Liquid Filtration: Effects of Chemical and Physical Factors on Filtration Performance for Micro- and Ultrafiltration Membranes

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INTRODUCTION

- **Micro-** (100 nm ~ 1 μm) and **ultra-filtration** (10 nm ~ 100 nm) using membranes have been widely used and considered an effective technique to separate suspended particles from liquid in many industries.
- Retention mechanisms of colloidal particles are **adsorption** (PPD*<1, small particle) and **size exclusion** (PPD*>1, large particle), depending on particle and pore size.
- The performance (efficiency) of liquid filtration is hard to predict due to **complex interactions** between solid surfaces in liquid.
- Pore size alone cannot explain filter performance well.
- Both theoretical and experimental studies are important.

Modeling

- Interaction energy

Experiment

- Concentration measurement method
- Polydisperse particle filtration

*PPD: Particle to pore diameter ratio

OUTLINE

- **Modeling**

- Two different membrane filters (PCTE* and PP*)
- Different chemical (ionic strength) and physical (filtration velocity) conditions
- Interaction energy between particle and filter

- **Experiment**

- Different characterization methods for measuring liquid-borne particle concentration (NTA* and ES-SMPS*)
- Polydisperse particle filtration (PES*)

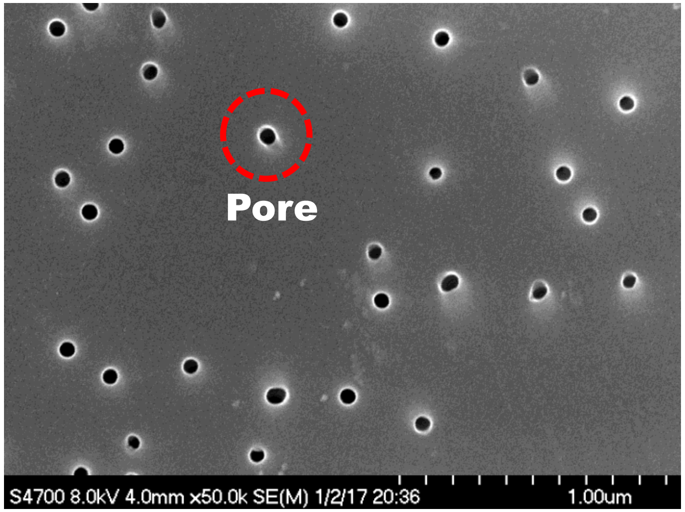
*PCTE: Polycarbonate track-etched (Nuclepore filter)
*PP: Polypropylene
*PES: Polyethersulfone

*NTA: Nanoparticle tracking analysis
*ES-SMPS: Electrospray-scanning mobility particle sizer

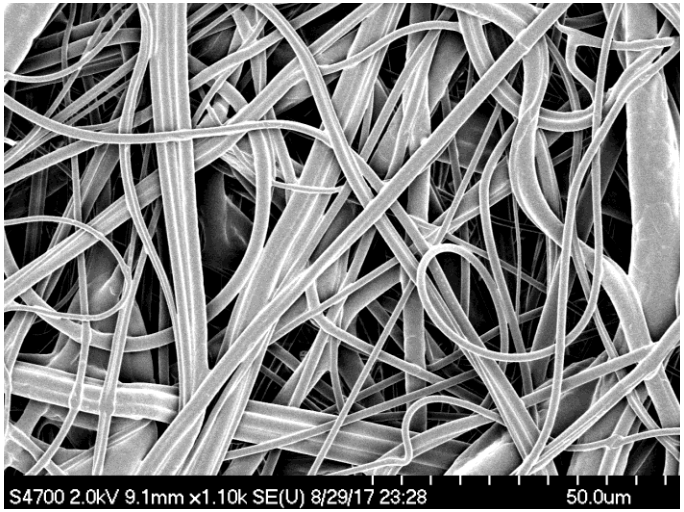
Polycarbonate track-etched (PCTE) and Polypropylene (PP) Filter Modeling

Filter and Particle System

PCTE (straight-through pore)



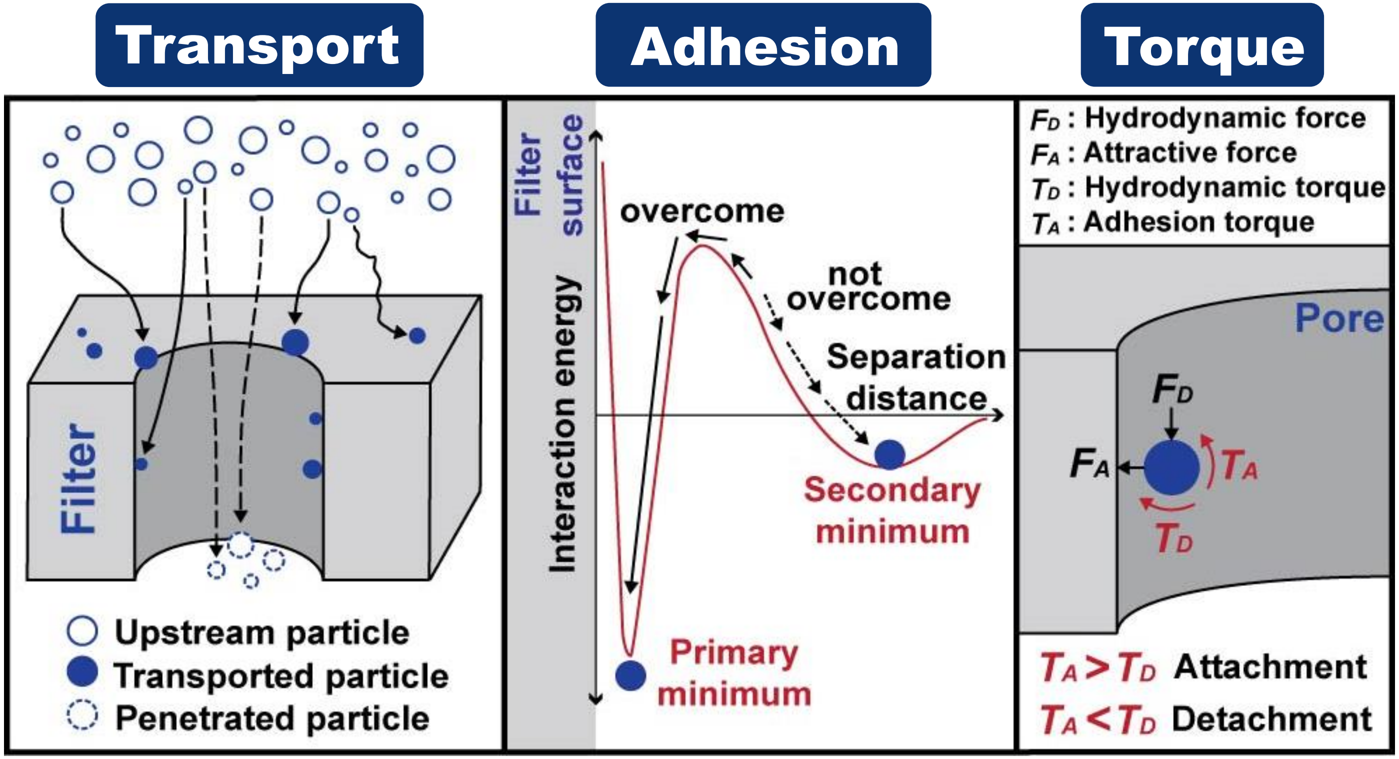
PP (fiber)



- **Two membranes with straight-through pores (PCTE*) and fibers (PP*) are modeled.**
- **Particles smaller than absolute pore sizes are used to consider adsorption (sieving is excluded).**
- **Surface interactions between particle and filter in different chemical (ionic strength) and physical (filtration velocity) conditions are considered.**

***PCTE: Polycarbonate track-etched membrane (Nuclepore filter)**
***PP: Polypropylene membrane**

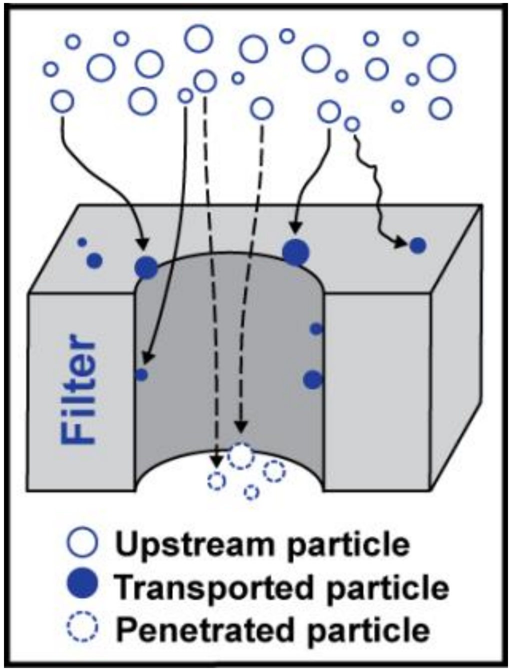
Deposition Process (3 Steps)



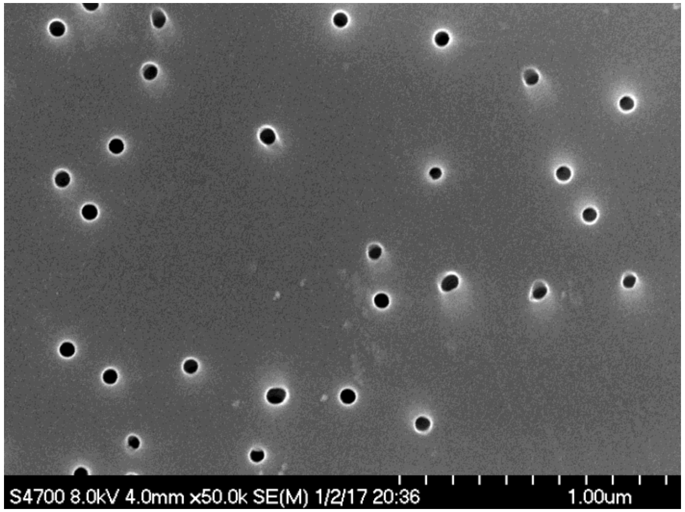
- **Particles are captured by membrane through 3 steps.**
  1) **TRANSPORT**: Contact efficiency (air and liquid filtration)
  2) **ADHESION**: Interaction energy (liquid filtration)
  3) **TORQUE**: Detachment (liquid filtration)

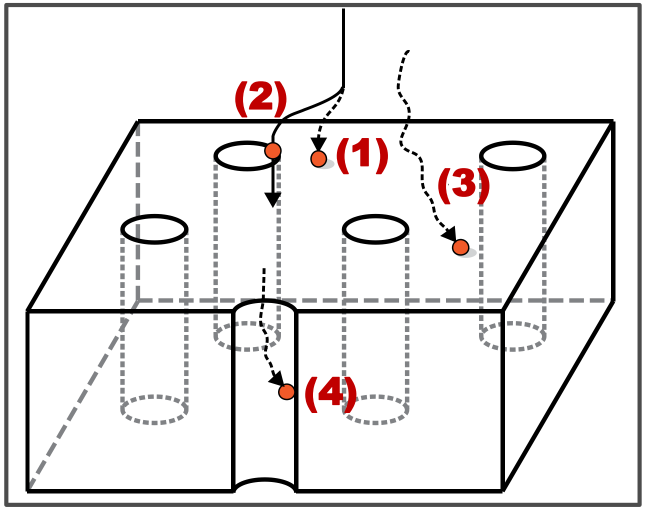
Particle Transport (PCTE)

Transport ← **Number of particles colliding with filter surface**



PCTE (straight-through pore)





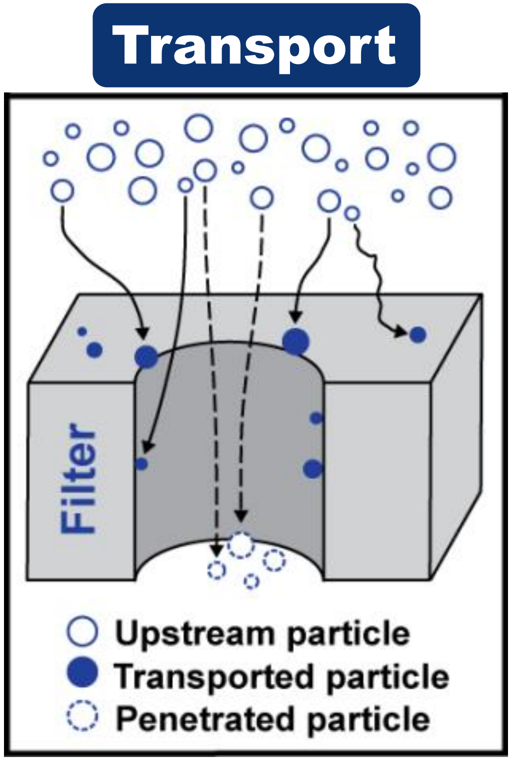
- **4 deposition mechanisms are considered for PCTE membrane.**
  1) **Impaction** on filter surface
  2) **Interception** on pore opening
  3) **Diffusion** on filter surface
  4) **Diffusion** on pore walls

→

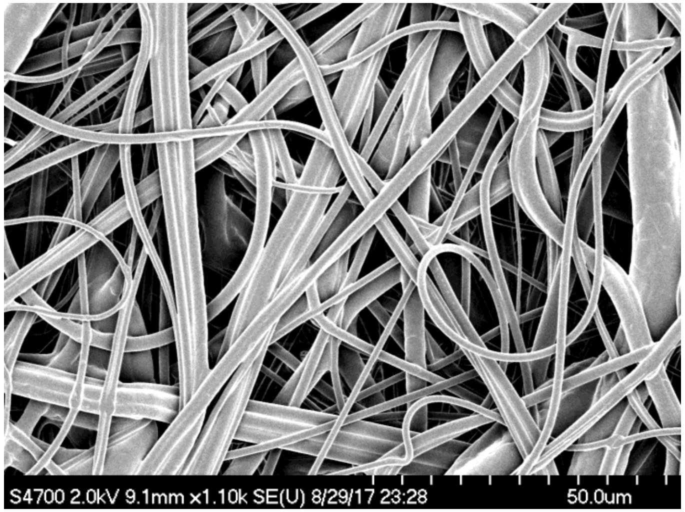
To get transport efficiency …
Aerosol filtration theory
Capillary tube model
(Air to liquid)

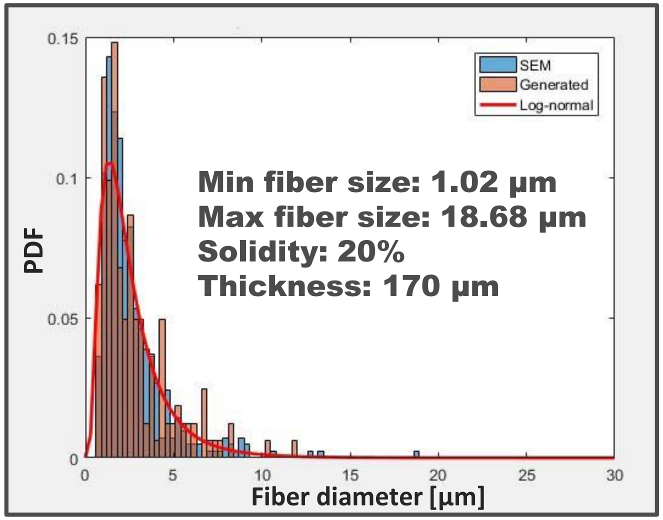
*H. Lee, D. Segets, S. Süß, W. Peukert, S. Chen, D.Y.H. Pui, J. Memb. Sci. 524 (2017) 682–690.

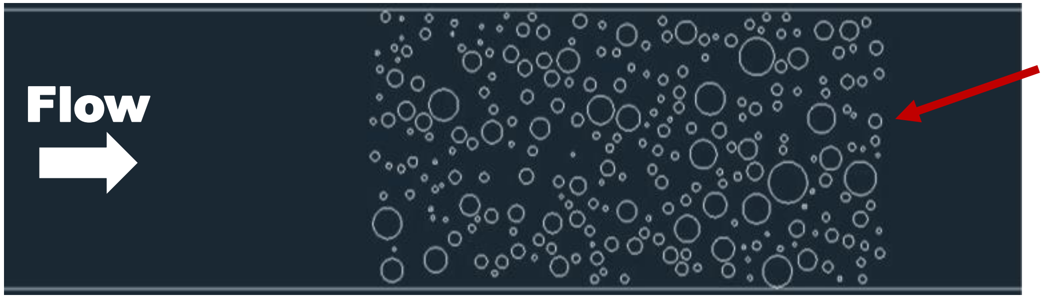
Particle Transport (PP)



PP (fiber)





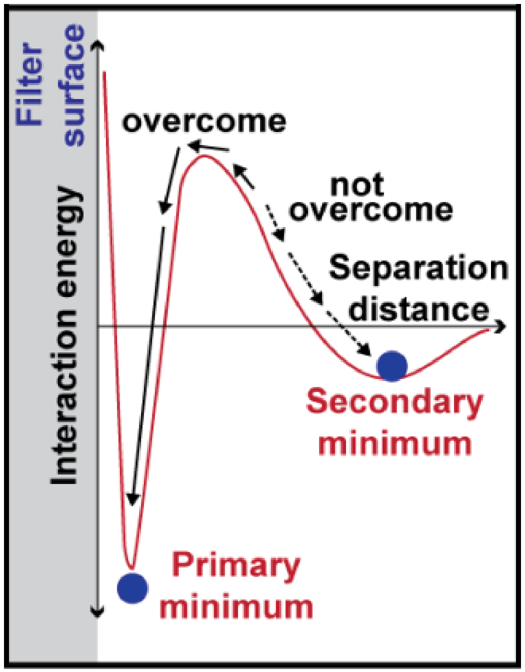


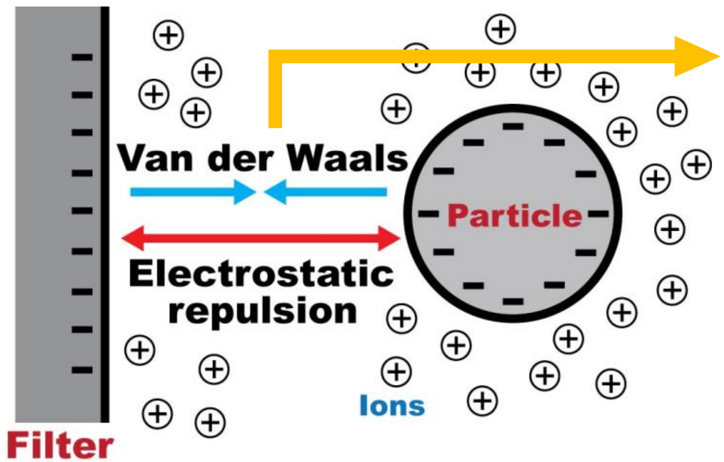
Polydisperse fibers (2D)

- Calculation domain with polydisperse fibers is generated based on SEM image (fiber diameter) and filter information (solidity).
- Ansys Fluent software is used for flow and particle simulation.

Particle Adhesion (DLVO Theory)

Adhesion





- **Solution chemistry**
- **Particle/filter material**
- **Particle size**
- **Separation distance**

Attachment ratio

$$= \frac{\#\text{ of attached particles}}{\#\text{ of colliding particles}}$$

Obtained from **TRANSPORT**

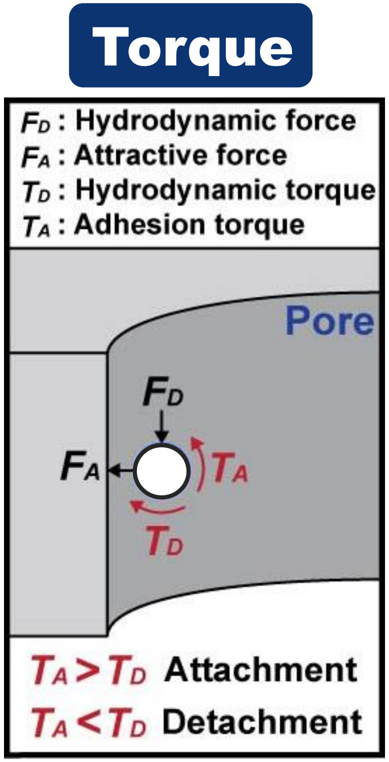
DLVO theory* **describes the force between charged surfaces interacting through a liquid medium.**

- **From total interaction energy curve, successful attachment ratio (successful adhesion) and corresponding adhesion energy can be obtained.**
- **Attachment energy (attraction) is used for calculating adhesion torque.**

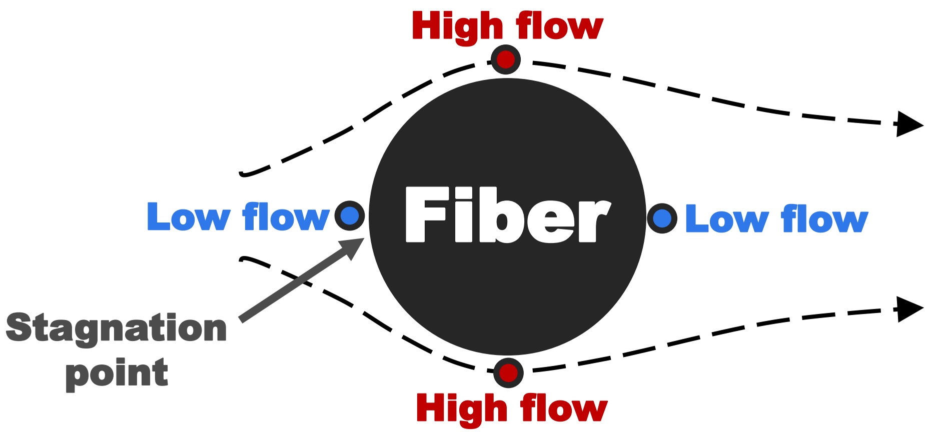
***DLVO: Derjaguin–Landau–Verwey–Overbeek**

*H. Lee, D. Segets, S. Süß, W. Peukert, S. Chen, D.Y.H. Pui, J. Memb. Sci. 524 (2017) 682–690.

Adhesion and Hydrodynamic Torque



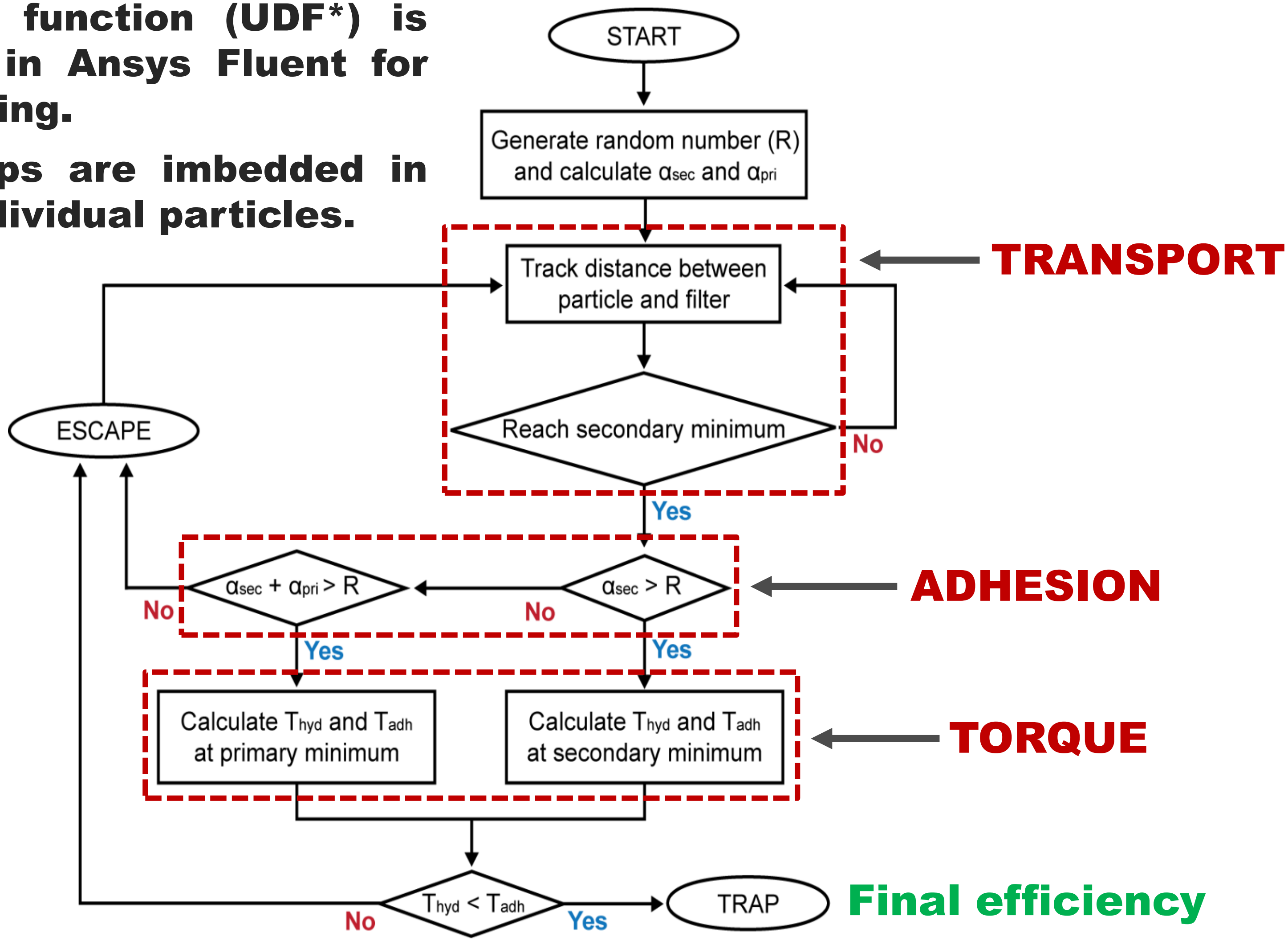
Adhesion torque is not a function of adhesion location, but hydrodynamic torque is a function of it due to flow velocity difference.



- **Adhesion torque** is obtained from total DLVO interaction curve, and **hydrodynamic torque** can be accessed by flow simulation.
- Away from stagnation points, higher hydrodynamic force acts on particles.
  - Easily detached from surface

Particle Tracking Analysis Using UDF

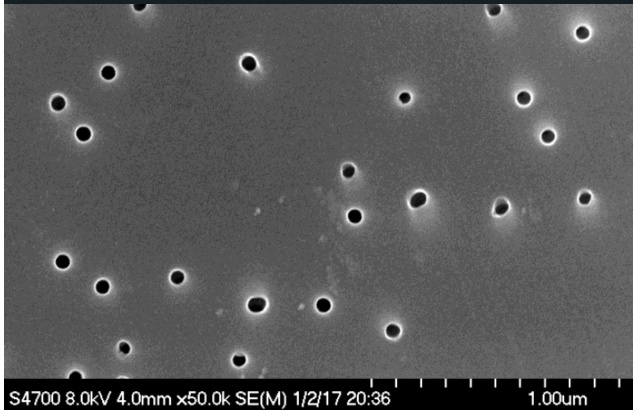
- **User defined function (UDF*) is incorporated in Ansys Fluent for particle tracking.**
- **All three steps are imbedded in UDF for all individual particles.**



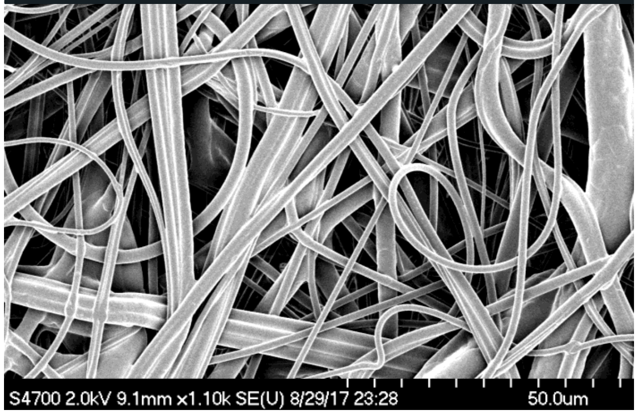
***UDF: User defined function**

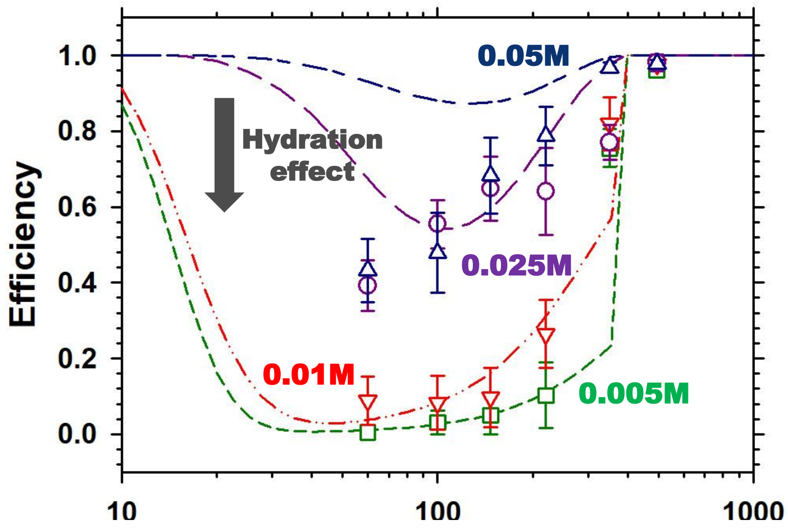
Filtration Efficiency (PCTE and PP)

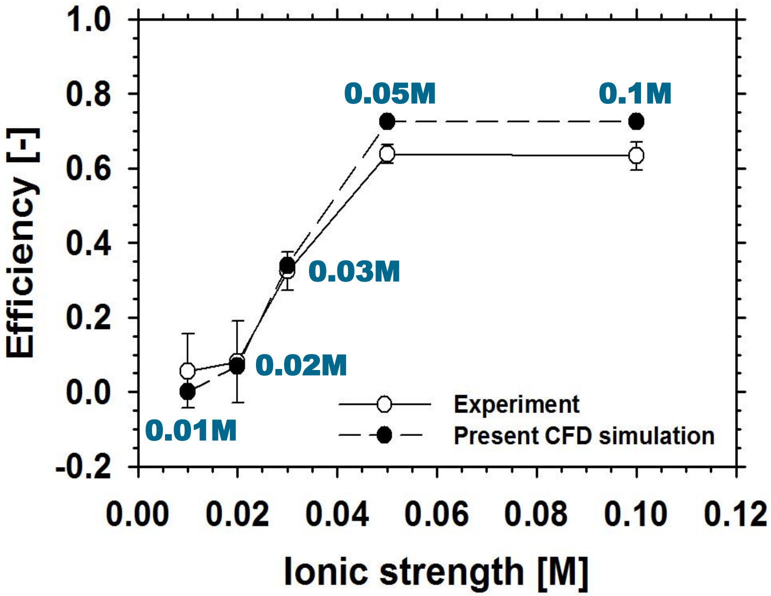
PCTE (Straight-through)



PP (Fiber)







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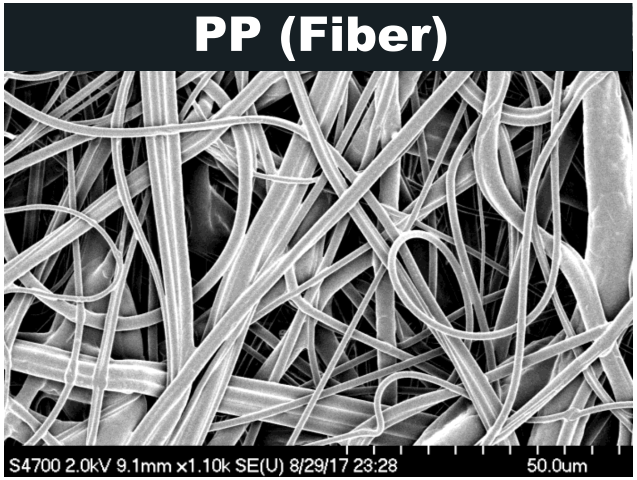
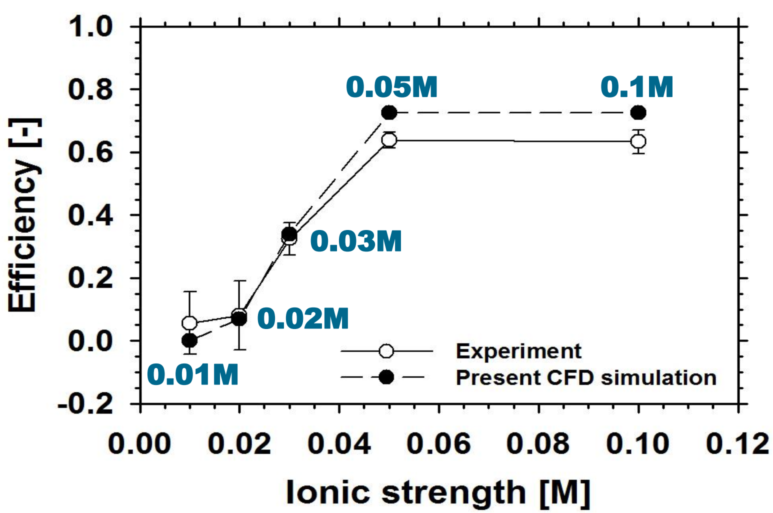
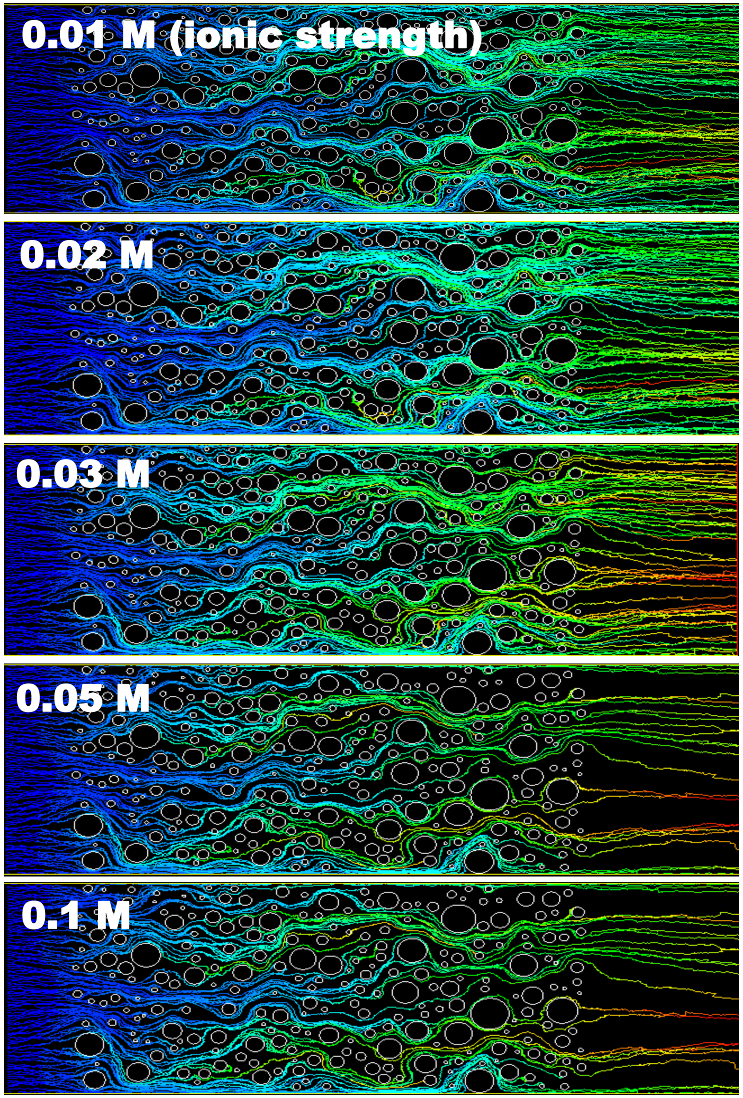
Particle Trajectory (PP Membrane)







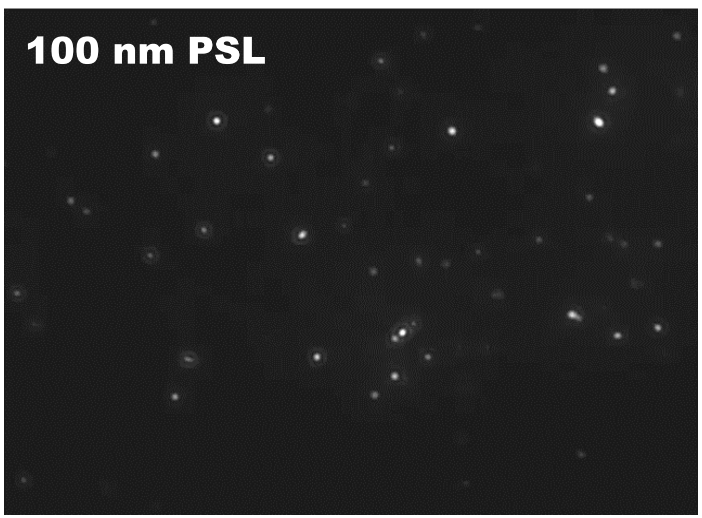
- **Higher ionic strength enhances adhesion, reducing double layer repulsion.**

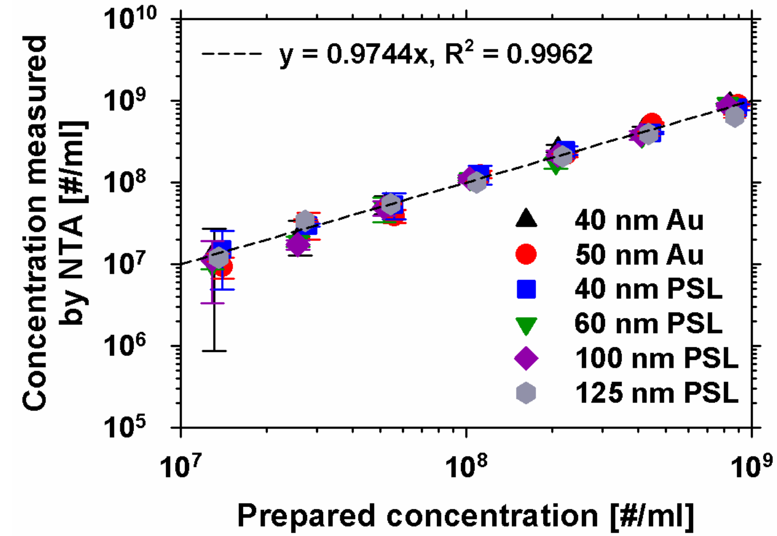
Characterization of Polydisperse Particles

Concentration Measurement Method 1

- **For evaluation of membrane filter, accurate concentration measurement methods are required with proper purposes.**

Nanoparticle Tracking Analysis (NTA)





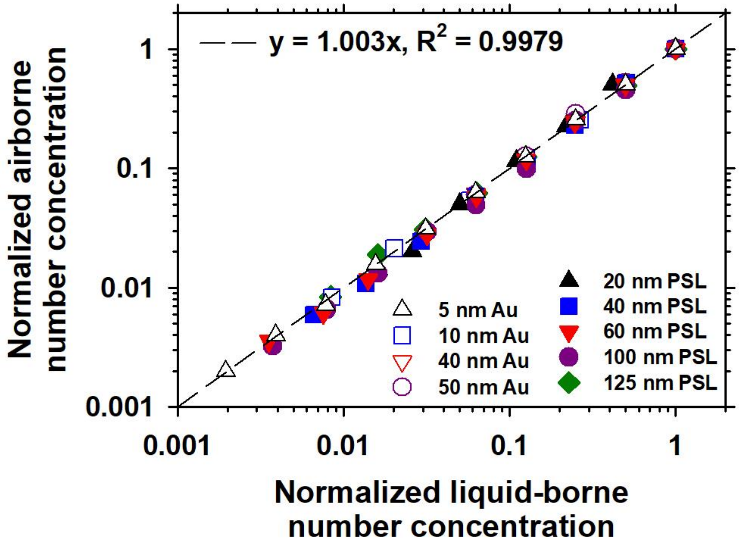
- **NTA can measure particle size and concentration.**
- **Detection range of particle size is from 20 nm to 1 μm.**
- **Linear relation between prepared and measured concentration is obtained.**

Concentration Measurement Method 2

- For evaluation of membrane filter, accurate concentration measurement methods are required with proper purposes.

Electrospray-Scanning Mobility Particle Sizer (ES-SMPS)

ES



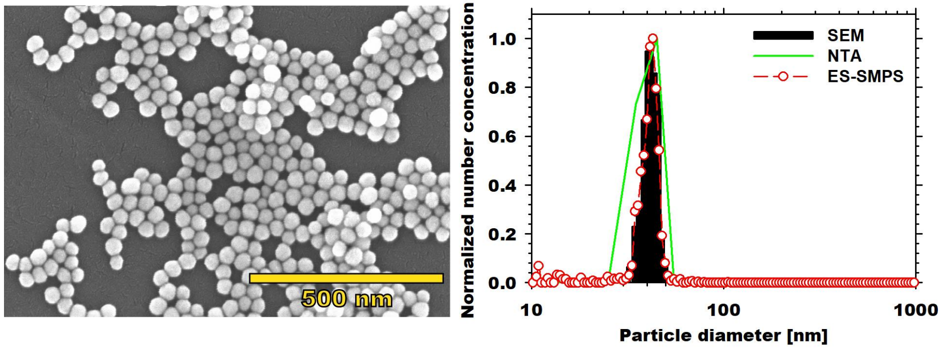
SMPS

- ES-SMPS is based on aerosolization method.
- Detection range of particle size is from **1 nm to larger particles**.
- **Linear relation** between airborne and liquid-borne particle concentration is obtained.

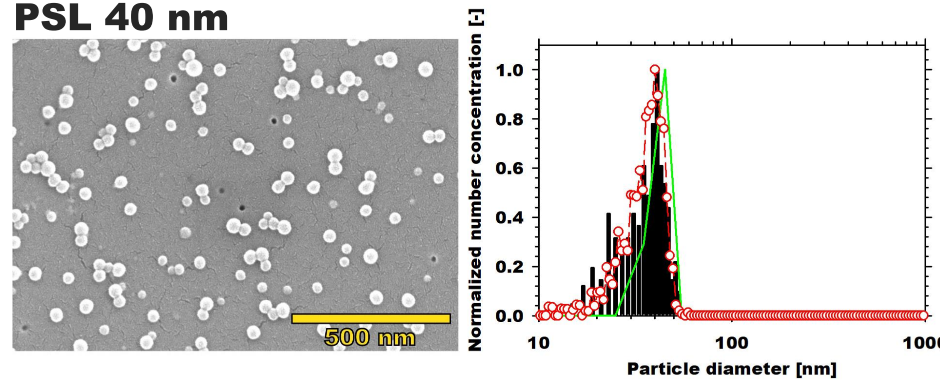
* H. Lee, S.-C. Chen, C. Kim, E. Westenburg, S.I. Moon, D.Y.H. Pui, Sep. Purif. Technol. 184 (2017) 34–42.

SEM, NTA and ES-SMPS (Monodisperse Particle)

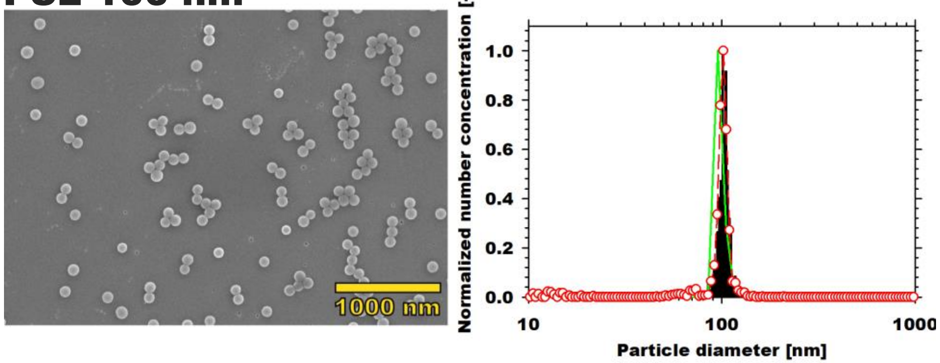
Au 40 nm



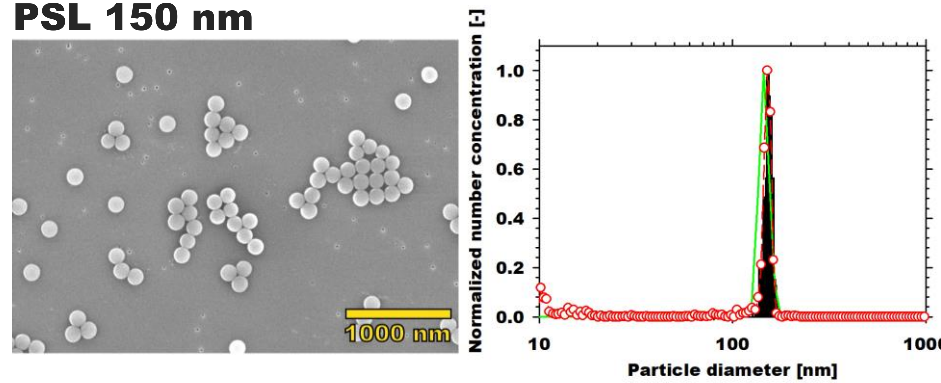
PSL 40 nm



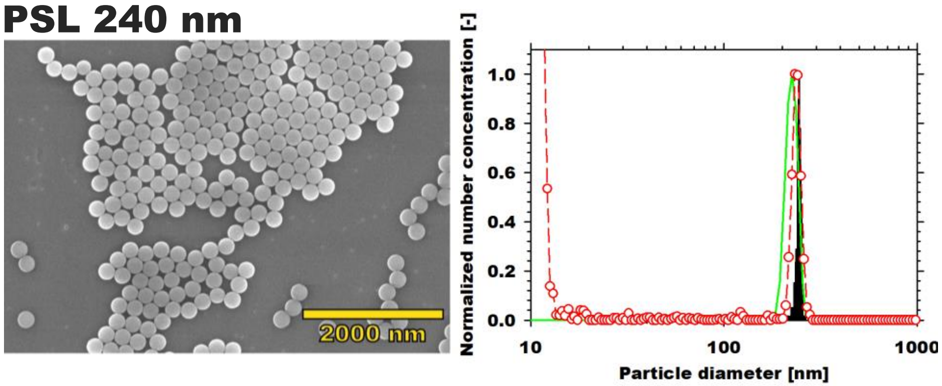
PSL 100 nm



PSL 150 nm



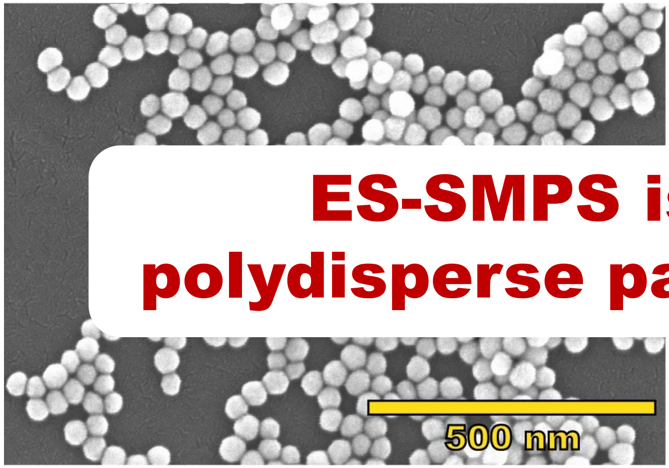
PSL 240 nm



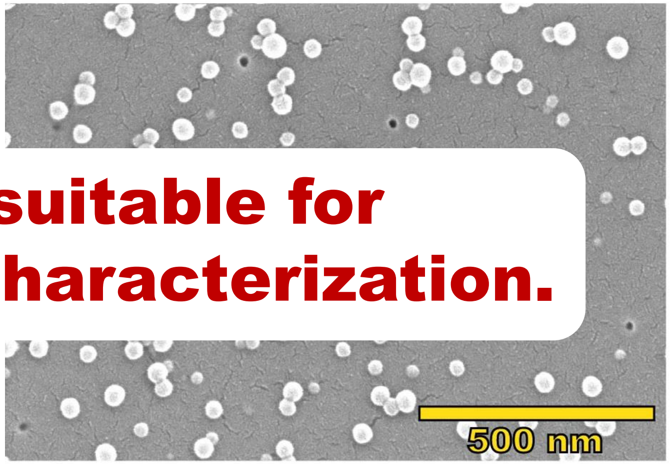
- **Generally, NTA and ES-SMPS measure particle size well.**
- **Standard deviations obtained by ES-SMPS are more accurate (Au 40 nm and PSL 40 nm).**

SEM, NTA and ES-SMPS (Monodisperse Particle)

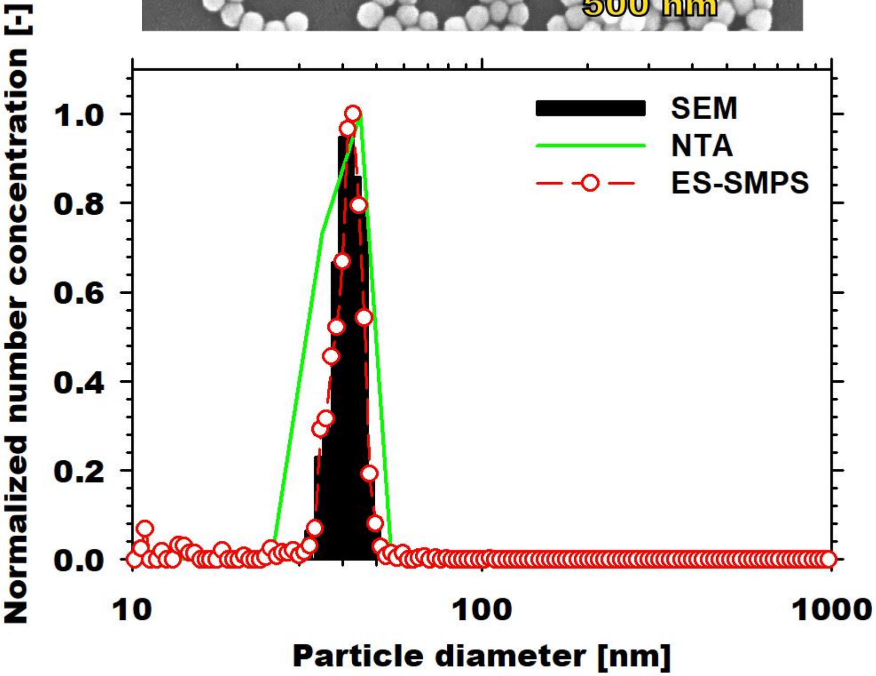
Au 40 nm

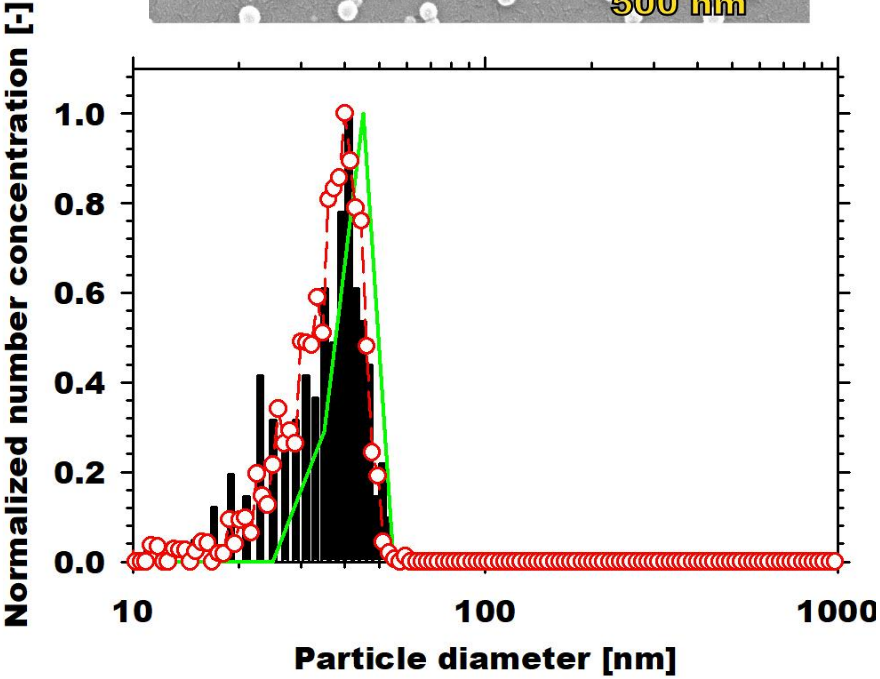


PSL 40 nm



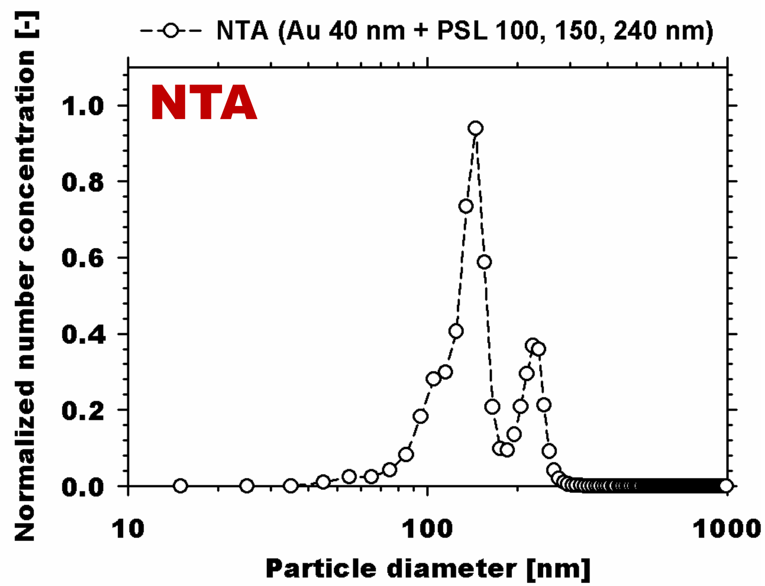
ES-SMPS is more suitable for polydisperse particle characterization.

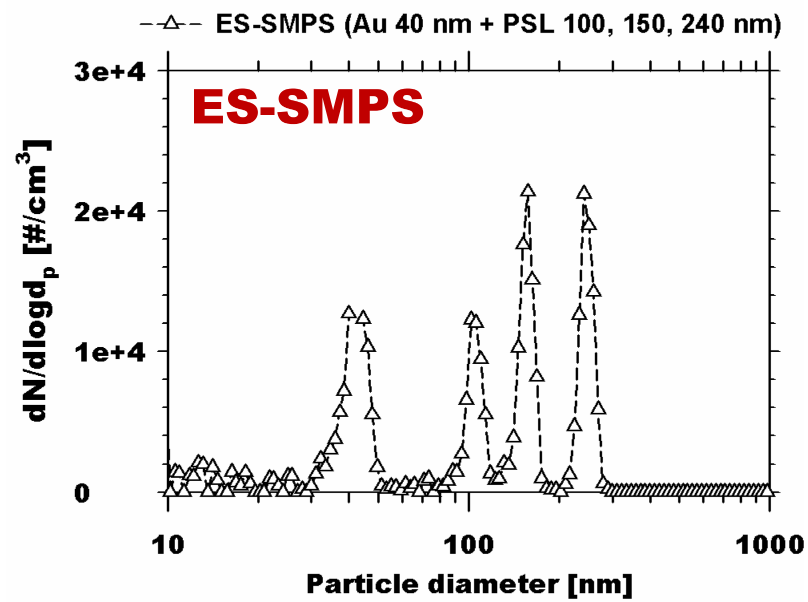




NTA and ES-SMPS (Polydisperse Particle)

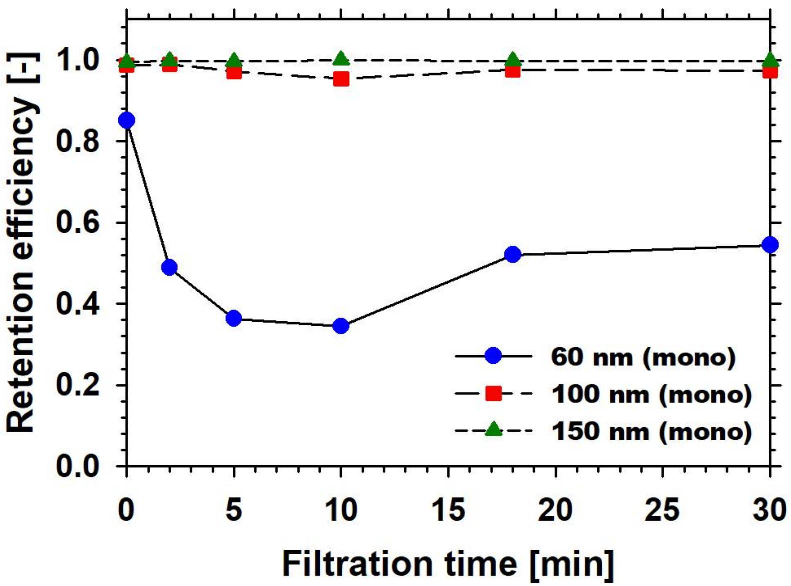
Au 40 nm + PSL 100, 150, 240 nm Mixture

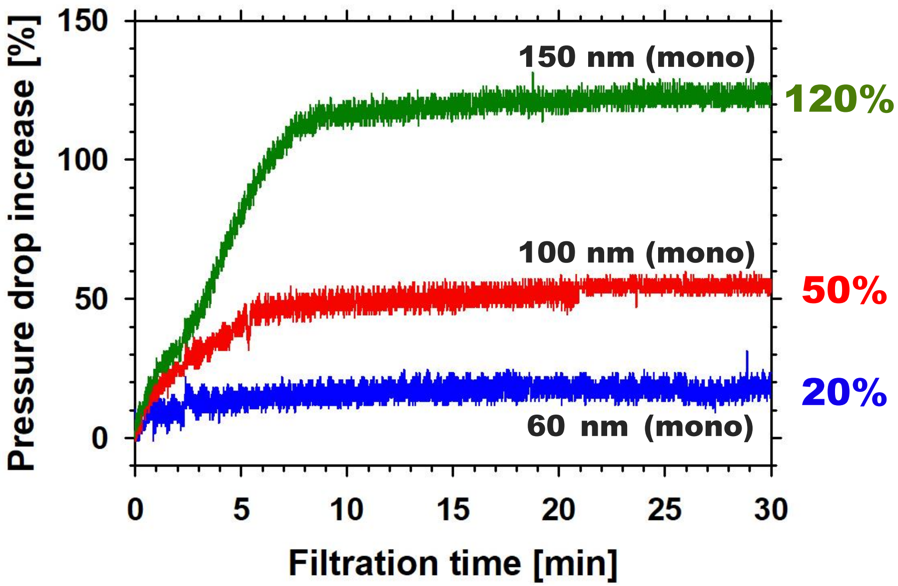




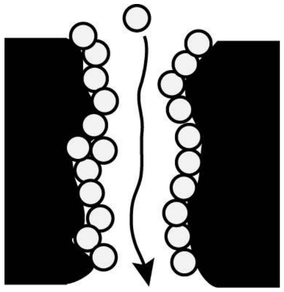
- **NTA** cannot distinguish four different sizes correctly due to the nature of NTA operating conditions (e.g., camera level)
- **ES-SMPS** can analyze particle sizes and concentrations as well.
  - ES-SMPS can be used for polydisperse particle filtration tests.

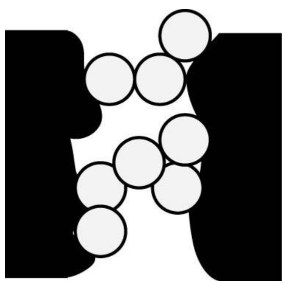
Monodisperse Particle Filtration

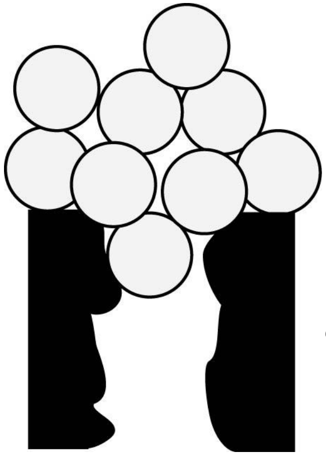




- Monodisperse particles were filtered by 0.03 µm (30 nm) rated PES* membrane (Polyethersulfone).
- Relatively low efficiency of 60 nm PSL particles were obtained.





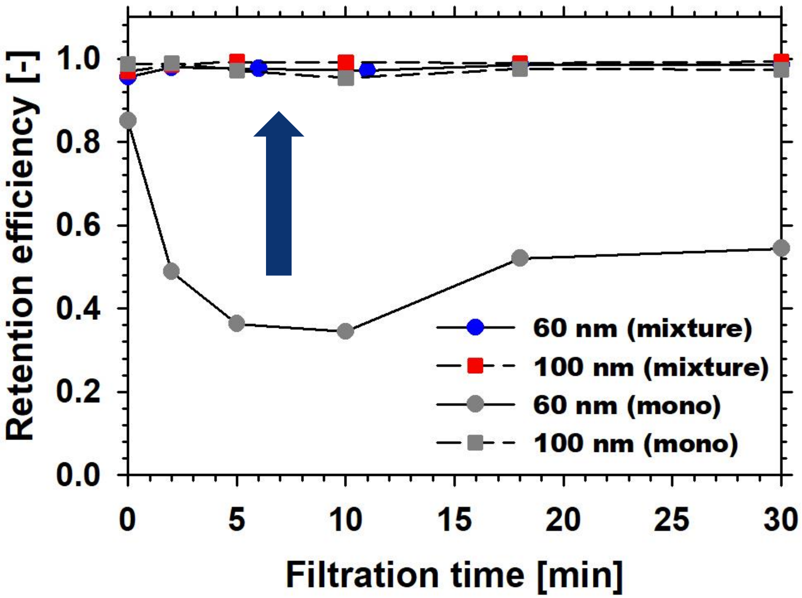


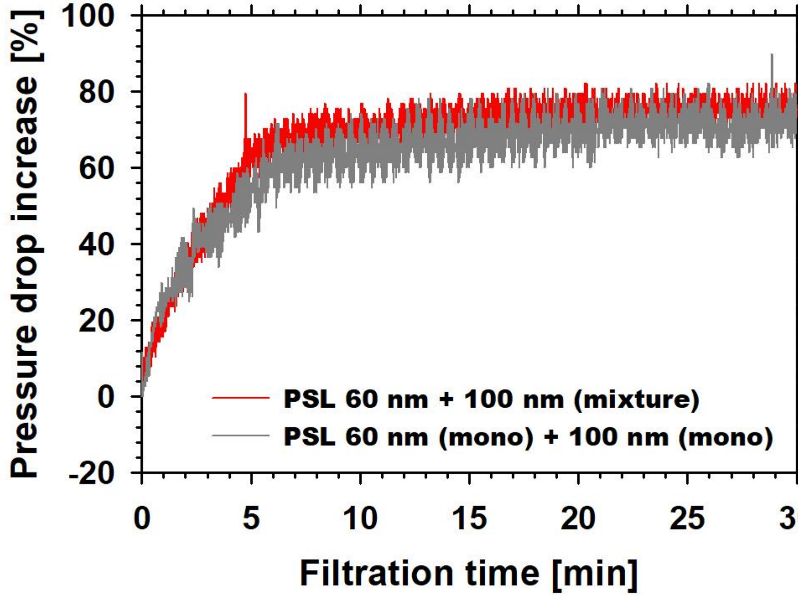
***PES: Polyethersulfone**

*D.A. Ladner, M. Steele, A. Weir, K. Hristovski, P. Westerhoff, J. Hazard. Mater. 211–212 (2012) 288–295.

Polydisperse Particle Filtration 1

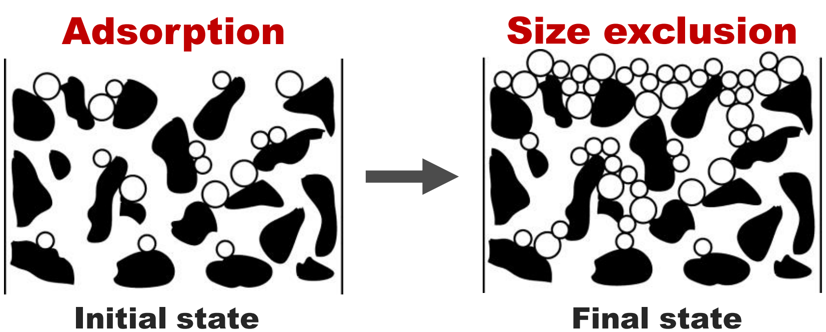
PSL 60 + 100 nm Mixture





- **Retention efficiency of 60 nm PSL particles was significantly enhanced when challenging the membrane with 100 nm PSL particles (mixture).**
- **Pressure drop increases in monodisperse (superposition) and polydisperse particle cases were similar.**

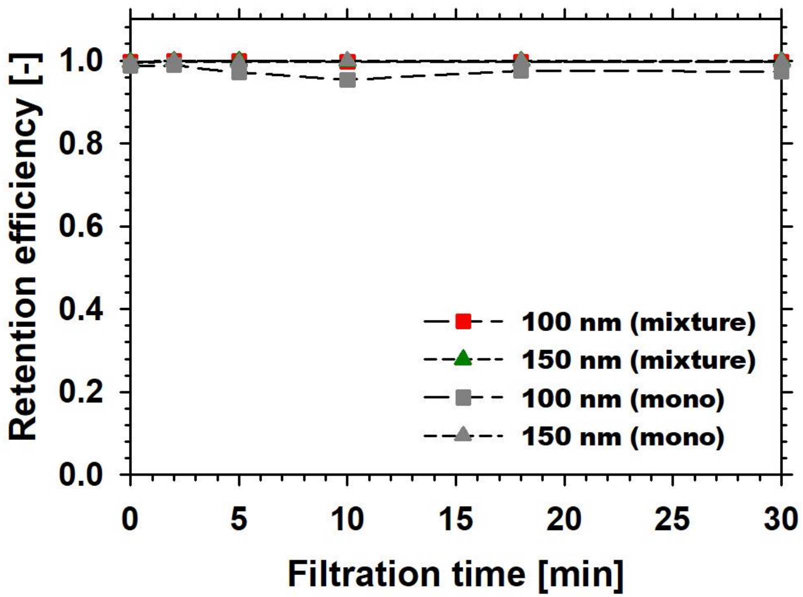
Efficiency increase (60 nm)

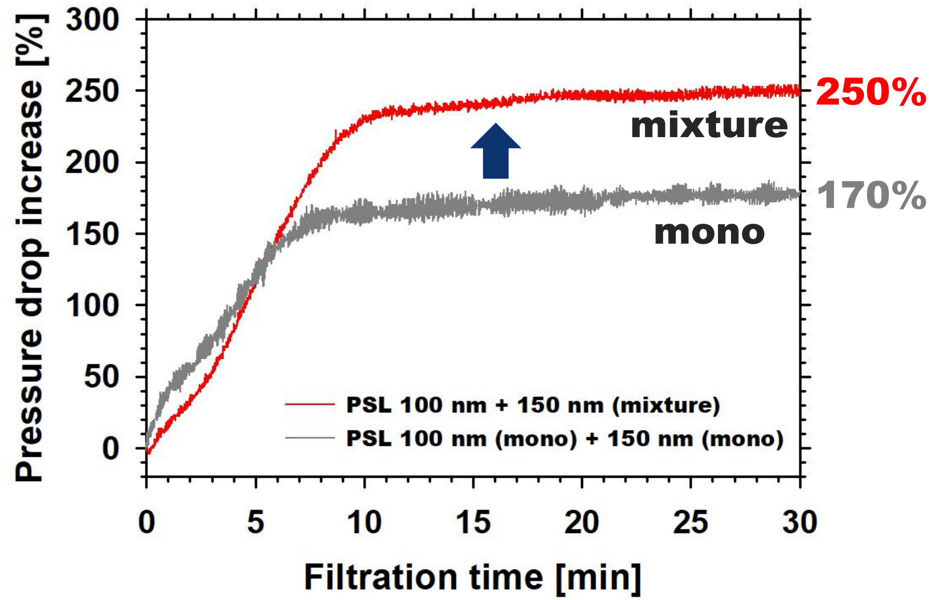


No breakthrough

Polydisperse Particle Filtration 1

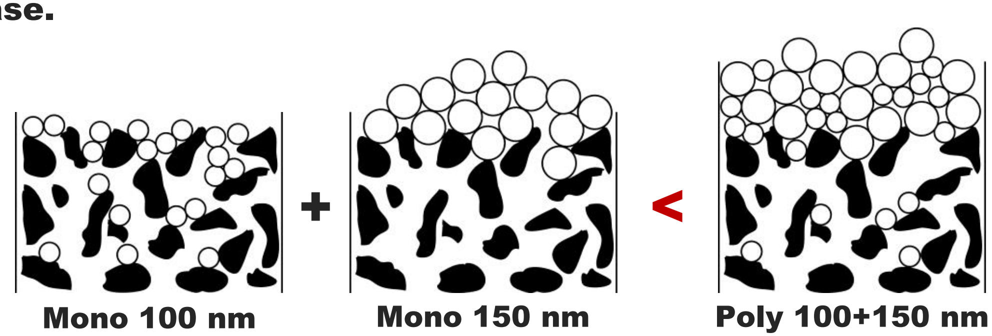
PSL 100 + 150 nm Mixture





- **Retention efficiencies of monodisperse and polydisperse particles are similar.**
- **Pressure drop increase of polydisperse particle case was much larger than monodisperse particle case.**

Pressure drop increase (polydisperse)



Thicker cake layer
Higher packing density

CONCLUSION

Modeling

- **Adsorption of colloidal particles onto membrane can be predicted by three steps (transport, interaction and force analysis).**
- **Simulation methods using CFD can be applied to different structures of membranes.**
- **Depending on chemical and physical conditions, filtration performance varies significantly (PPD<1).**

Experiment

- **NTA and ES-SMPS methods are useful for characterizing colloidal particles.**
- **ES-SMPS can be used for polydisperse particle filtration tests.**
- **Different mixture conditions result in different loading characteristics (efficiency and pressure drop).**

Thank you

Q & A