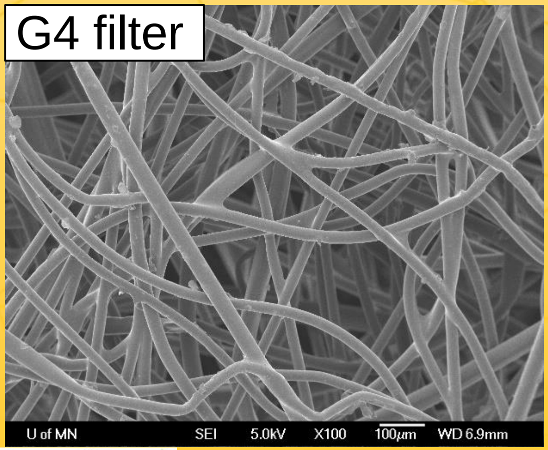


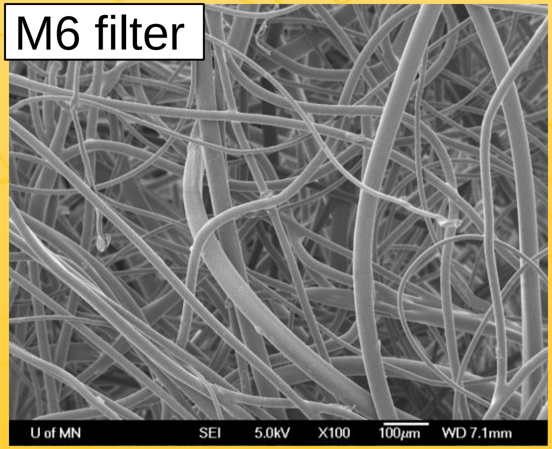
Testing condition

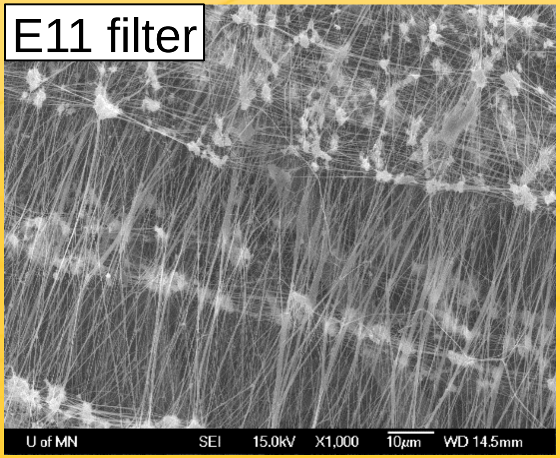
Properties of tested filter media

Filter		Areal weight ($g\ m^{-2}$)	Thickness (mm)	Permeability ($mm\ s^{-1}$)	Average Diameter (μm)
Pre-stage	G4 filter	363±2	6.79	3100	28.3
	M6 filter	385±2	3.46	730	19.7
Final stage	E11 filter (PTFE membrane filter)	160±3	0.37	85	--

G4,M6: efficiency rating EN 779: 2012
E11 : efficiency rating EN 1822-1-2009
see the appendix







Testing condition

Fine & Coarse Particles:

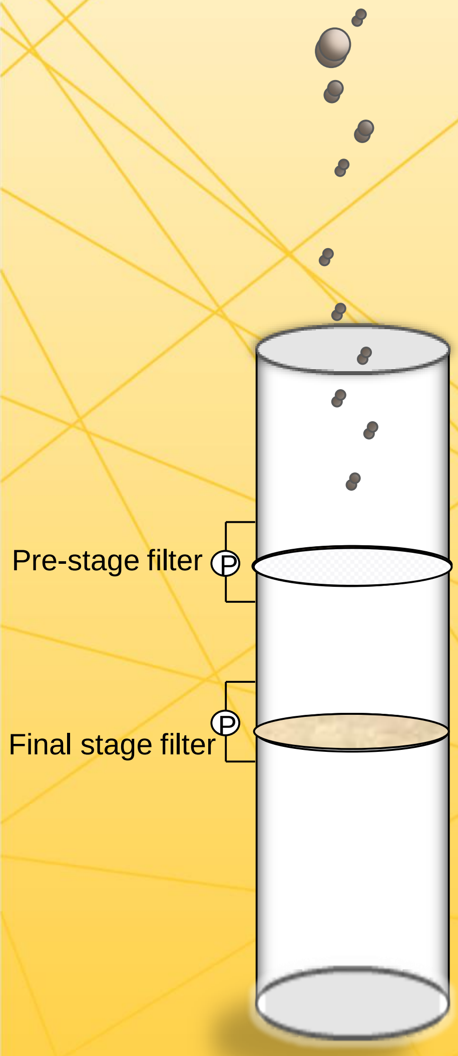
- **KCl:** 4% v/v potassium chloride aqueous solution
- **A2:** ISO 12103-1 Arizona test dust, A2 fine

Aerosol mixing ratio	KCl/A2	0%/100%, 6%/94%, 11%/89%, 33%/67%, 100%/0%

Pre-stage & Final stage face velocity:

Face velocity (cm s^{-1})	Pre-stage/Final stage	G4 & E11	65.2/2.1, 65.2/3.1, 65.2/5.2
		M6 & E11	30.2/5.2, 50.2/5.2, 65.2/5.2

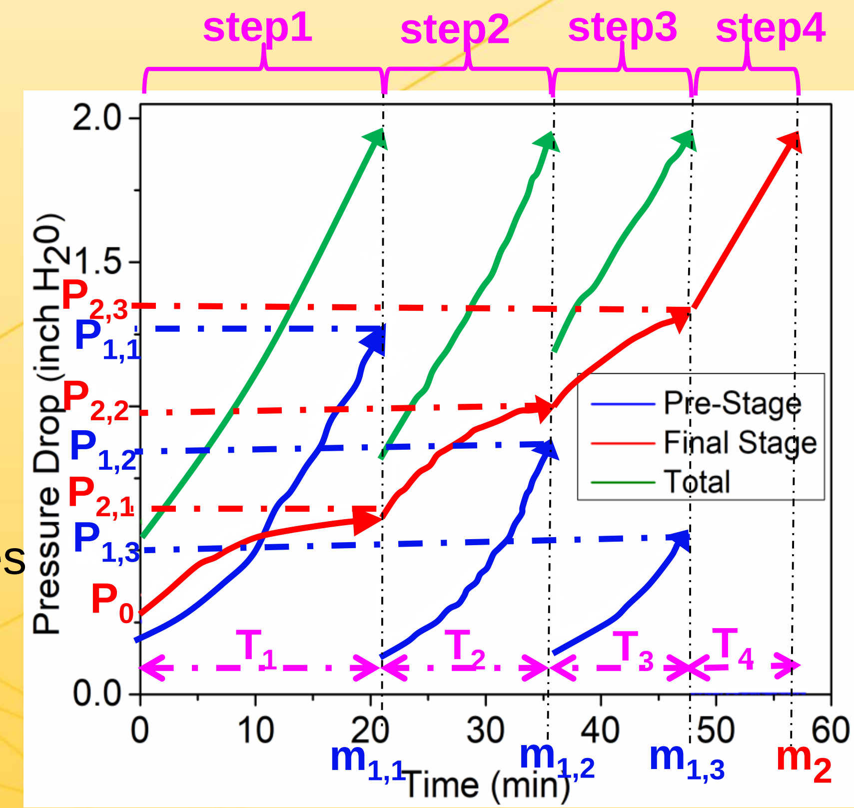
Testing Process



When P_T=2 inch H_2O
Remove pre-filter
Install a new pre-filter

Replace pre-filter three times

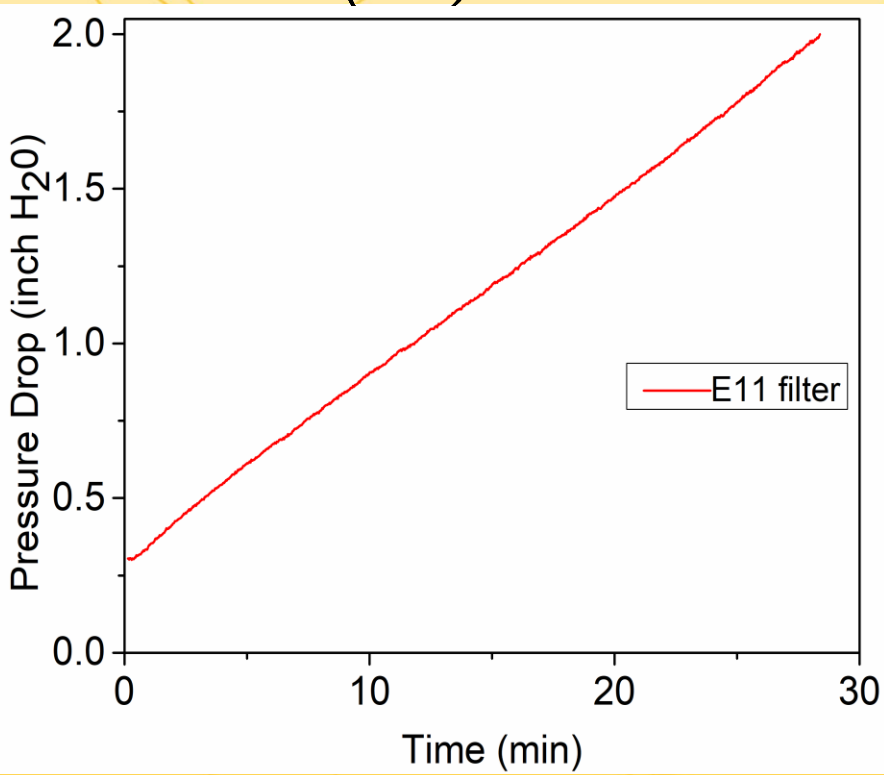
Until P_T=2 inch H_2O



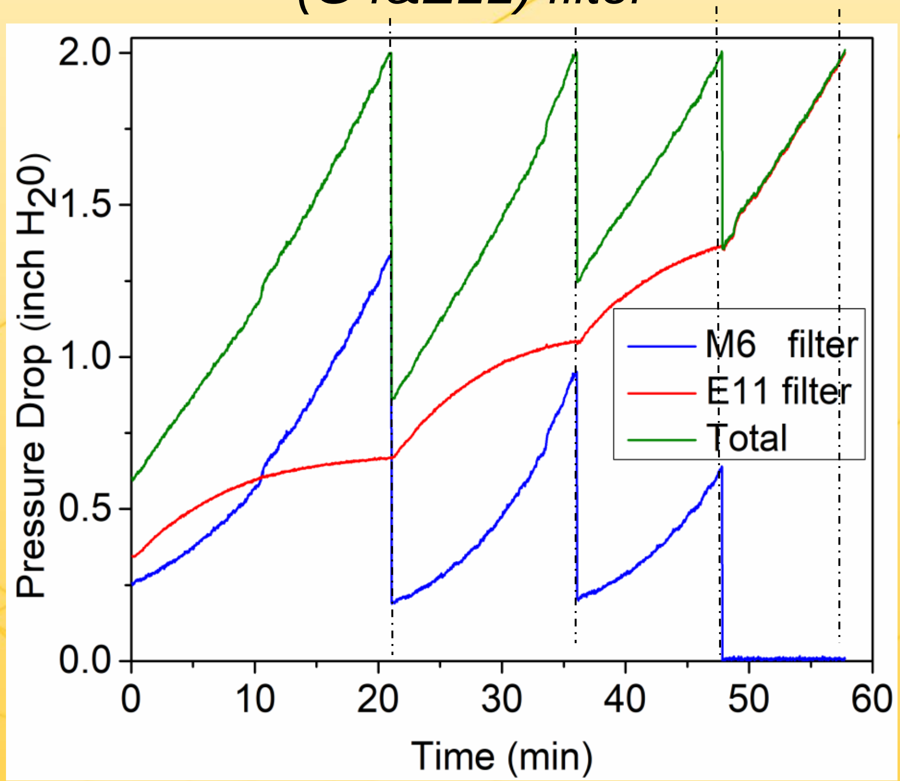
P_0 : initial pressure drop of main filter;
$P_{1,n}$: pressure drop of the n^{th} pre-filter at the end of the n^{th} step;
$P_{2,n}$: pressure drop of the main filter at the end of the n^{th} step;
$m_{1,n}$: mass gain of the n^{th} pre-filter at the end of the n^{th} step;
m_2 : mass gain of main filter at the end of the 4^{th} step;
T_n : time duration of the n^{th} step.

Reference test cases

Without pre-filter (reference)
(E11) filter



With pre-filter (two-stage case)
(G4&E11) filter



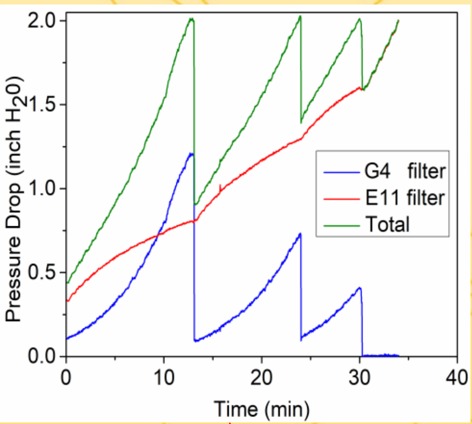
For every two-stage test case, a reference test case was conducted, under exactly the same test condition as the two-stage case, but without a pre-filter in front of the main filter.

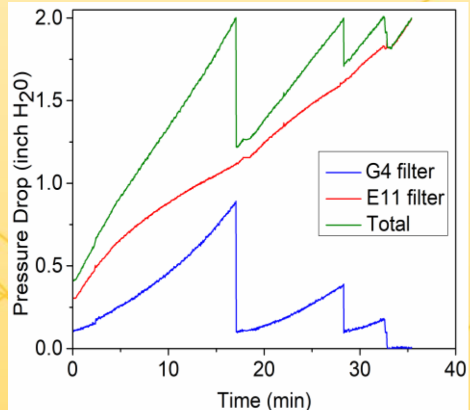
Examples of raw data

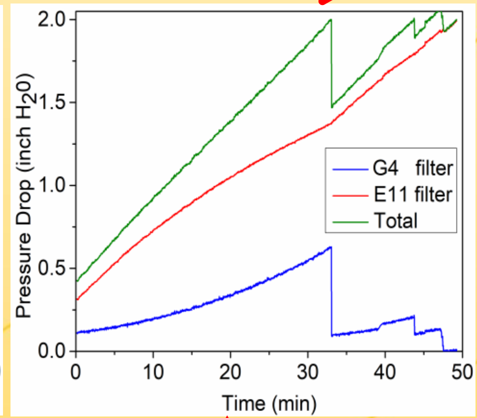
(G4&E11) filter

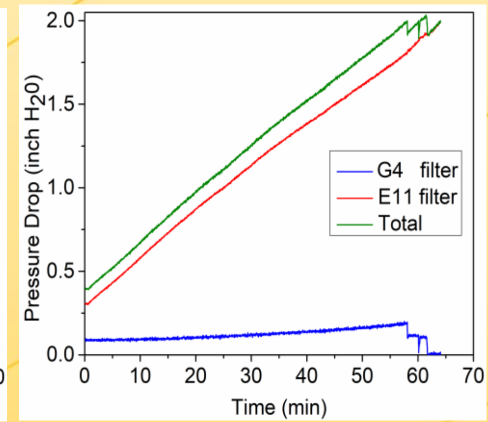
U_1=65.2 cm/s, U_2=***5.2*** cm/s

KCl/A2 0%/100% | 11%/89% | 33%/67% | 100%/0%



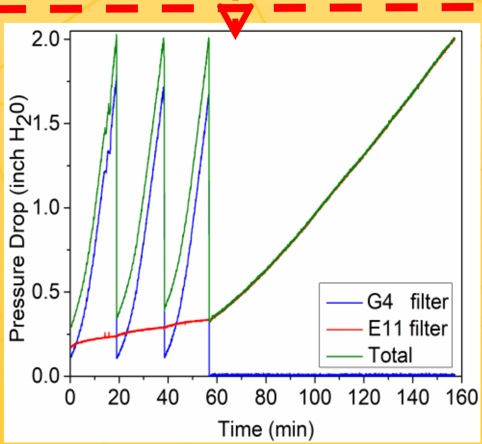


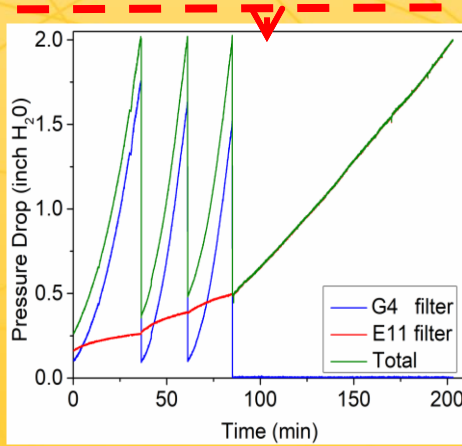


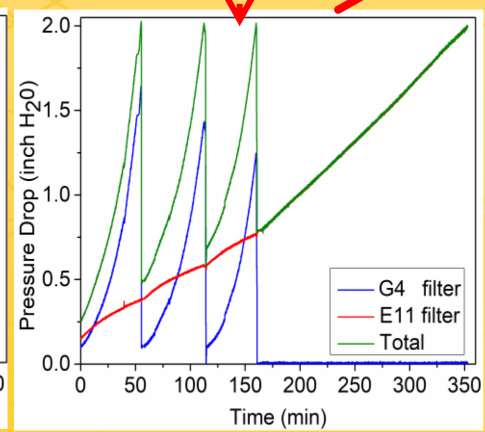


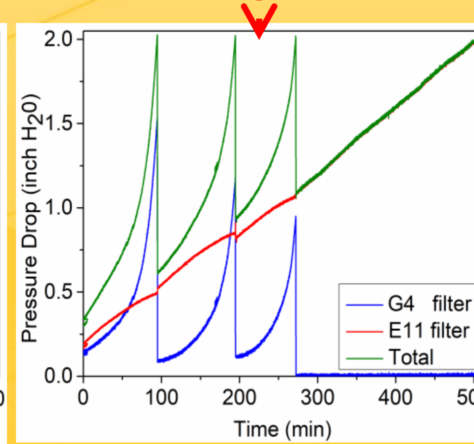
U_1=65.2 cm/s, U_2=***2.1*** cm/s

KCl/A2 0%/100% | 11%/89% | 33%/67% | 100%/0%

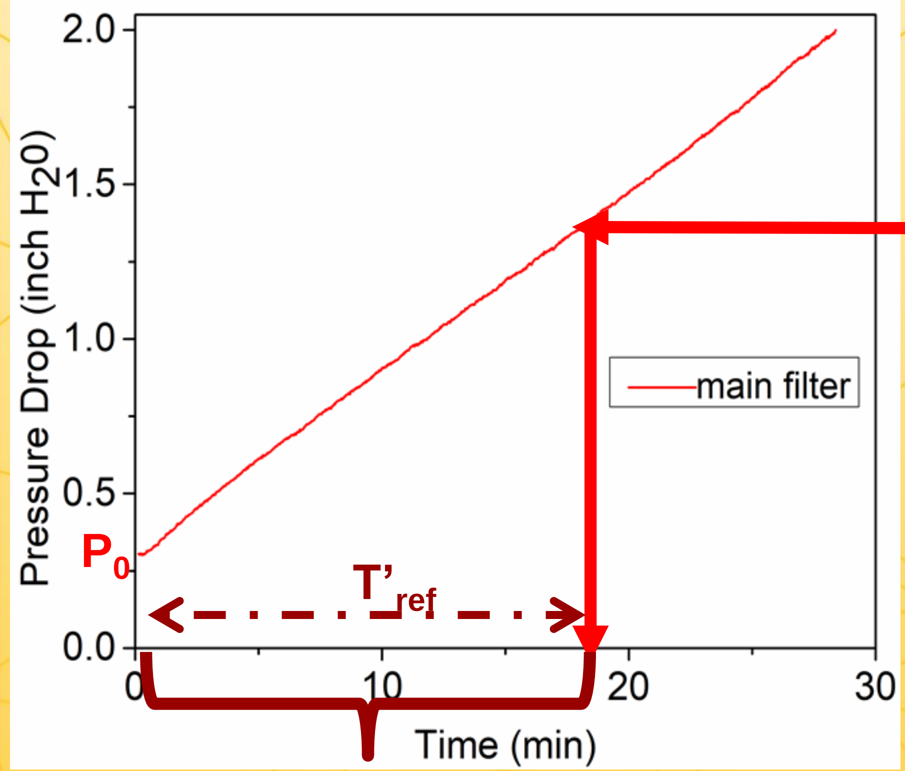


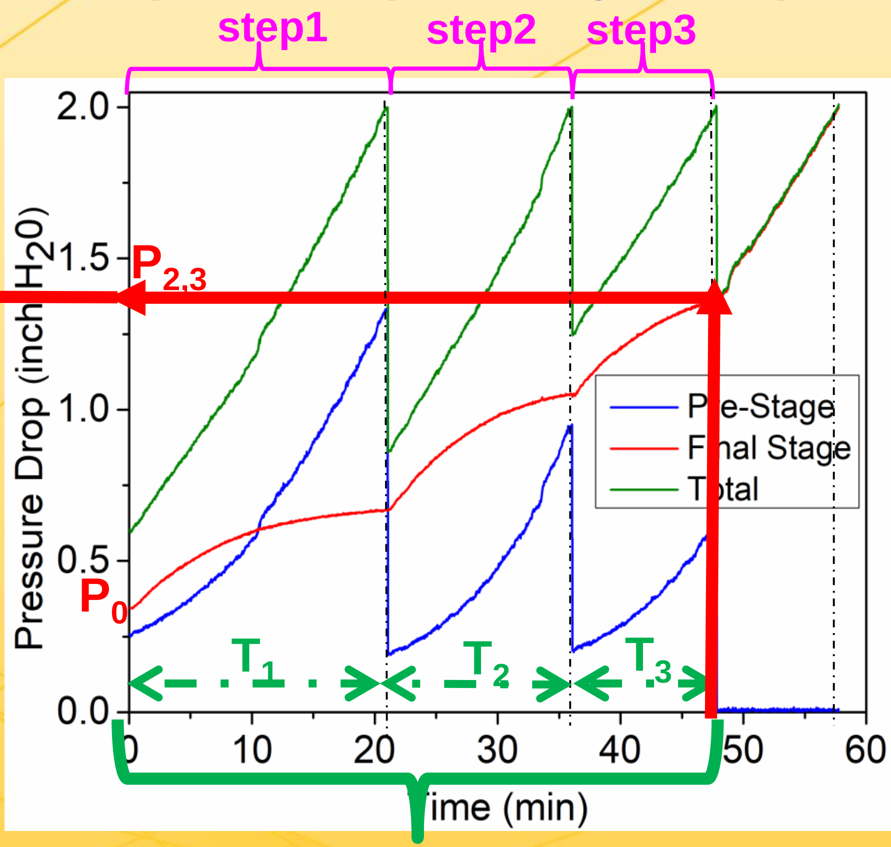






Results analysis – *Self-defined indexing parameters, T**





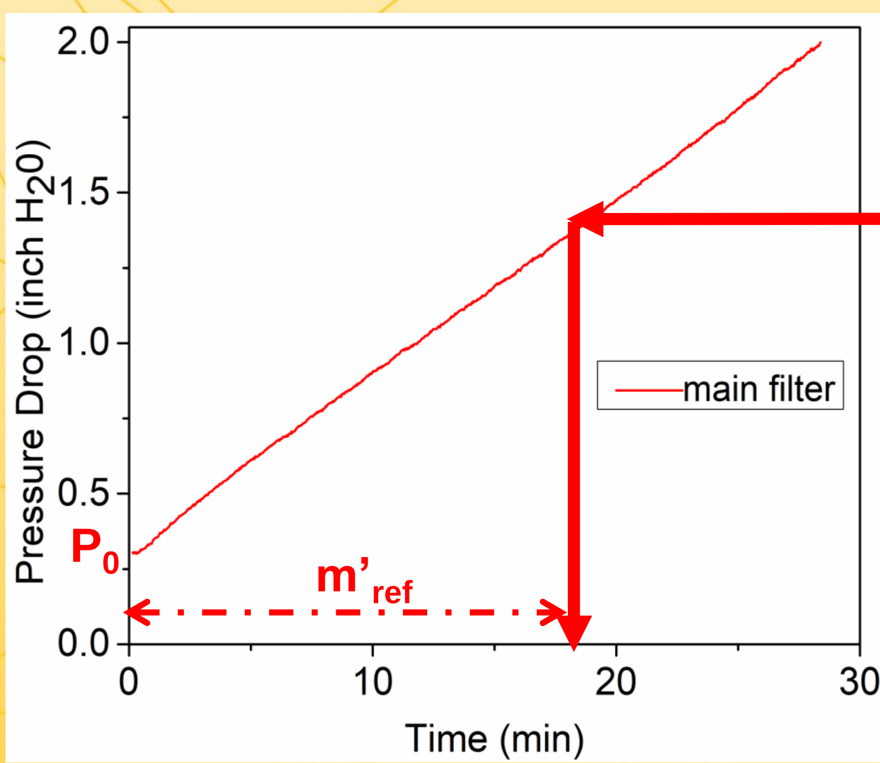
$$T^* = \frac{(T_1 + T_2 + T_3)}{T'_{ref}} = \frac{48.7}{17.4} = 2.7$$

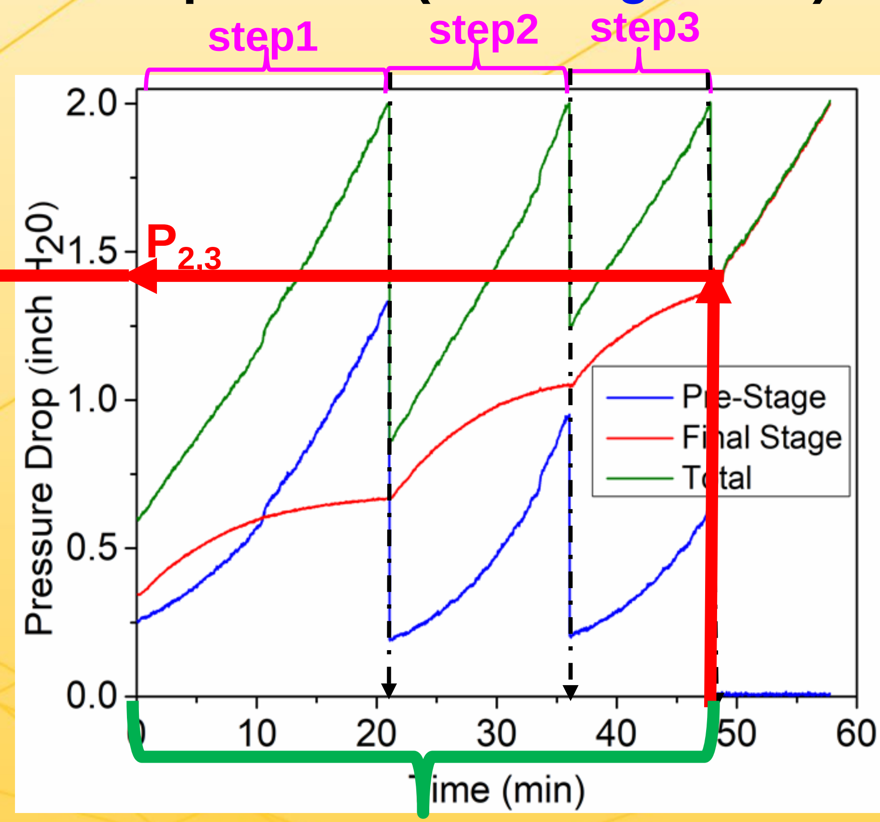
T* : How long is the service life of the main filter extended by adding a pre-filter.

The higher T* is, the longer of main filter service life is extended.

Results analysis – *Self-defined indexing parameters, M**

Without pre-filter(reference) | **With pre-filter (two-stage case)**





$(m_p + m_f)_{1\text{-}3}$

$$M = \frac{m}{u}$$

$$(m_p)_{1\text{-}3} = m_{1,1} + m_{1,2} + m_{1,3}$$

$$(m_f)_{1\text{-}3} = m_{2,1} + m_{2,2} + m_{2,3}$$

$$(M_P + M_f)_{1\text{-}3} = \left(\frac{m_P}{u_1}\right)_{1\text{-}3} + \left(\frac{m_f}{u_2}\right)_{1\_}$$

$$\boxed{M^* = \frac{(M_p + M_f)_{1\_3}}{M'_{ref}}}$$

$$\boxed{= \frac{11.5}{3.2} = 3.6}$$

M*: How much is the mass collection increased by adding a pre-filter.

The higher of M*, the more two-stage filters' dust holding capacity are increase.

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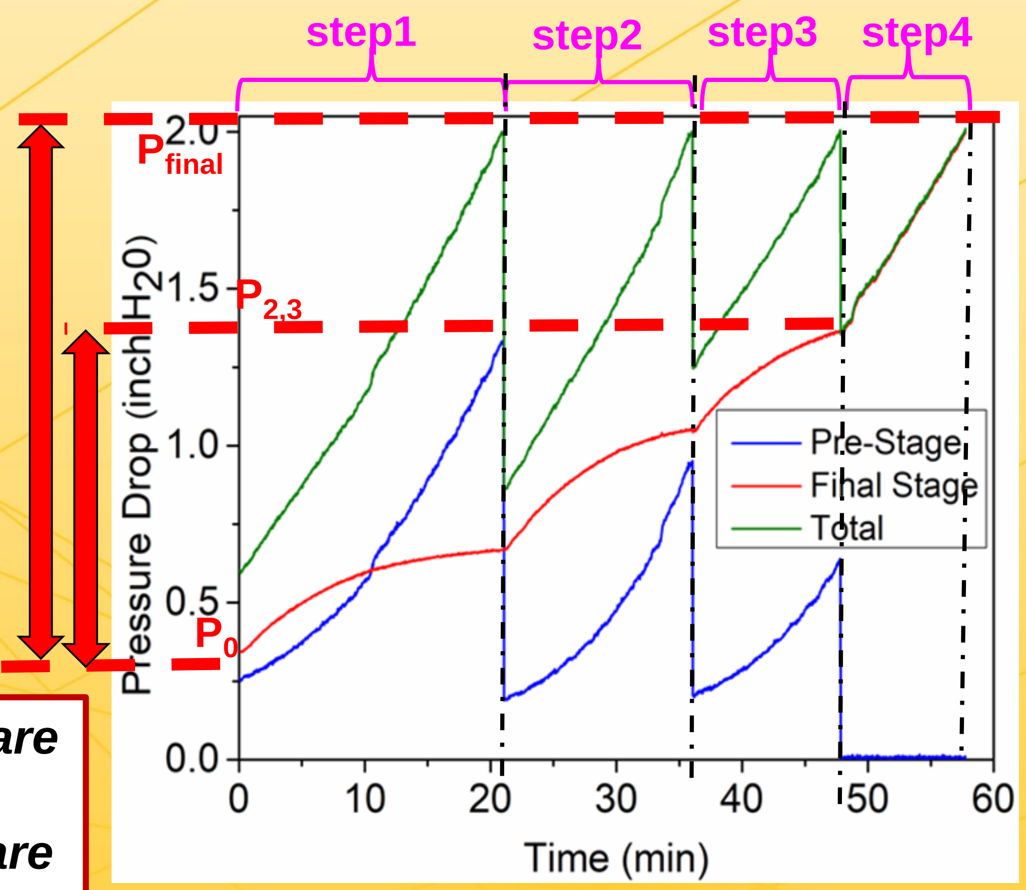
Results analysis – *Self-defined indexing parameters, P**

With pre-filter (two-stage case)



$$P^* = \frac{(P_{2,3} - P_0)}{(P_{final} - P_0)}$$ **=62 %**

$0<P^*<1$

P*: inversely-proportional to the contribution of pre-filter, in terms of pressure drop.

- ***High P* means fewer particles are captured by the pre-filter;***
- ***Low P* means more particles are captured by the pre-filter.***

Summarized Results (I) – Effect of ***pre-filter***

Testing results with a pre-filter

U_1=65.2 cm/s, U_2=2.1 cm/s

Filter		Particles	$P_{2,3}$ (inch H_2O)	$(M_P+M_f)_{1\text{-}3}$ $mg/(cm \cdot s^{-1})$	M'_{ref} $mg/(cm \cdot s^{-1})$	$T_1+T_2+T_3$ (min)	T'_{ref} (min)	P* (%)	M* (--)	T* (--)
Pre-stage	Final stage									
G4	E11	100% A2	0.35	39.6	11	55.6	14.6	***14***	***3.6***	***3.8***

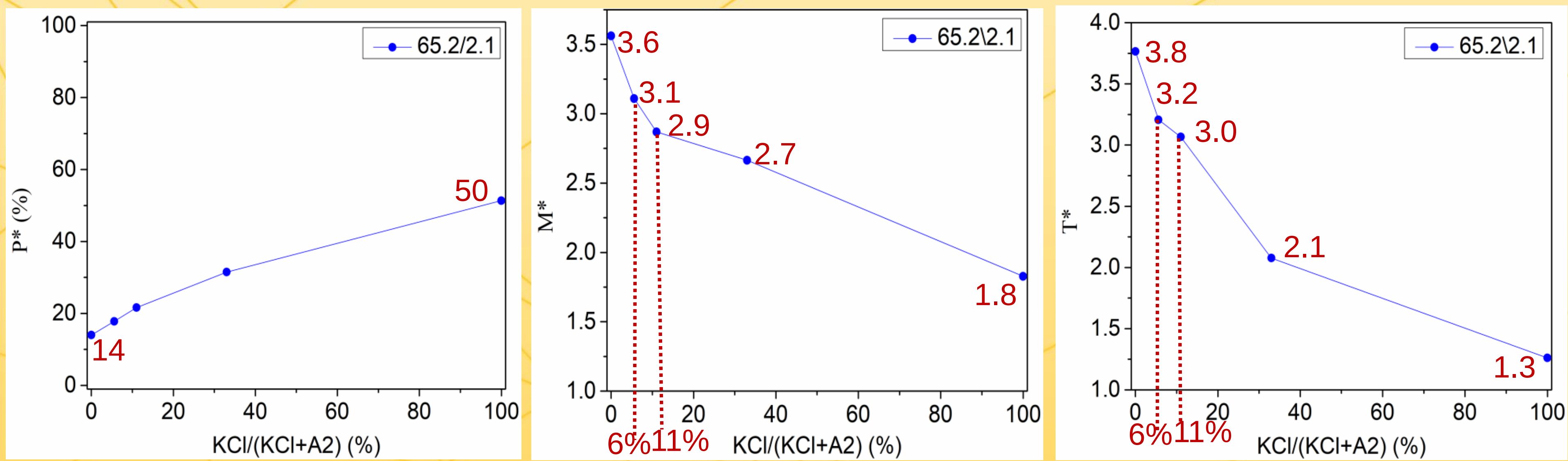
Installing a pre-filter in front of a main filter can increase the dust holding capacity of a filtration system, and extend the service life of a main filter effectively.

Summarized results (II)

–Effect of ***aerosol mixing ratio***

(G4&E11) filter

U_1=65.2 cm/s, U_2=2.1 cm/s



With the fraction of fine particles increases (0%→ 6%→ 11%→ 33%→ 100%):

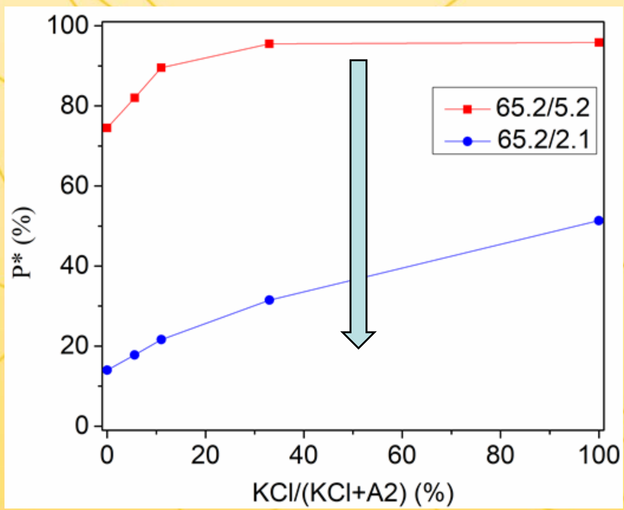
- **More** particles are captured by the main filter;
- The total dust holding capacity of the two stages **decreases**;
- The service life of the main filter **decreases**.

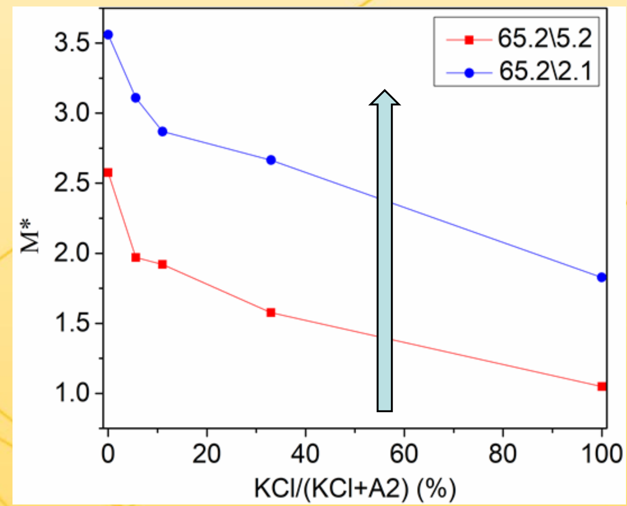
Even a small fraction of fine particles can reduce the dust holding capacity of a two-stage system and the service life of the main filter.

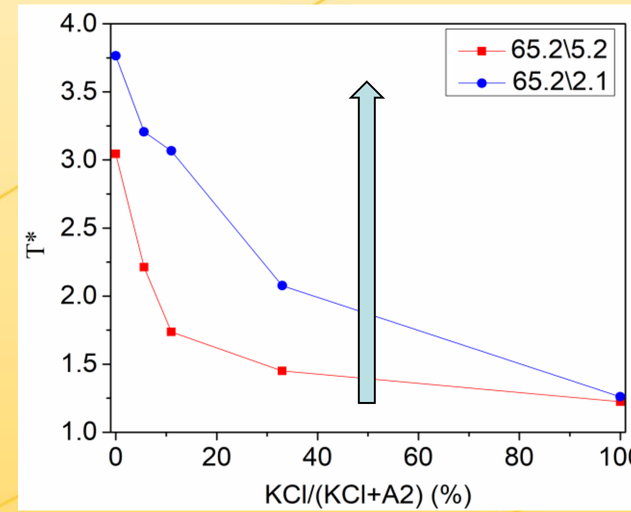
Summarized Results (III)

– Effect of ***face velocity ratio***

(G4&E11) filter







At higher face velocity ratio, more particles are collected on pre-filter, leading to:

- ***Slower*** increase of main stage pressure drop;
- ***Higher*** total dust holding capacity of two-stage filter;
- ***Longer*** service time of the main filter.

The detailed relationship between the **velocity ratio** and the **absolute velocity values of each stage** requires more investigation.

Summary

- A simple two-stage filter loading test system was successfully developed, capable of being used to investigate the loading characteristics of a two-stage filtration system cost- and time-effectively.

- Installing a pre-filter in front of a main filter can effectively increase the total particle holding capacity of the filtration system, and extend the service life of the main filter.

- The effectiveness of the pre-filter is strongly affected by the incoming particle size distribution. Even a small fraction of fine particles can reduce the dust holding capacity of a two-stage filtration system, and can reduce the main filter's service life significantly.

- The selection of face velocities of the two stages can affect the performance of a two-stage filtration system. Higher velocity difference between two stages results in longer service time of the main stage, but requires more frequent replacement of the pre-filter.

Future work

- To investigate how the selection of pre-filter media and main filter media influence the loading characteristics of a two-stage filtration system.
- To investigate more in details on how the velocity ratio and the absolute velocity values of each stage influence the loading characteristics of a two-stage filtration system.
- To develop a evaluation formula, based on those self-defined indexing parameters and the information of filter cost and replacement cost, which can be used as a guideline of selection and optimization of a two-stage filtration system.

Thank you!

Q&A

Appendix

EN 779: 2012

Table 1— Classification of air filters 1)

Group	Class	Final test pressure drop Pa	Average arrestance (A_m) of synthetic dust %	Average efficiency (E_m) of 0,4 µm particles %	Minimum Efficiency [a] of 0,4 µm particles %
Coarse	G1	250	$50 \leq A_m < 65$	-	-
	G2	250	$65 \leq A_m < 80$	-	-
	G3	250	$80 \leq A_m < 90$	-	-
	G4	250	$90 \leq A_m$	-	-
Medium	M5	450	-	$40 \leq E_m < 60$	-
	M6	450	-	$60 \leq E_m < 80$	-
Fine	F7	450	-	$80 \leq E_m < 90$	35
	F8	450	-	$90 \leq E_m < 95$	55
	F9	450	-	$95 \leq E_m$	70

[a] Minimum efficiency is the lowest efficiency among the initial efficiency, discharged efficiency and the lowest efficiency throughout the loading procedure of the test.

EN 1822-1-2009

Table 1 — Classification of EPA, HEPA and ULPA filters

Filter Group / Filter Class	Integral value		Local value [a b]	
	Efficiency (%)	Penetration (%)	Efficiency (%)	Penetration (%)
E 10	≥ 85	≤ 15	---[c]	---[c]
E 11	≥ 95	≤ 5	---[c]	---[c]
E 12	≥ 99,5	≤ 0,5	---[c]	---[c]
H 13	≥ 99,95	≤ 0,05	≥ 99,75	≤ 0,25
H 14	≥ 99,995	≤ 0,005	≥ 99,975	≤ 0,025
U 15	≥ 99,999 5	≤ 0,000 5	≥ 99,997 5	≤ 0,002 5
U 16	≥ 99,999 95	≤ 0,000 05	≥ 99,999 75	≤ 0,000 25
U 17	≥ 99,999 995	≤ 0,000 005	≥ 99,999 9	≤ 0,000 1

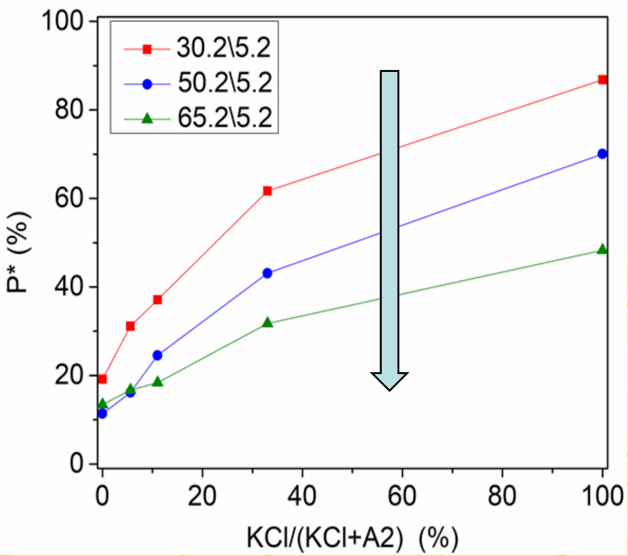
[a] See 7.5.2 and EN 1822-4.

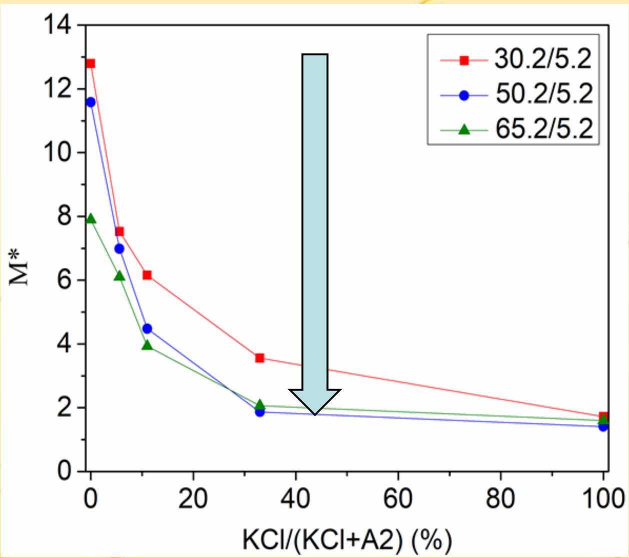
[b] Local penetration values lower than those given in the table may be agreed between supplier and purchaser.

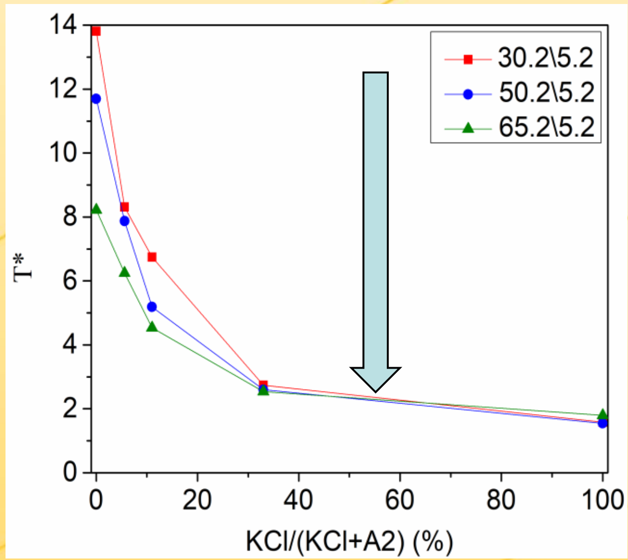
[c] Group E filters (Classes E10, E11 and E12) cannot and shall not be leak tested for classification purposes.

Summarized Results

(M6&E11) filter







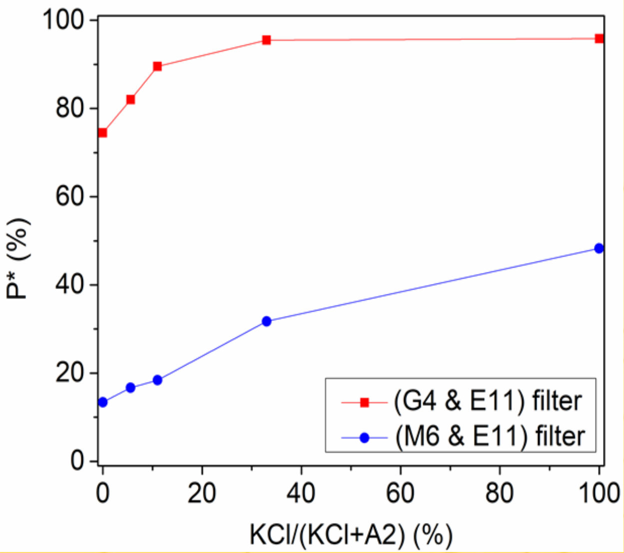
- When using M6 media instead of G4 media as the pre-filter, similar trend was found for the effectiveness of pre-filter, and the effectiveness of fine-coarse aerosol ratio;

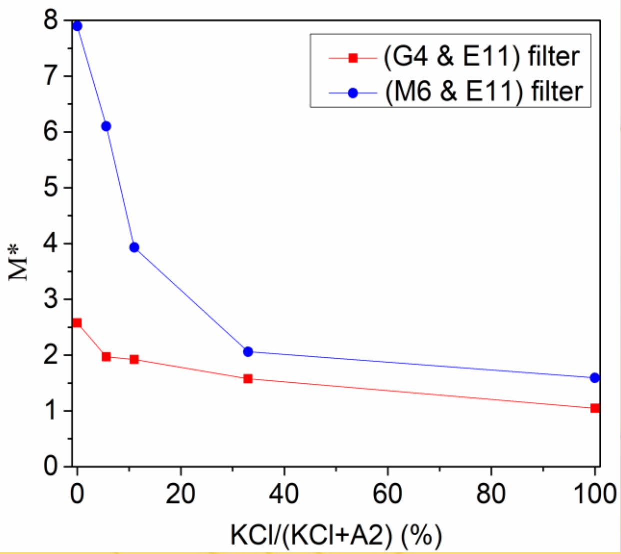
- When we increase the face velocity of pre-stage, though the pressure drop of E11 filter increases slowly, the dust holding capacity of two-stage filtration system and service life of E11 filter decrease.

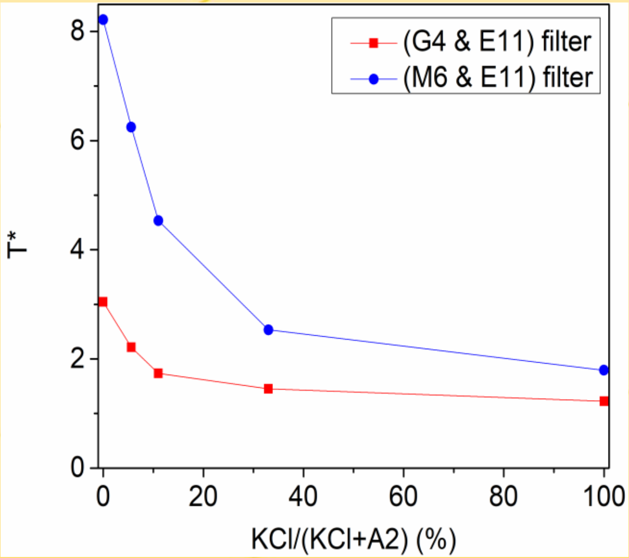
Summarized Results – Effect of *filter combination*

(G4&E11) filter vs (M6&E11) filter

U_1=***65.2*** cm/s, U_2=***5.2*** cm/s







When replacing pre-filter from G4 to M6:

- More particles are captured by the pre-stage (M6) filter;
- M6 filter increase more dust holding capacity than G4 filter;
- The service life of main filter are extended longer.

- Requiring more replacements of pre-filter in order to fully utilize the main filter;
- More investigating and cost information are needed for better system optimization