Clogging and Restructuring Behaviors of Solid and Oil Mixtures on Air Intake Filter Media

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Presented at 51st CFR Review Meeting, Minneapolis, MN
May 5th, 2017

Introduction

- Current air filter test standards employ pure solid (ISO dust, carbon black, cotton linter, NaCl, KCl, etc.) or pure liquid/oil (DEHS, PAO, etc.) as testing aerosol. Only pure solid particles are used to assess the filter holding capacity/lifetime or to condition/age the filter in standards.

- Filters used in field may face aerosols from various sources with different physical states, e.g. mixtures of solid and liquid (oil) particles for filters used for colloid/mist removal, including cooking or oil handling application, offshore oil drilling platform, and etc.

- Although the clean filter efficiency may not be affected much by aerosol physical state, the filter loading and clogging behaviors can be much different.

Test variables

- Solid particles
  - **Sodium chloride particles** from a Collison-type atomizer (TSI 3076)
  - **Soot particles** from a propane diffusion flame burner (home-made)

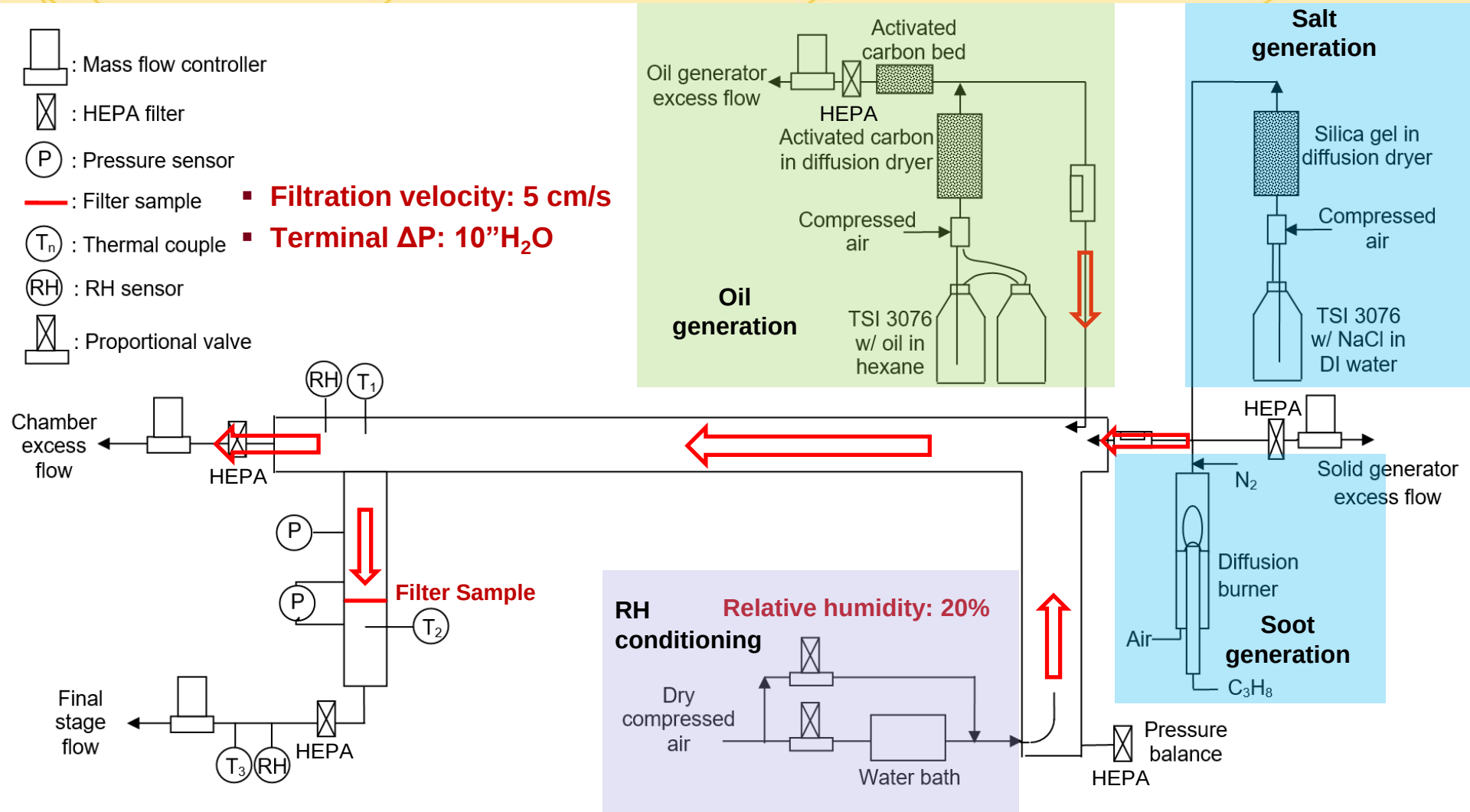
- Properties of tested oils

Oil	Chemical name	Density [g/cc]	Viscosity @ 25 °C [10^{-3}Pa·s]	Surface tension [10^{-3}N/m]
DEHS	Dioctyl sebacate	0.912	24	32
N44*	1-Decene, homopolymer, hydrogenated (PAO)	0.825	71	32
N140*		0.835	250	32
N415*		0.843	830	32
N1400*		0.848	3000	32

*** : viscosity standard oil from Cannon Instrument Company**

- Solid-oil mixing ratio:
  - **Volume** fraction varied from 100%-0% (pure solid) to 0%-100% (pure oil), with 10% increment (e.g. solid fraction at 100%, 90%, 80%,…10%, 0%). A 5%-95% exception was added for soot-oil mixtures.

Schematic of test setup

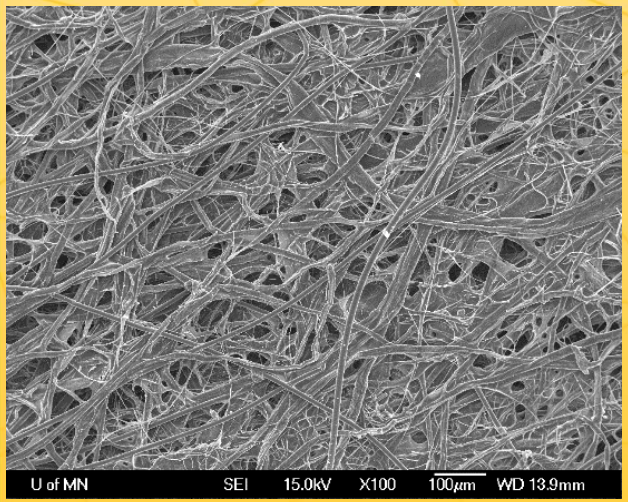


Filter media tested

- Properties of tested filter media

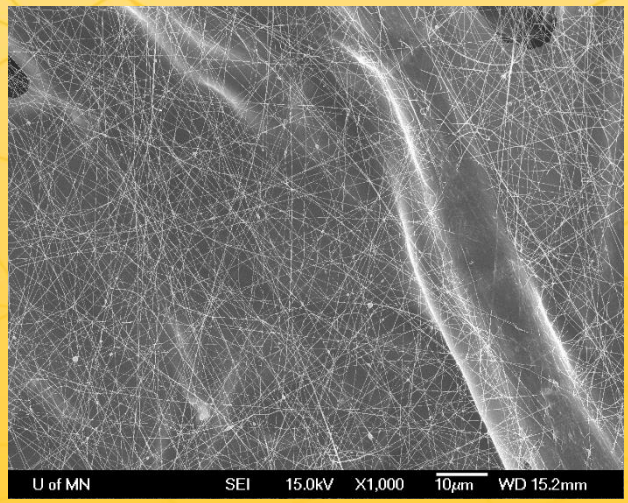
Media	Material	Abbr. name	Areal weight [g/m^2]	Efficiency rating	Initial ΔP @ 5 cm/s [inchH_2O]
A	cellulose	Cellulose	118±7	F7	0.35±0.08
B	cellulose w/ nanofiber coating on top	Nanofiber	123±1	F8-F9	0.27±0.01
C	ePTFE	PTFE	116±1	H11	0.29±0.01

Media A: Cellulose



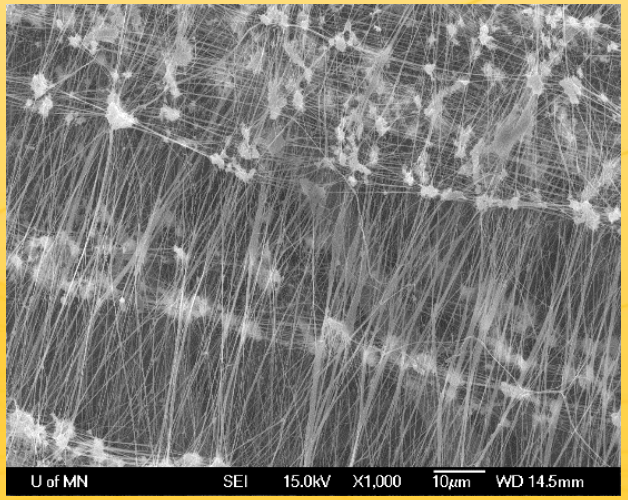
x100

Media B: Nanofiber



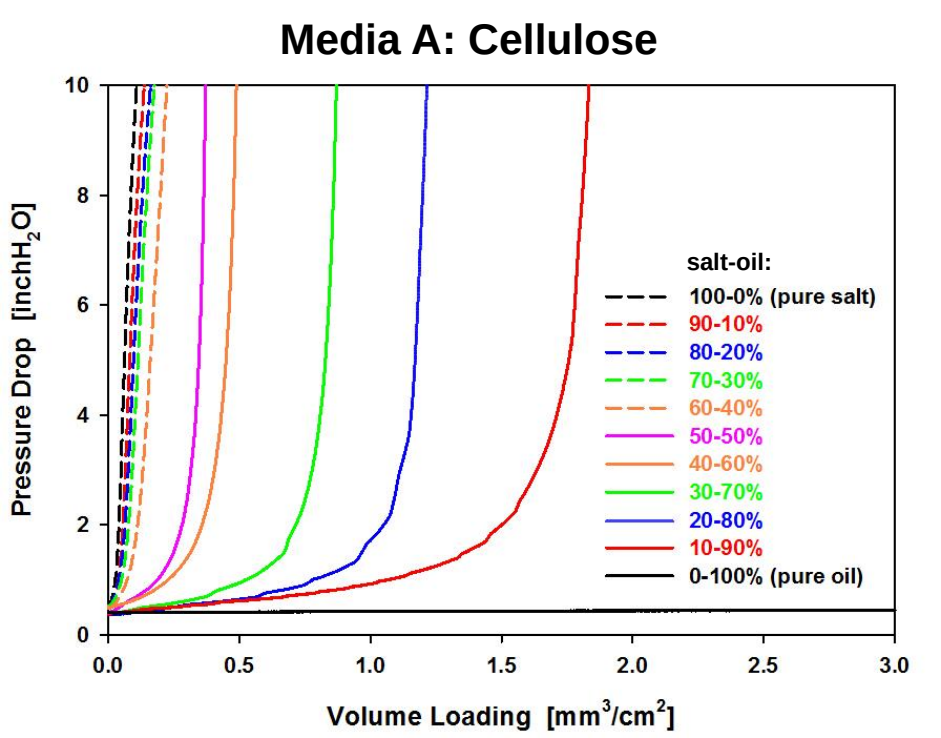
x1000

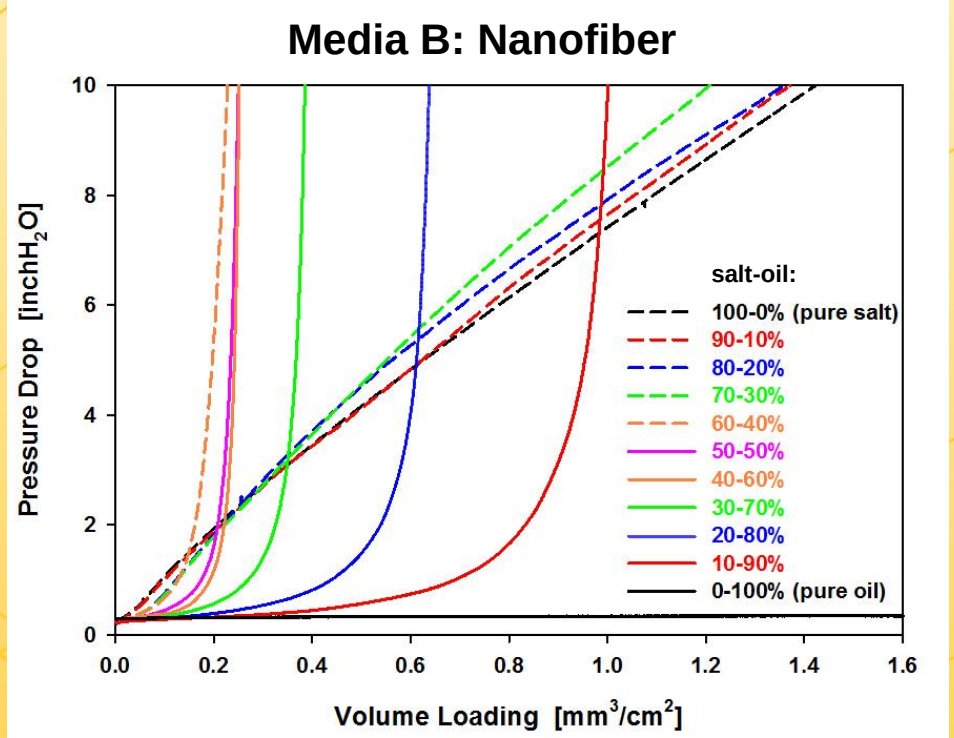
Media C: PTFE



x1000

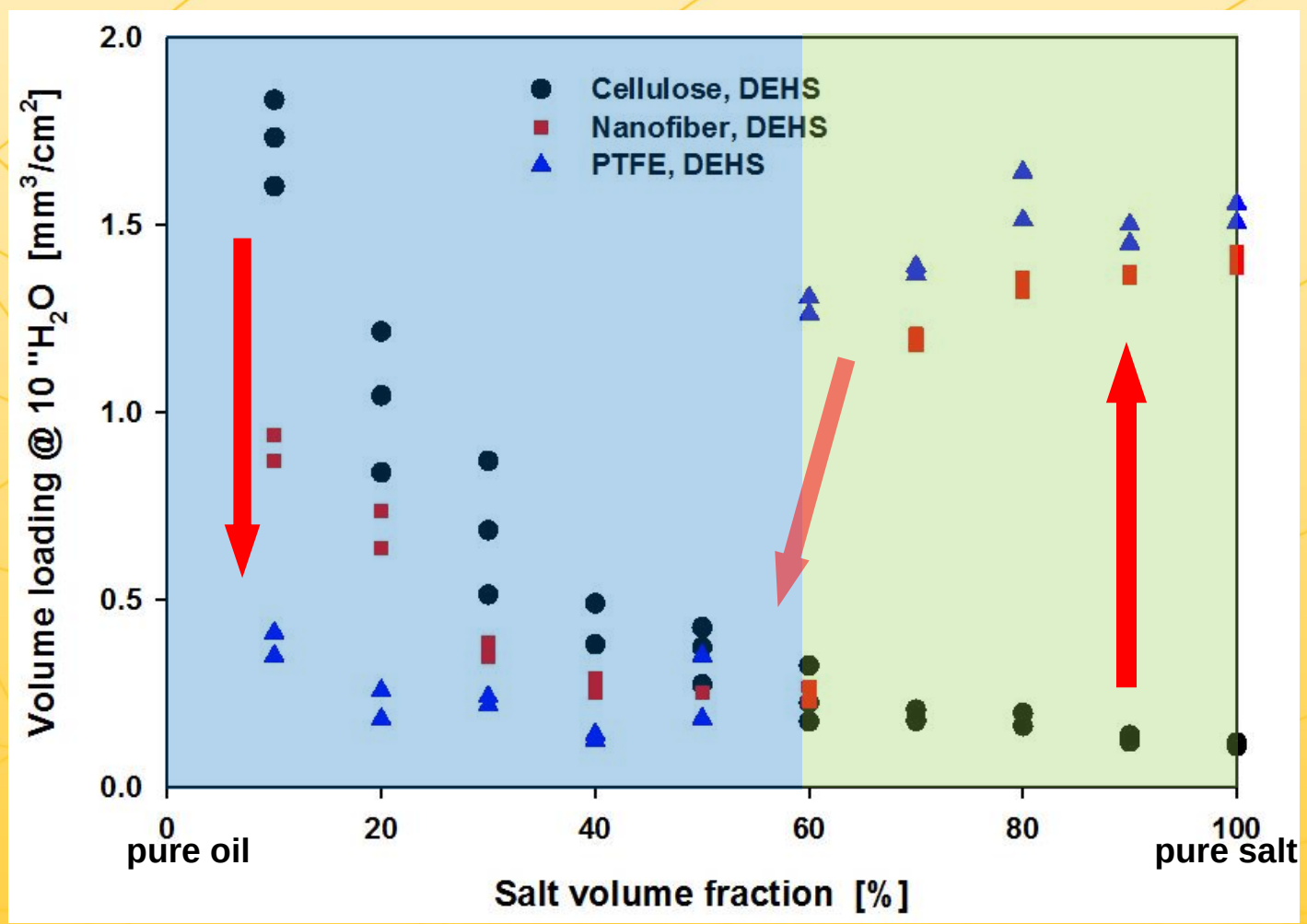
Loading curves of salt-oil particle mixtures



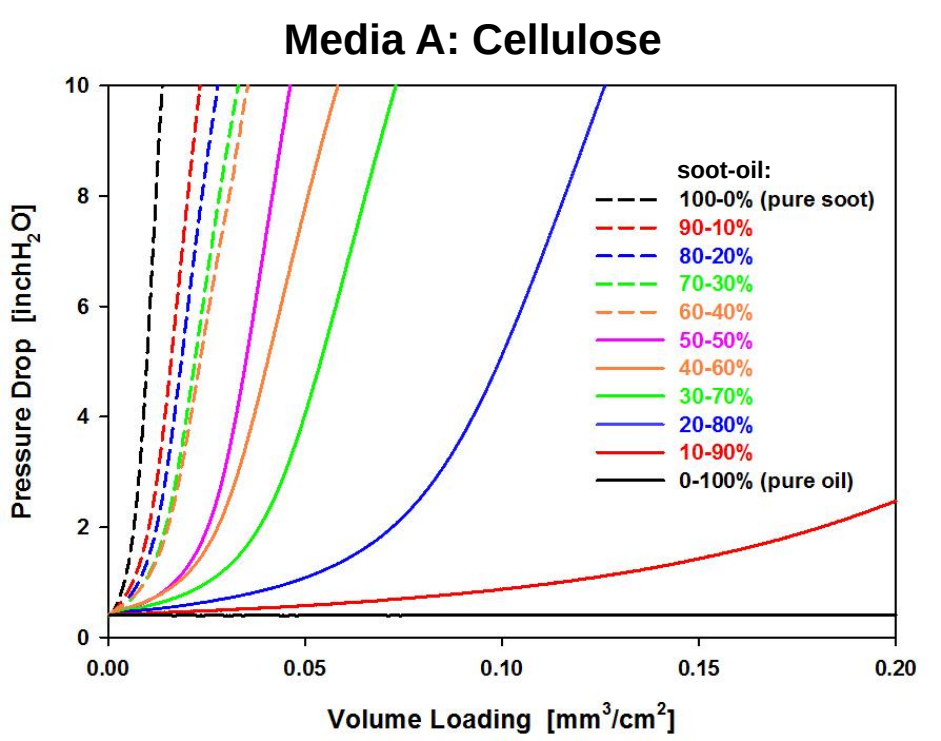


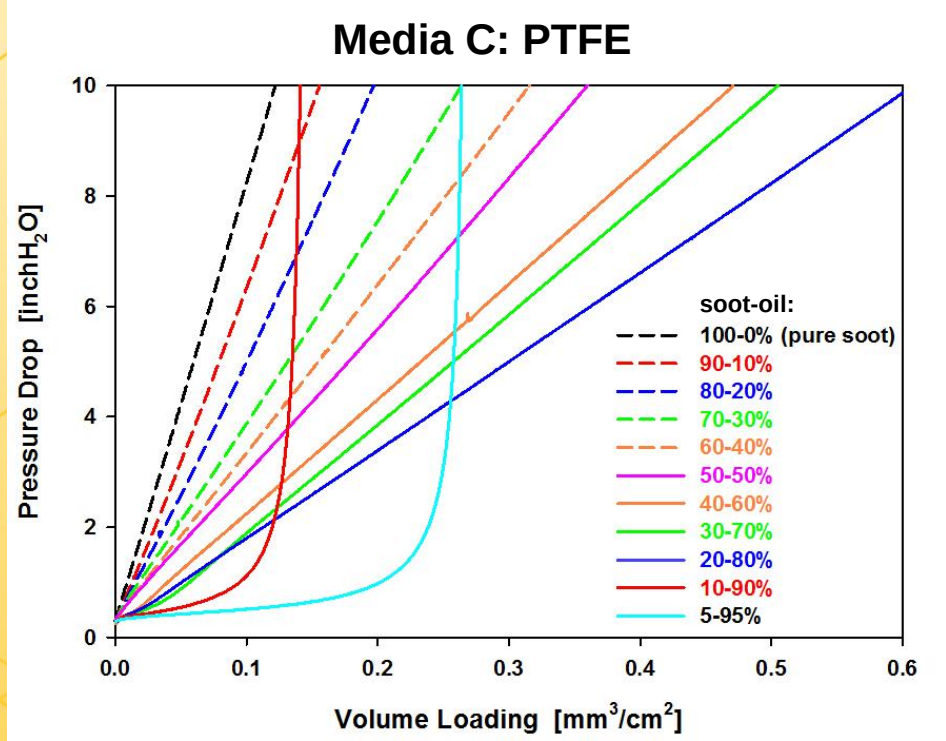
- The clogging of cellulose media (Media A) slows down with increasing oil fraction.
- Clogging of nanofiber (Media B) and PTFE (Media C, not shown) switches from nearly surface loading at high solid fraction to a different pattern (with concave-up loading curve) at high oil fraction.

Holding capacity of salt-oil particle mixtures



Loading curves of soot-oil particle mixtures

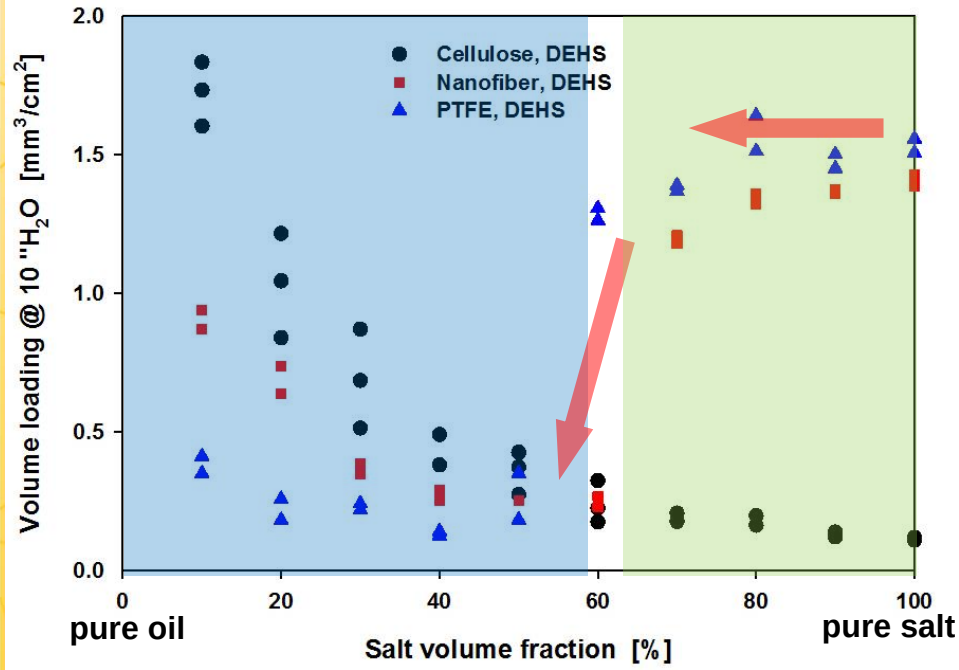




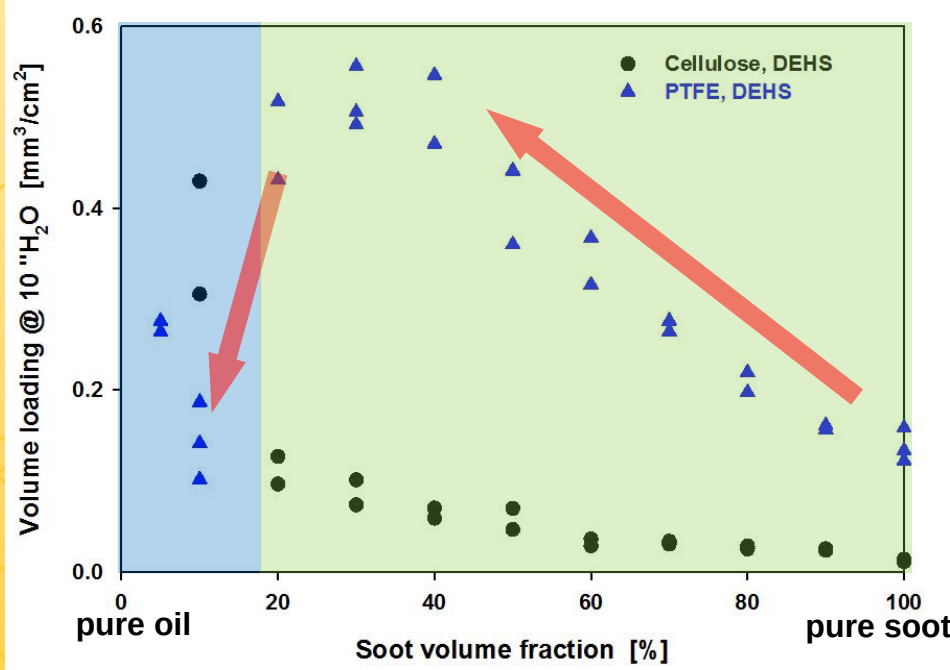
- Similar to salt-oil mixture loading, pressure drop of cellulose media (Media A) by soot-oil mixture increases slower with increasing oil fraction. The clogging happens at lower volume loading than salt-oil case because of finer size of soot particles than salt.
- Also similarly, the clogging of PTFE (Media C) have transition between two patterns, while the switch happens at higher (90%) oil fraction.

Holding capacity of solid-oil particle mixtures

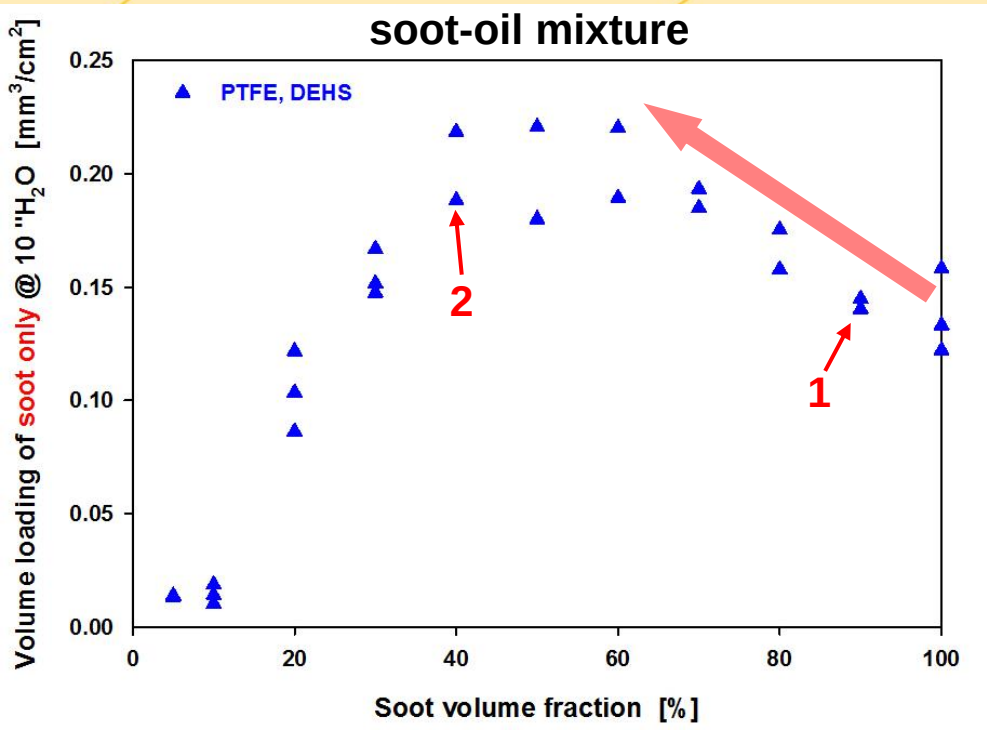
salt-oil mixture



soot-oil mixture



Interaction between solid & oil particles?

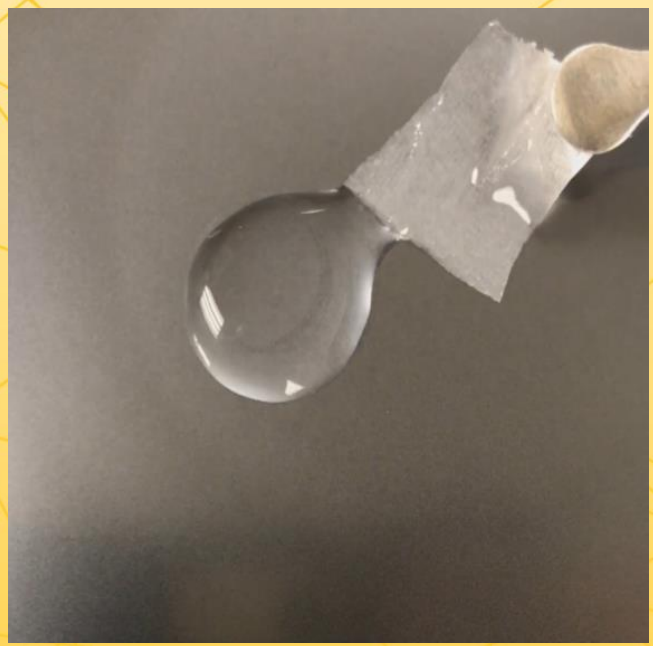


Point #	Media	Solid case	Solid fraction [%]	Volume loading [mm³/cm²]		Final ΔP [inchH_2O]
				Solid	Oil	
1	PTFE	Soot	90	0.140	0.016	10
2			40	0.188	0.282	

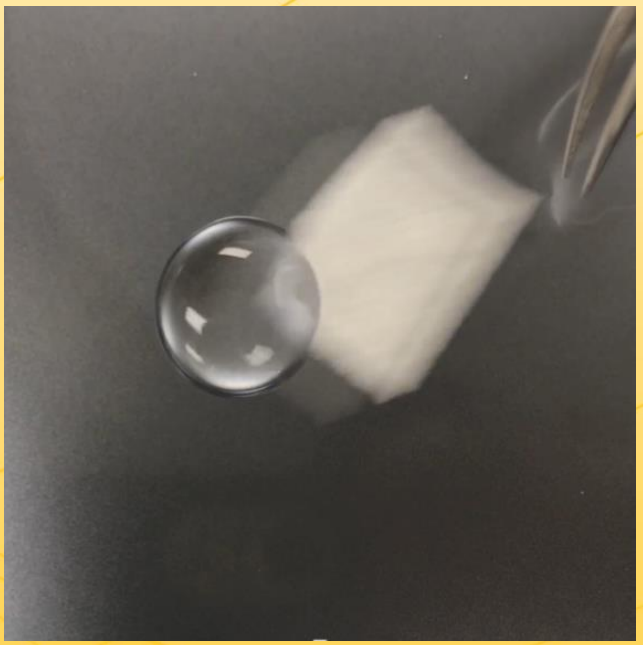
- Samples of certain volume fraction hold more solid and more oil (simultaneously) than other fractions, under same clogging pattern. **Why?**

Interaction between solid & oil particles

Water infiltrates into porous Kimwipes® tissue
(capillary)



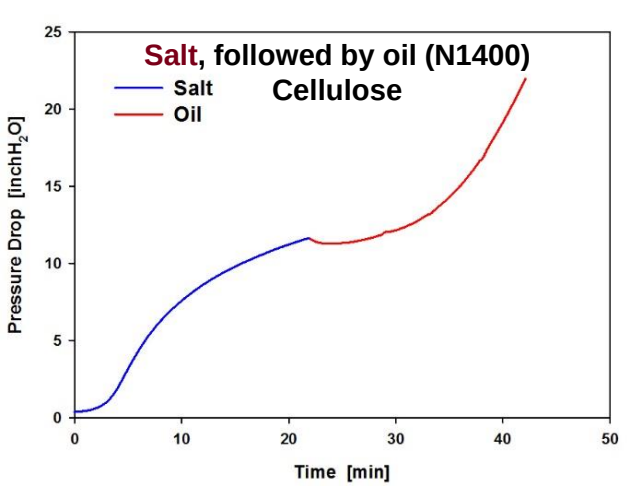
Water pulls light porous Kimwipes® tissue into itself
(surface tension)

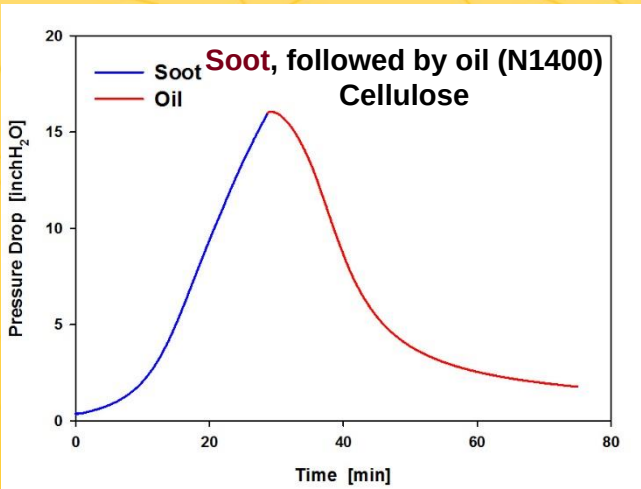


- Interaction between solids and liquid (oil) could change the structure of both forms, potentially affect the pressure drop build-up and clogging behavior on filter media.

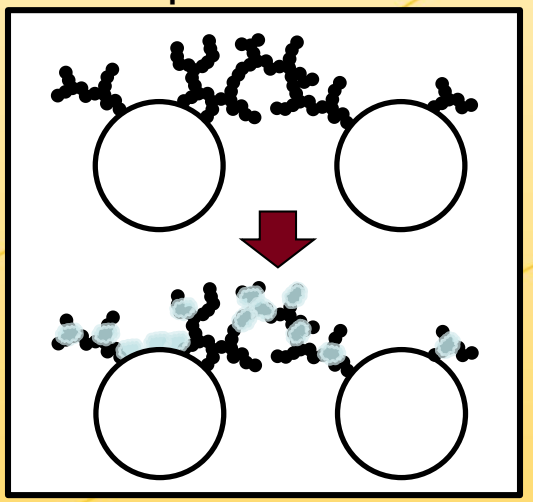
Sequential loading – solid followed by oil, cellulose

- Solid and oil particles are loaded to filter samples sequentially, to probe the possible interaction between solid and oil deposits.

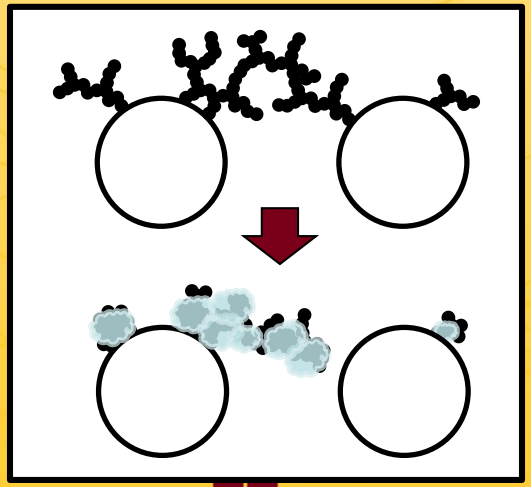




Oil fills in pores of solid dendrite

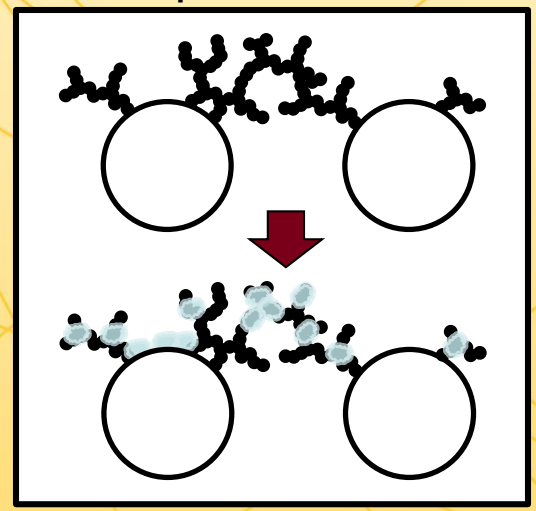


Oil shrinks/breaks solid dendrite

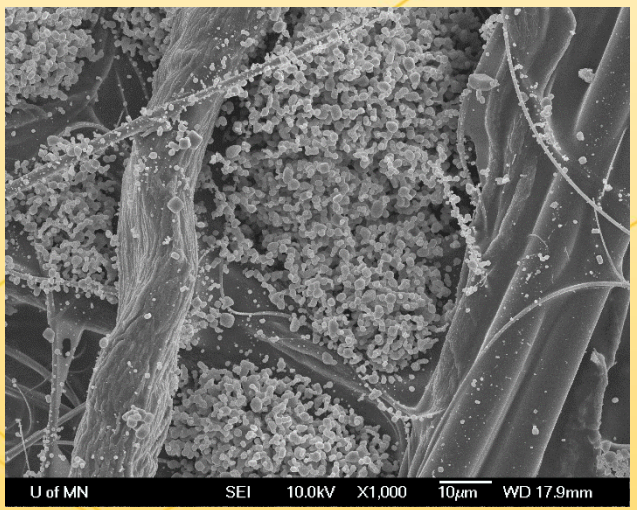


Sequential loading – solid followed by oil, cellulose

Oil fills in pores of solid dendrite

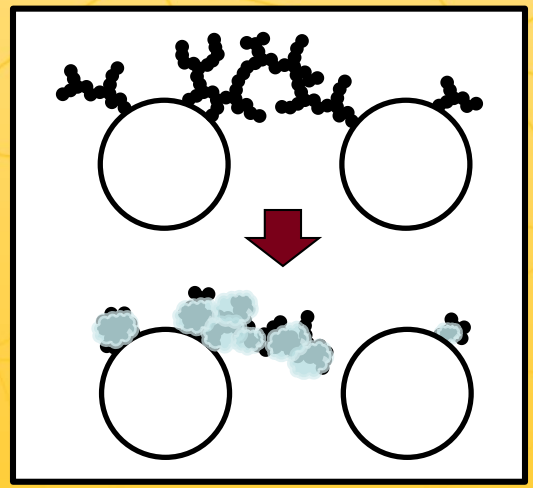


Cellulose, pure salt

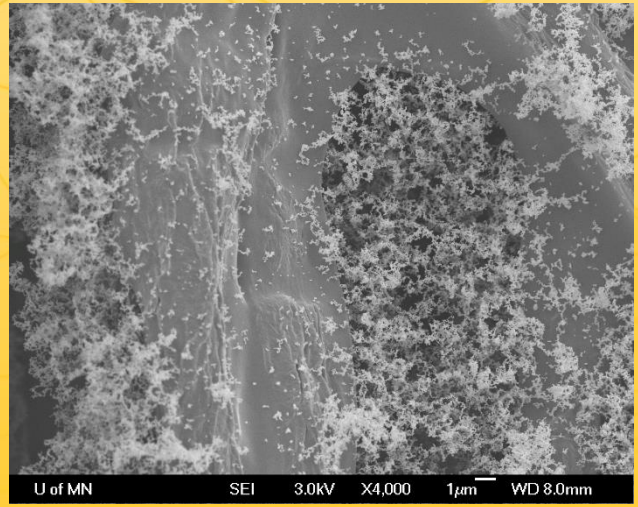


Cellulose, salt, followed by oil (N1400)

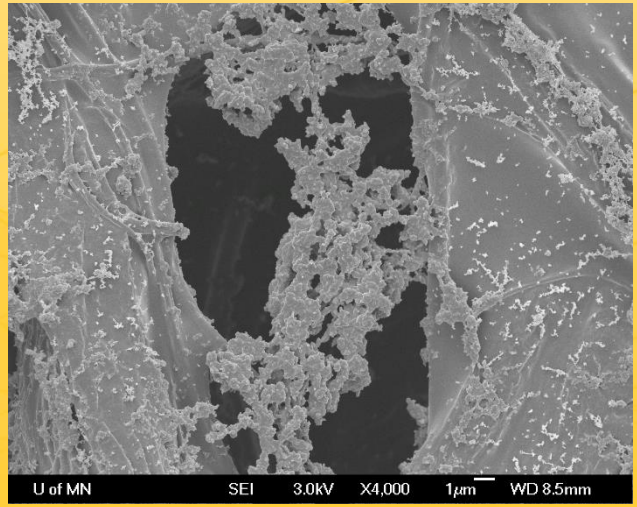
Oil shrinks/breaks solid dendrite



Cellulose, pure soot

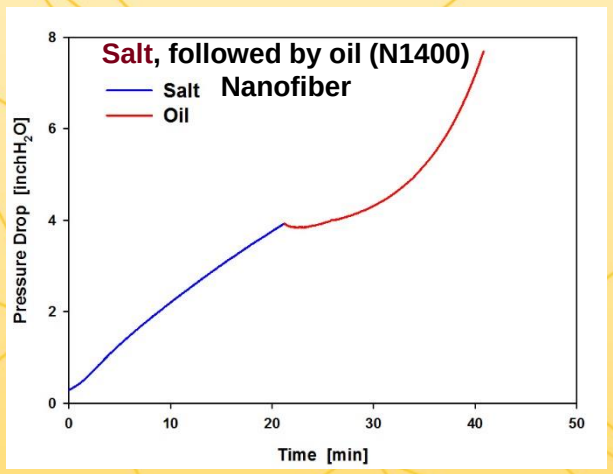


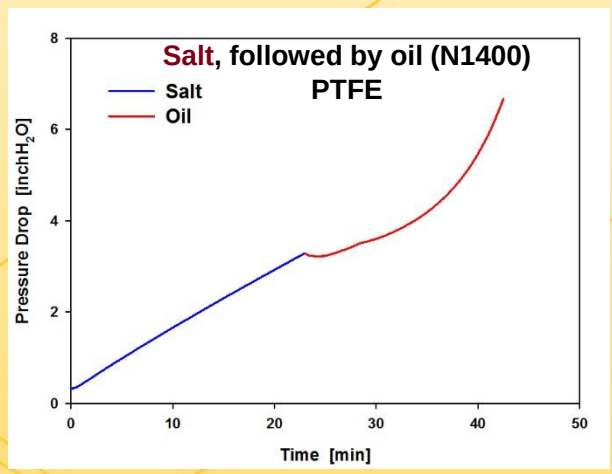
Cellulose, soot, followed by oil (N1400)



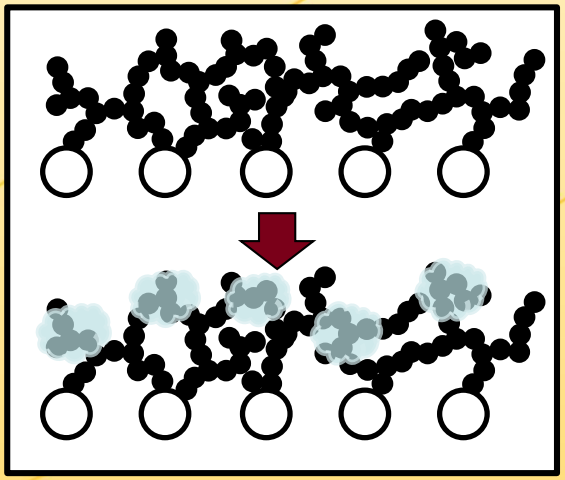
Sequential loading –

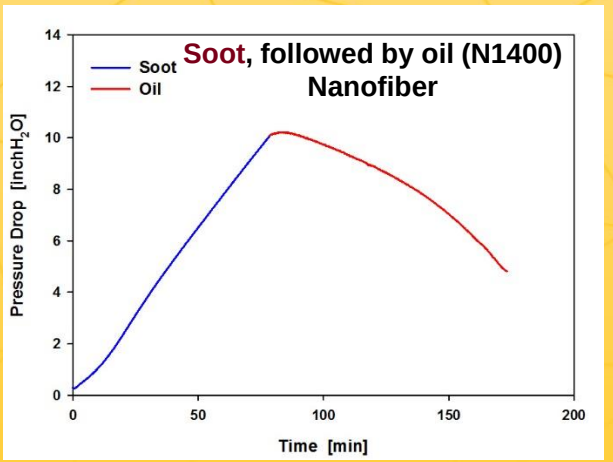
solid followed by oil, Nanofiber/PTFE

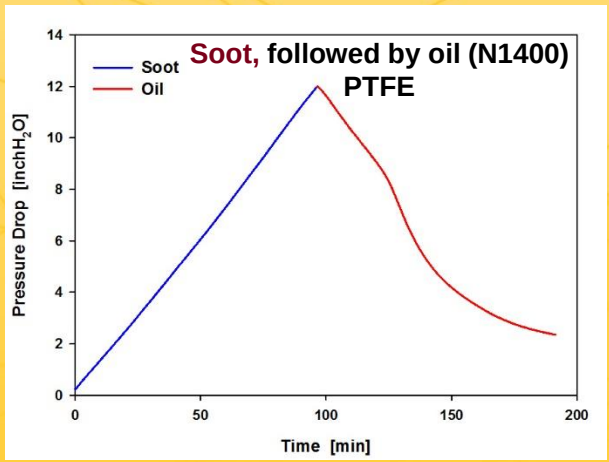




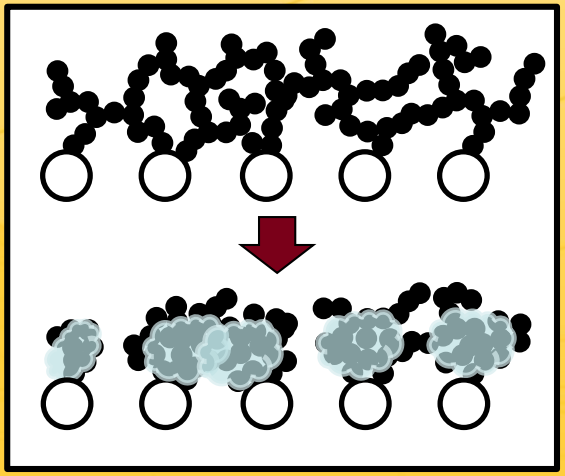
Oil fills in pores in solid cake







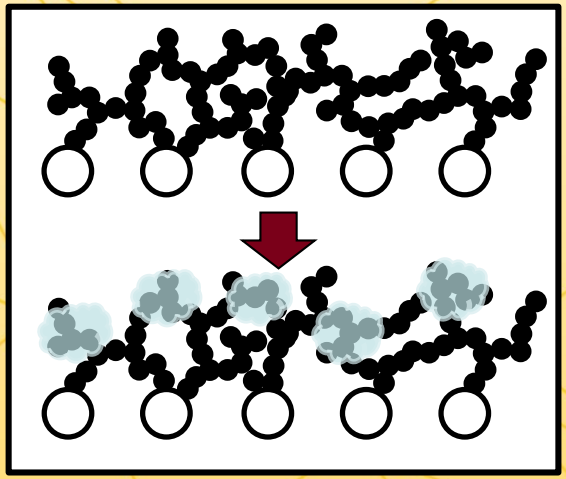
Oil breaks/cracks solid cake



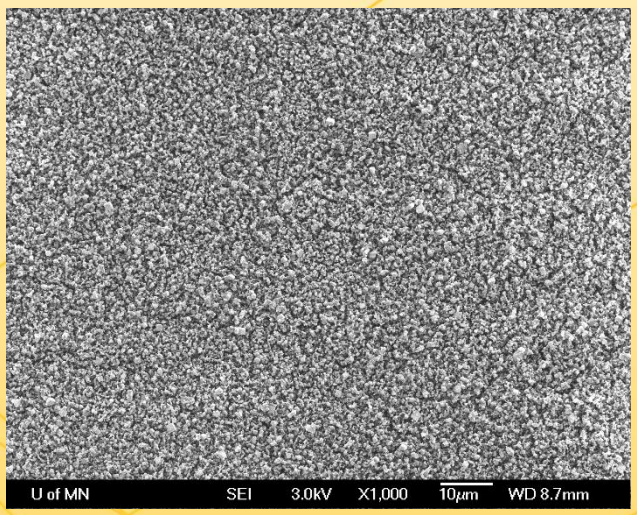
Sequential loading –

solid followed by oil, Nanofiber/PTFE

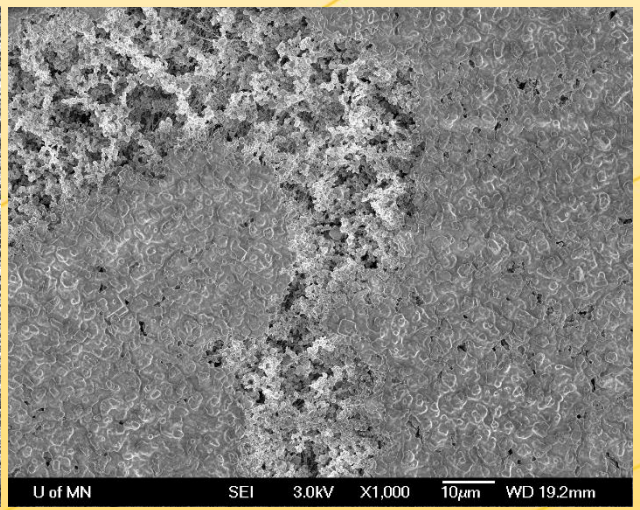
Oil fills in pores in solid cake



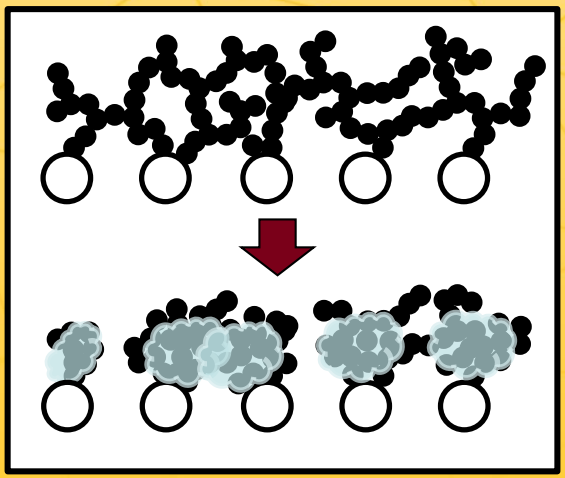
PTFE, pure salt



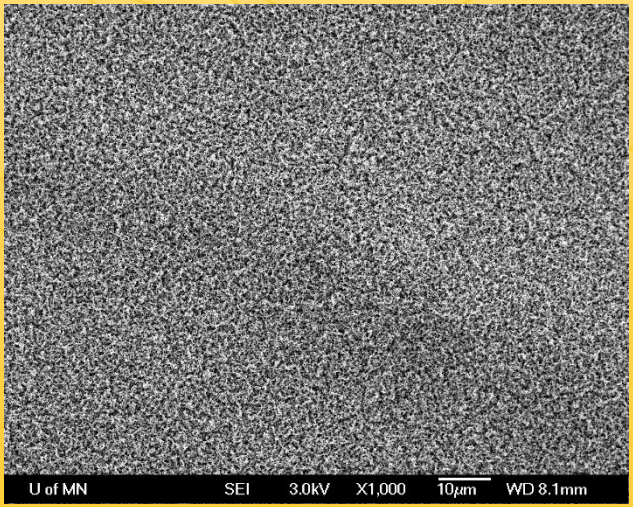
PTFE, salt, followed by oil (N1400)



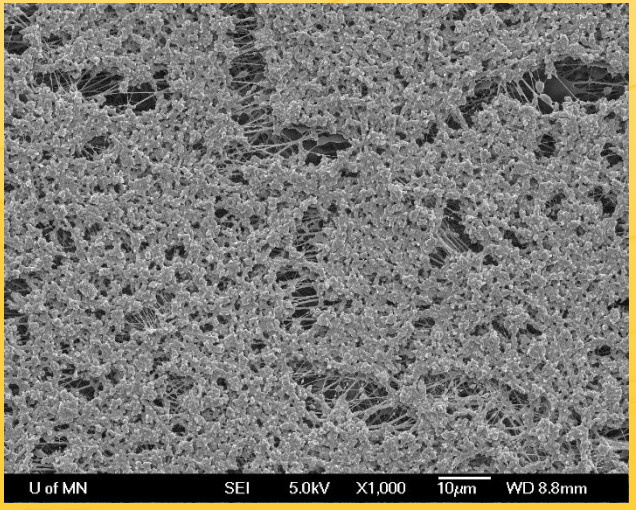
Oil breaks/cracks solid cake



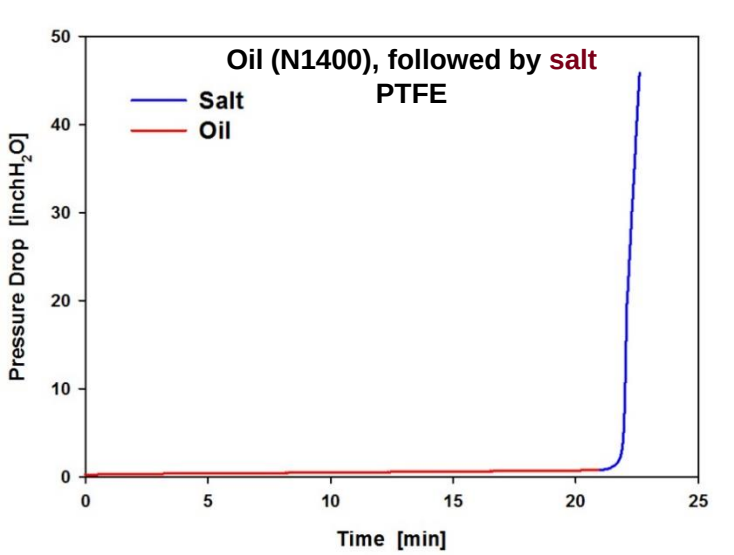
PTFE, pure soot

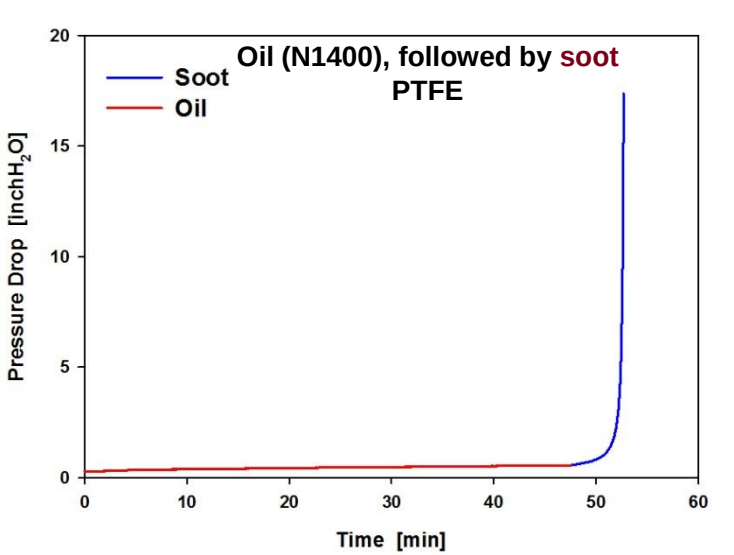


PTFE, soot, followed by oil (N1400)

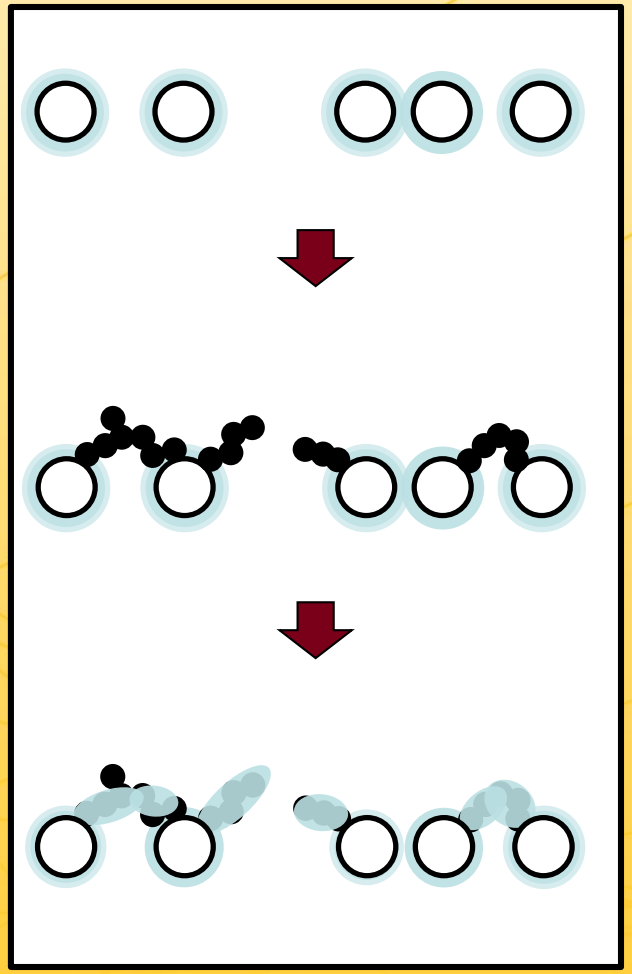


Sequential loading – oil followed by solid





Oil forms film on solid bridges, blocking filter pores



Sequential loading – oil followed by solid

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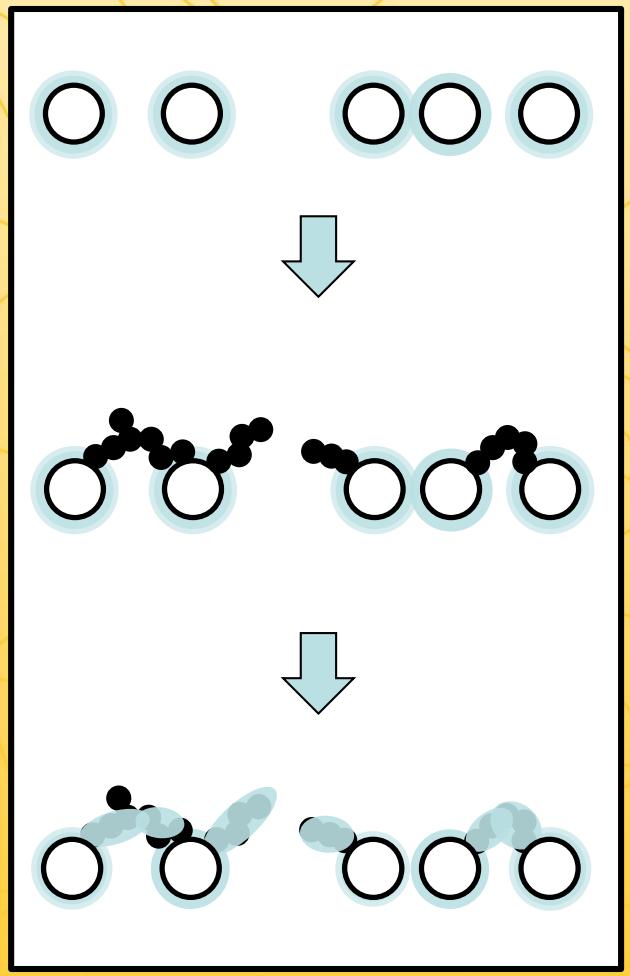
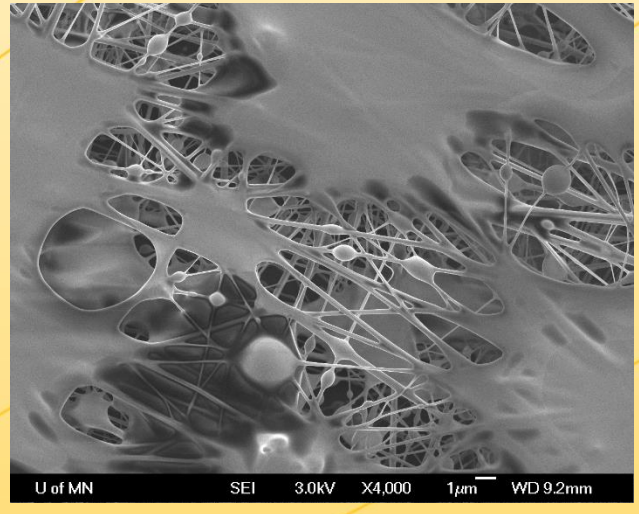
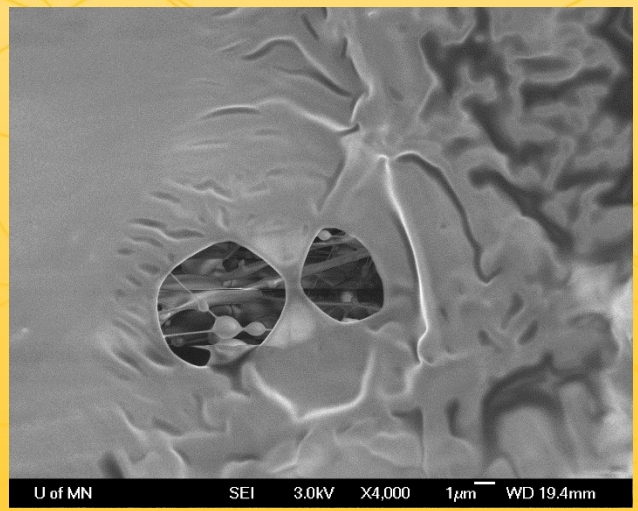


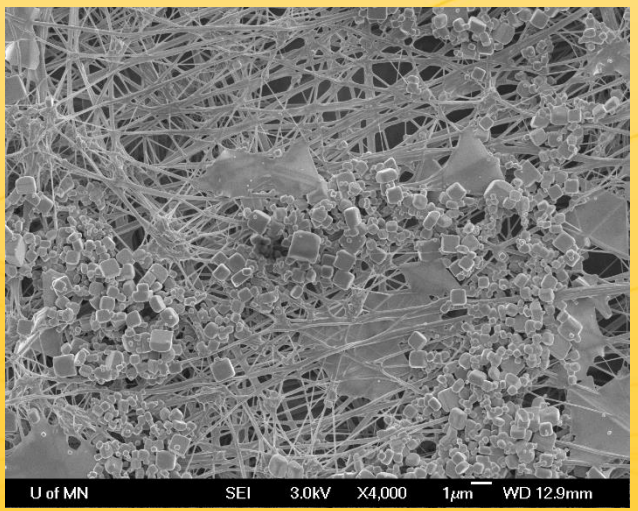
Pure oil (N1400) on PTFE



N1400, followed by salt on PTFE



DEHS, followed by salt on PTFE

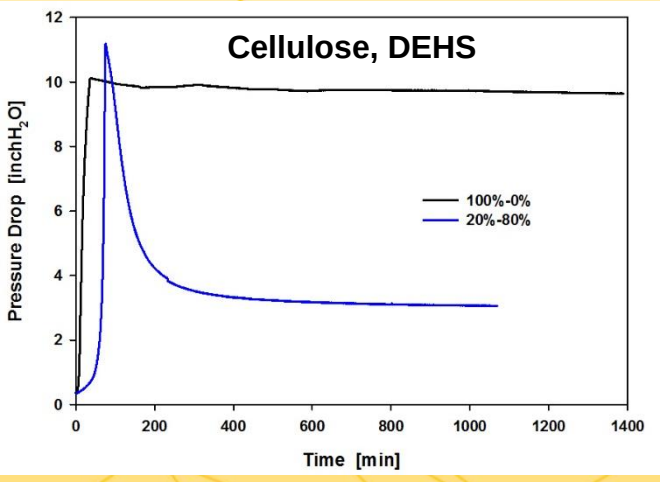


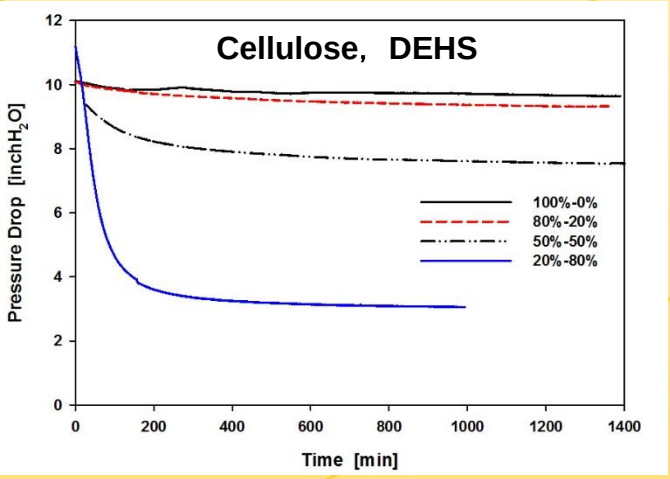
Summary

Difference	Solid	Oil
Space occupied	branching out from fiber surface; occupying more space	staying on any surface; occupying less space
Permeability of occupied space	porous dendrite/cake; permeable (with pressure penalty)	dense film; nearly impermeable
Ability to move	staying after deposition (if no liquid or vapor/humidity interaction)	able to redistribute (viscosity dependent)

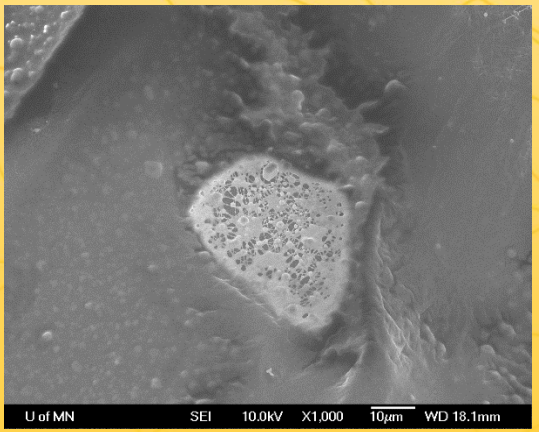
Interaction between solid and oil particles: coalescing into each other		
Favorable scenario	shrinking / breaking solid dendrite	Cellulose Media
	breaking / cracking cake of solids	Nanofiber & PTFE Media at high solid fraction
Unfavorable scenario	oil forming dense film on bridging solids, blocking filter pores	Nanofiber & PTFE Media at high oil fraction; Already formed solid dendrite/cake
Affecting factors	strength of solid dendrite/cake, oil surface tension & viscosity, deposition amount & sequence, loading rate, pore size distribution, media oleophilicity, etc.	

Appendix: Redistribution of oil on loaded filter – ΔP decaying

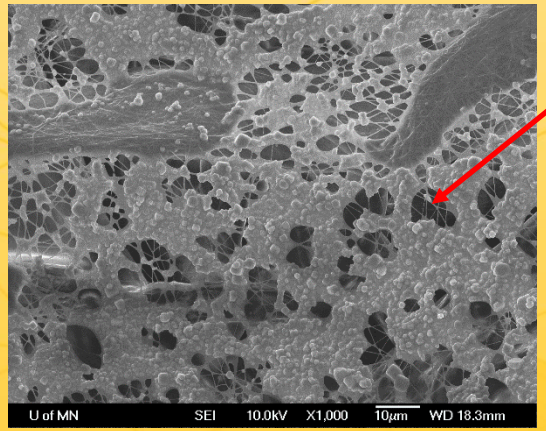




Nanofiber, 20%salt – 80%N415



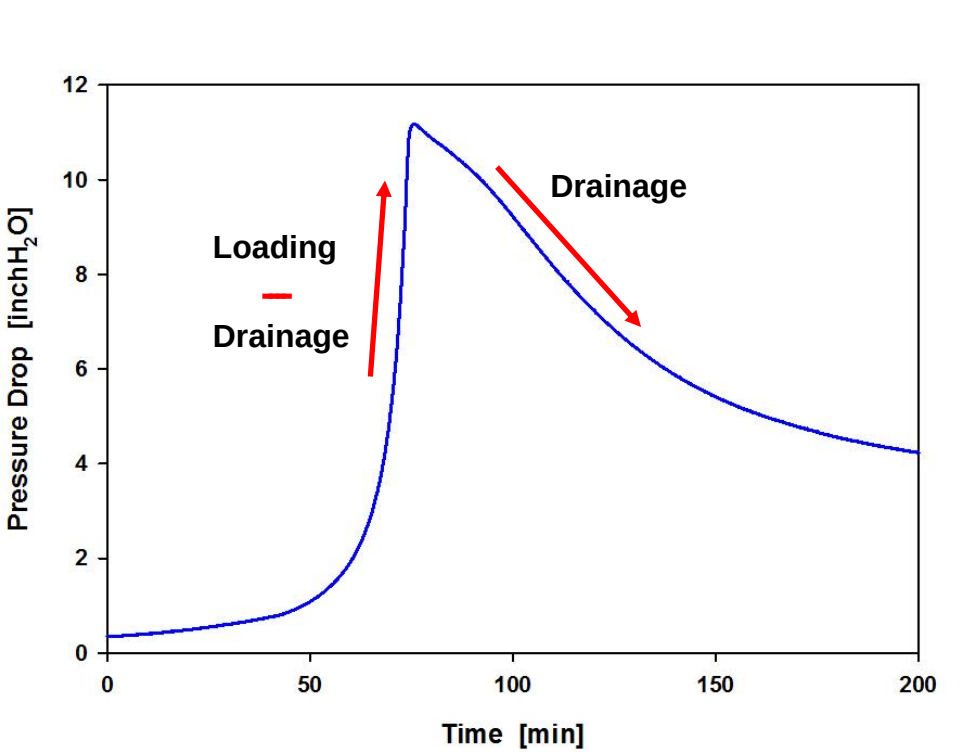
Nanofiber, 20%salt – 80%DEHS



Drainage after clogging

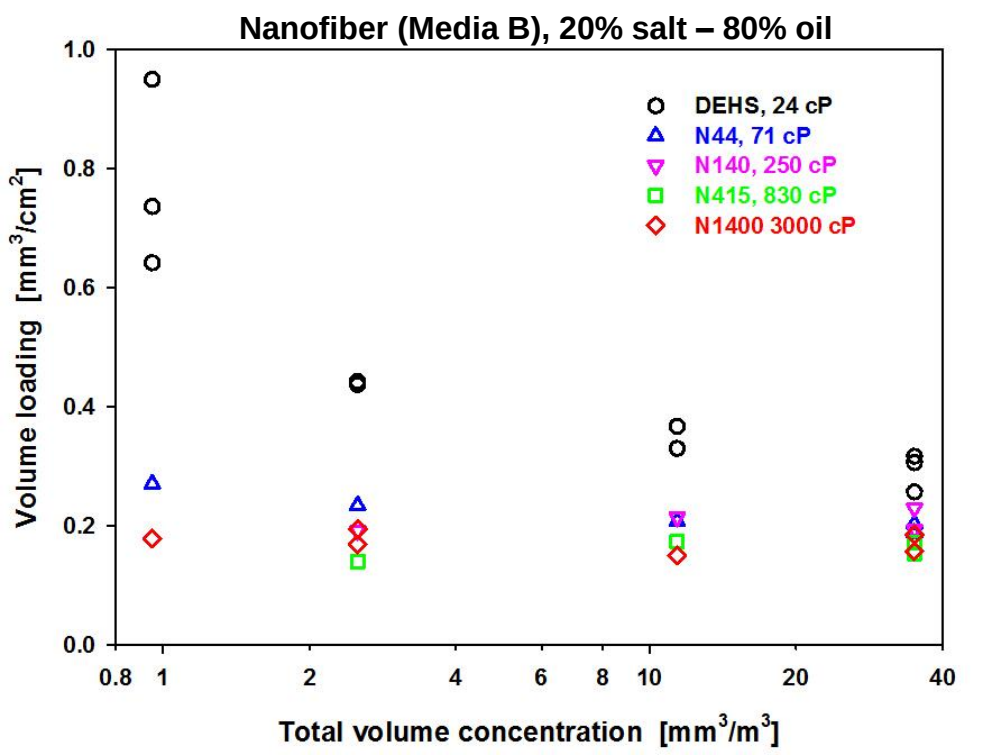
- ΔP of loaded filter sample gradually decays after aerosol feeding pauses while flow stays ON, which is mostly attribute to redistribution of oil in the media.

Appendix: Redistribution of oil on loaded filter – loading vs. drainage



- Observed pressure drop evolution over time is a result of competition between particle loading (increasing deposits of slid and oil on filter) and oil drainage (oil migrating within filter media by flow, gravity, capillary, etc.).
- Varying loading rate (upstream particle concentration) may change clogging behavior and result in a slower clogging.

Appendix: Redistribution of oil on loaded filter – effect of loading rate on clogging



- Final volume loading increases with decreasing aerosol feeding rate for DEHS (low viscosity @ 24 cP), which is a consequence of competition between loading and drainage rate. (The lowest upstream concentration @ ~1 mm^3/m^3 is much lower than typical lab condition, but still greater than typical field condition.)
- Final volume loading of all other oils (71-3000 cP) stays almost unchanged, because of higher viscosity (, and high roughness of solid deposited fiber).