WARSAW UNIVERSITY OF TECHNOLOGY
Faculty of Chemical and Process Engineering

Surface phenomena in separation of dispersed liquid contaminants using the coalescing filters

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Presentation plan

Introduction

Principles of the coalescence filtration and applications

Surface and depth coalescence

Droplets behaviour on the fibers (SE, R-P instability)

Flow regimes, modelling of the proces

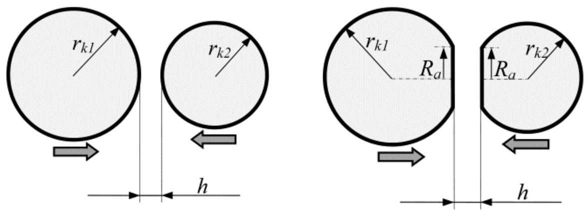
Experimental setup and some results

Coating of filters to obtain superhydrophobic and low-adhesion surface

Modelling of the dynamic contact angles and droplet movement using CFD

Coalescence filters applications

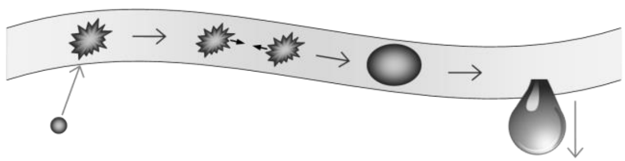
Coalescence – process of merging droplets



For effective separation

(by gravity, centrifugal force, membrane)

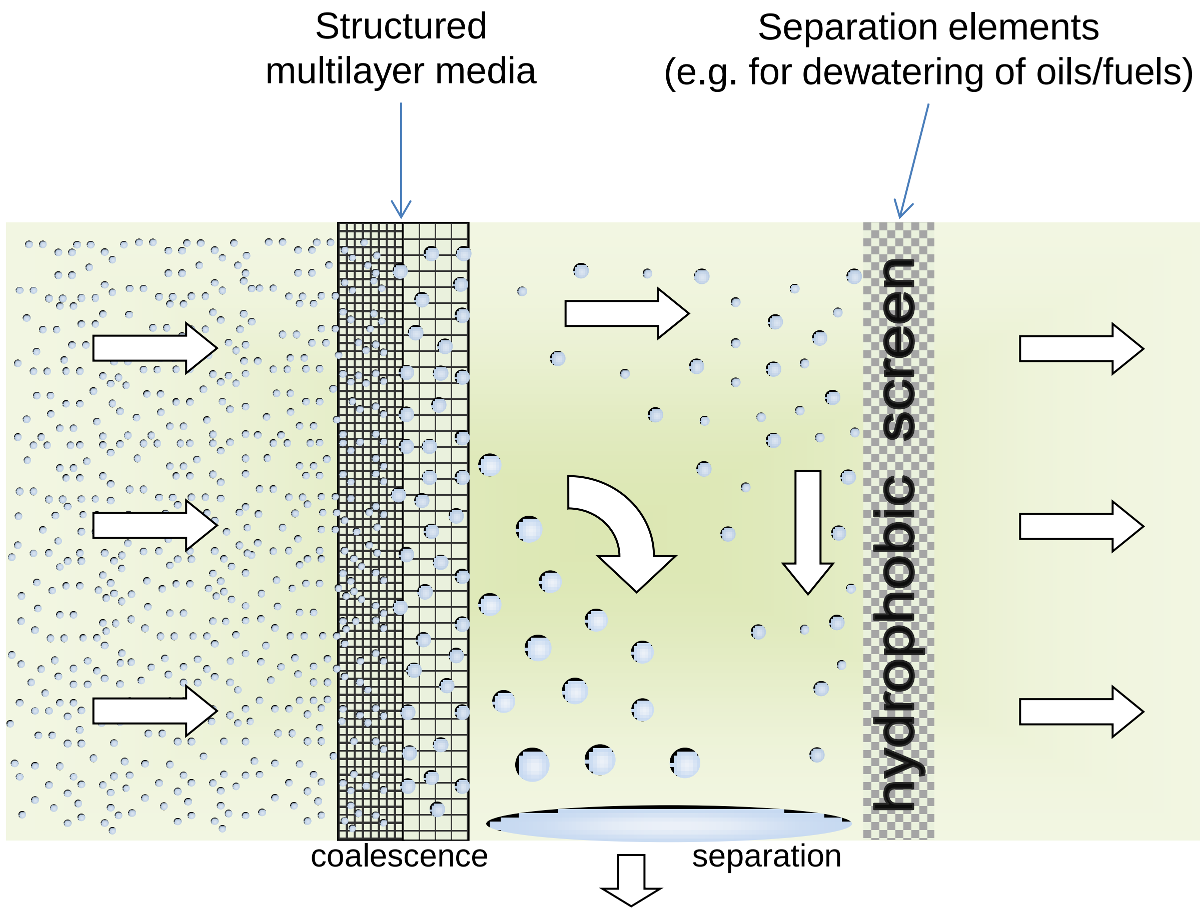
droplets must grow to a reasonable size



Four general categories of application:

- equipment protection (prevent corrosion, protect catalysts etc.),
- recovery of valuable products,
- obtaining high quality (purity) products – pollutants removal,
- meeting environmental discharge limits.

Principles of L/L coalescence filters separation

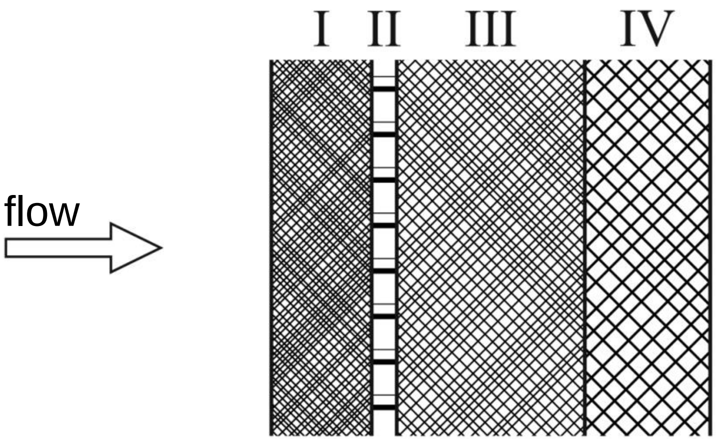


Principles of L/L coalescence filters separation

Coalescence media:

- deep bed process
- multilayer structures

I-primary coalescence layer
II-support
III-intermediate (secondary coalescence) layer
IV-drain layer



Separation media:

- surface process

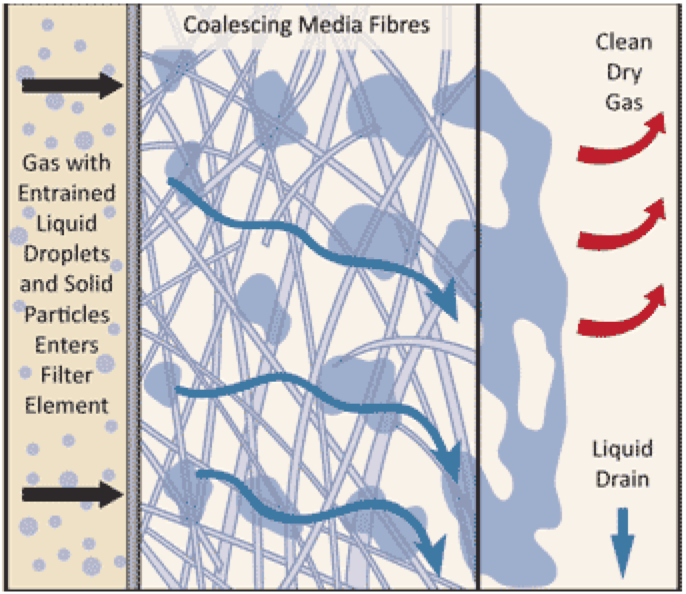
Automotive diesel filters (celullose, fibreglass)

Separation elements
2nd stage for jet fuel (kerosene), diesel fuel
(Teflon coated SS mesh, hydrophobized nylon mesh, hydrophobic fibrous celullose)

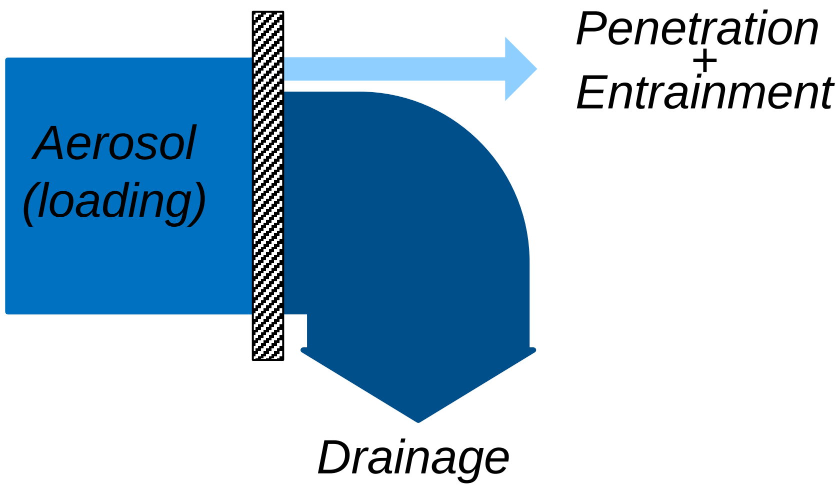
Principles of G/L coalescence filters separation

Difference comparing to L/L coalescers:

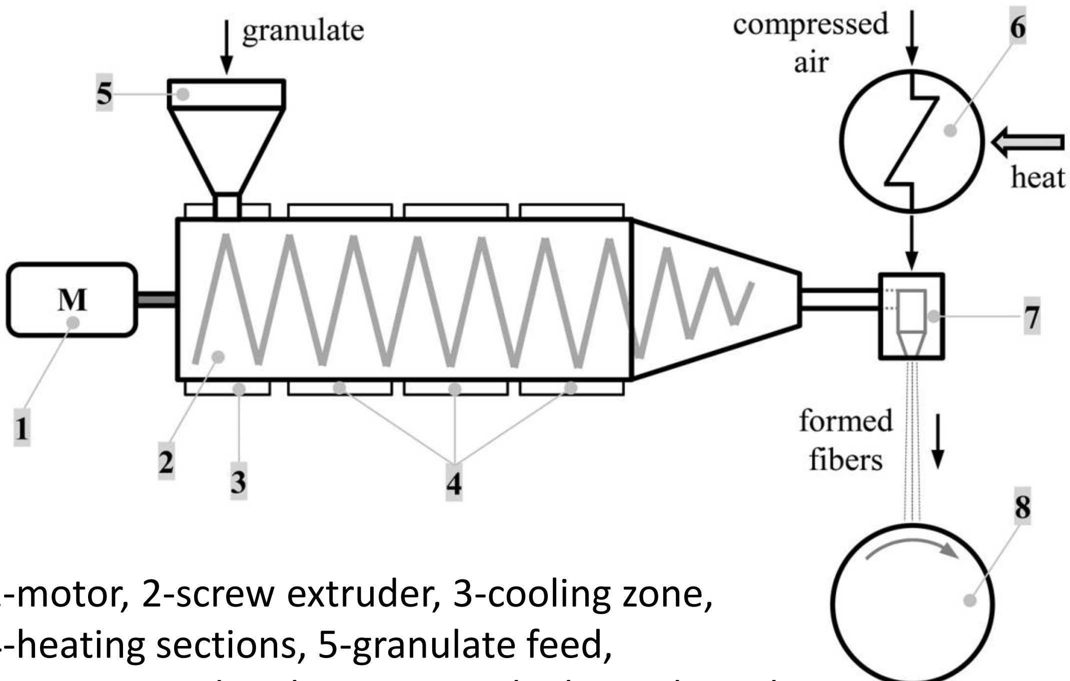
in properly operated filter liquid is usually drained in form of layer – on the outlet or internally (inside the porous structure)



Picture taken from Kelburn Engineering website

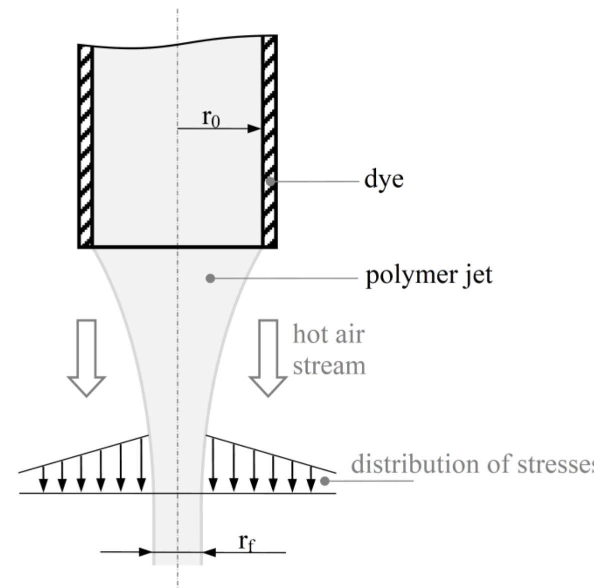


Melt-blow technique (producing the polymer filter media)

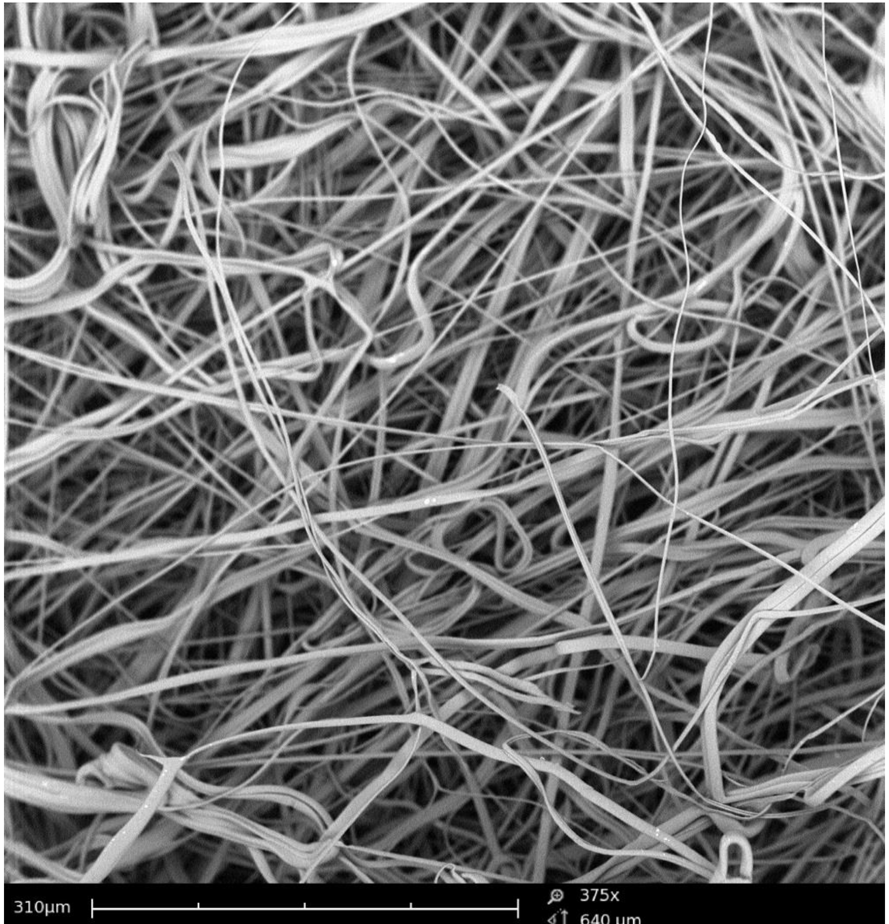


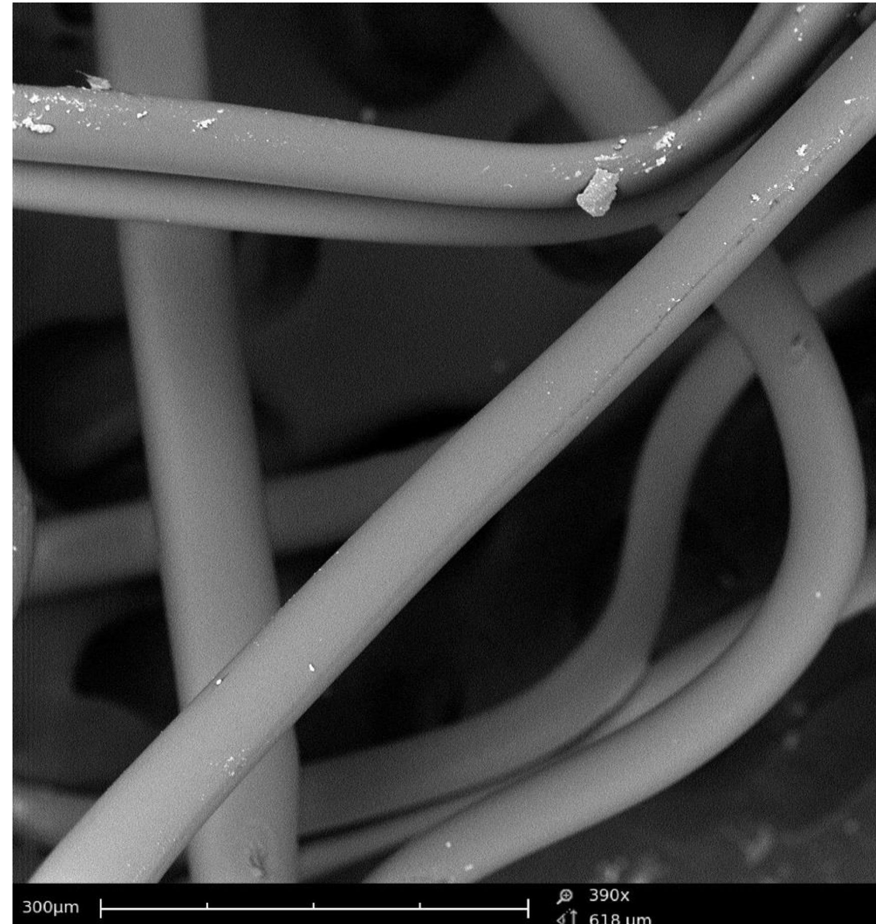
1-motor, 2-screw extruder, 3-cooling zone,
4-heating sections, 5-granulate feed,
6-compressed air heater, 7-multichannel nozzle,
8-receiver drum

Fibre formation

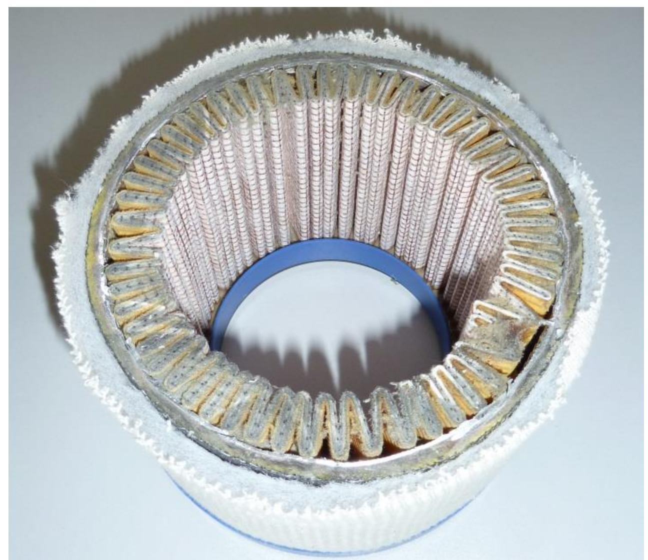


Polymer fibrous media produced using the melt-blow technique



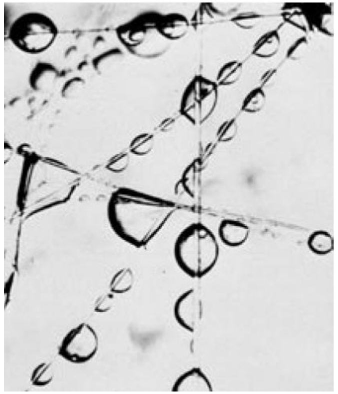


Coalescence elements

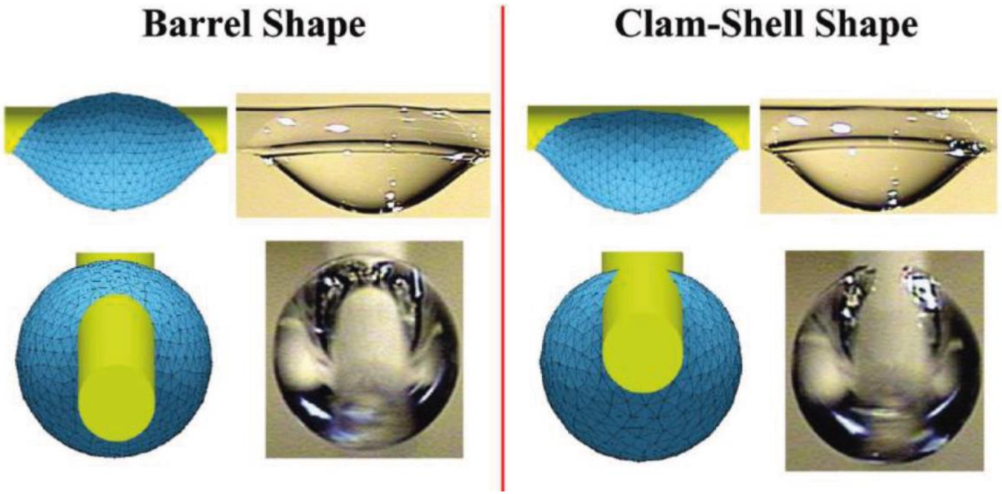


Droplets attached to fibres

A look into nature



Equilibrium geometric shape of a droplet on a fiber



Langmuir 2011, 27, 3685–3692

Surface Evolver (OA software) – minimizes the energy of a surface subject to constraints; the minimization by evolving the surface down the energy gradient

$$F = \gamma_{LG} A_{LG} + (\gamma_{SL} - \gamma_{SG}) A_{SL} + \int \int \int_V (\rho g z)\, \mathrm{d}V$$

Rayleigh-Plateau instability

A well-known Rayleigh-Plateau instability cause liquid jets or <u>films</u> to break into series or array of droplets.

e.g. melt-blow — <u>liquid on the fibres of coalescing filters</u>

Even if the surface is perfectly wetted, the thickness of stable film is limited –
– the predominant wavelength of this instability is $\lambda = 2\pi\sqrt{2}r_f$ *

* Annu. Rev. Fluid Mech. 1999, 31, 347–384

The thickest possible film - when the wavelength is equivalent to the circumference of the liquid cylinder coating the fiber:

$$2\pi\sqrt{2}\, r_f = 2\pi(r_f + h_t)$$

$$h_t = r_f(\sqrt{2} - 1)$$

CFD (OpenFOAM)

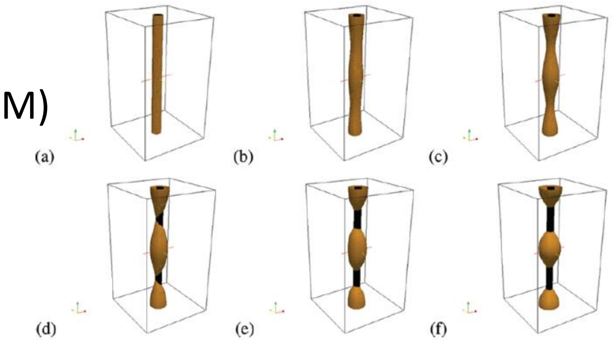


Figure 1. Series of images showing the simulation of the breakup of a liquid film under the influence of the Plateau−Rayleigh instability from (a) $t = 0$ to (f) $t = 0.00092$.

Langmuir 2012, 28, 6731−6735

Modelling of the coalescence filtration

Operation:

1. collection of droplets onto fibres
2. merging on fibres to form large drops
3. detachment after reaching a certain size

Process is repeated within entire structure multiple times until reaching outlet

Inlet layers – capturing of small droplets
Outlet/drain layer – forming of large droplets (uniform in size)

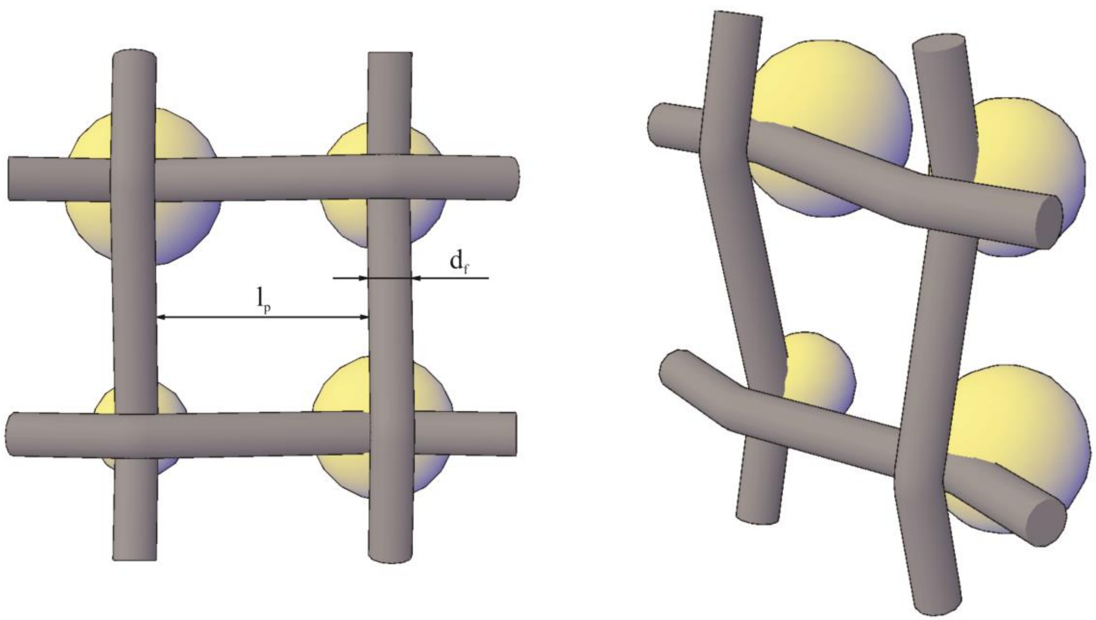
Upstream the coalescence filter: dispersion of fine droplets
Downstream the coalescer: dispersion of very large droplets

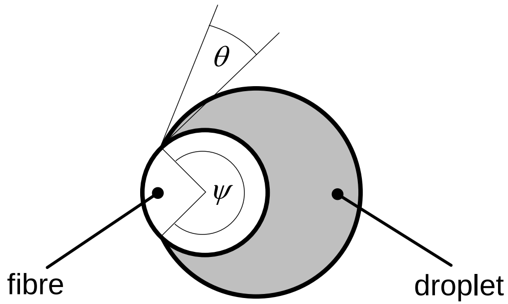
Modelling of the coalescence filtration – model formulation

Computational cell

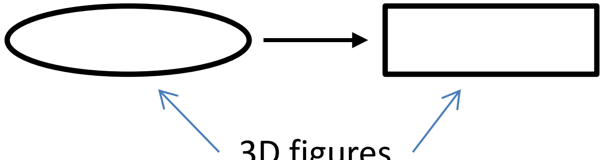
Assumptions:

- liquid accumulated in preffered locations (fibres intersections)
- immediate transport of all collected liquid to these locations
- no deformation





for $d_{df} >> d_f$



$$P = 2d_{df} + d_f \psi$$

Chemical Engineering Transactions 2013, 32, 1495-1500

Modelling of the coalescence filtration – efficiency of deposition

In flow throughout porous media droplets can grow due to:

I. Fibre assisted coalescence:

- deposition directly onto fibres
- coalescence with droplets attached to fibres

II. Coalescence of free-flowing droplets due to viscous shear (shear-induced coalescence)

EFFICIENCY OF DROPLETS DEPOSITION

Fibre (cylindrical collector):

- Interception (Bürkholz, 1989)
  (limiting trajectory concept)

$$y = \frac{d_f}{2} \frac{(1+N_R)\ln(1+N_R) - \frac{1}{2}(1+N_R) + \frac{1}{2}\frac{1}{(1+N_R)}}{Ku}$$

$$Ku = -0.5\ln\alpha - 0.75 + \alpha - 0.25\alpha^2$$

- Inertial impaction (Stechkina et al., 1969)

$$\eta_{in} = \frac{J\ Stk}{(2\,Ku)^2} \qquad J = \left(29.6 - 28\alpha^{0.62}\right)N_R^2 - 27.5\,N_R^{2.8} \qquad Stk = \frac{d^2 \rho_p\, u\, C_C}{18\,\mu\, d_f}$$

Droplet attached to the fibre (spherical collector):

- Interception (Lee and Liu, 1982)

$$\eta_R = \frac{1-\alpha}{Ku}\frac{N_R^2}{1+N_R}$$

- Inertial impaction (Langmuir and Blodgett, 1945)

$$\eta_{in} = \frac{Stk^2}{(Stk + 0.25)^2}$$

Modelling of the coalescence filtration – coalescence efficiency

Probability of deposition (when droplet approaches or collides the collector):

- for fibres = 100%
  (observed efficiency of droplet deposition is equal to efficiency of species collection on a fibre due to considered mechanisms)
- for deposition on droplets attached to fibres – a formalism based on the film drainage model is applied (Chesters, 1991)

$$\eta_{coal} = exp\left(-\frac{t_d}{t_c}\right)$$

t_d – drainage time (often referred as coalescence time)
t_c – contact time

Relations for undeformed droplets were used in the model:

$$t_d = \frac{3\pi\mu_c}{2F}\left(\frac{d_{d1}d_{d2}}{d_{d1}+d_{d2}}\right)^2 \ln\left(\frac{h_i}{h_f}\right)$$

$$t_c = \frac{1}{\dot{\gamma}}$$

h_i – initial film thickness
h_f – final film thickness
F – interaction force (exterted by flow)

Modelling of the coalescence filtration – structure saturation

$$S = \frac{V_L}{V_0}$$

volume occupied by dispersed phase liquid
total volume of voids

For thin and uniform media it can be estimated based on the pressure drop:

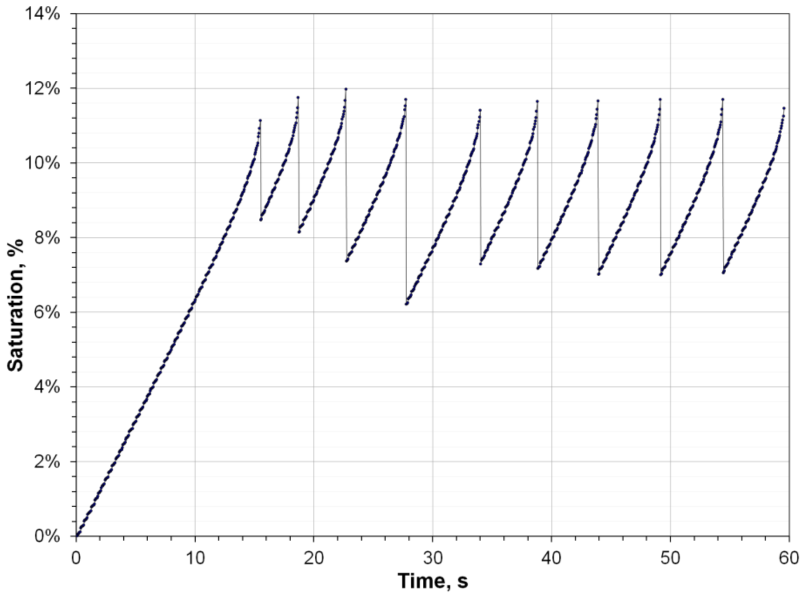
1-phase flow (continuous phase liquid)

$$\frac{\Delta p_1}{L} = \frac{36 \cdot u \cdot \mu_c \cdot K_1 \cdot (1-\varepsilon_1)^2}{d_F^{\ 2} \cdot \varepsilon_1^3}$$

2-phase flow

$$\frac{\Delta p_2}{L} = \frac{36 \cdot u \cdot \mu_c \cdot K_2 \cdot (1-\varepsilon_2)^2}{d_F^{\ 2} \cdot \varepsilon_2^3}$$

$$S = 1 - \frac{\varepsilon_2}{\varepsilon_1}$$



Time-dependent saturation profile: α=0.001, d_d=5μm, d_f=10μm, l_p=100μm, u=10mm/s, c=1 %vol., θ=30°.

	u	1 mm/s	5 mm/s	10 mm/s	50 mm/s	100 mm/s
θ = 30°	S	10.3 %	9.97 %	9.13 %	8.12 %	4.19 %
	A_F	0.6-30.3 %	3.2-31.7 %	6.5-34.1 %	16.5-38.4 %	36.5-46.9 %
θ = 60°	S	7.32 %	6.87 %	6.02 %	5.23 %	2.11 %
	A_F	4.2-40.4 %	11.5-42.7 %	18.6-45.1 %	32.7-50.9 %	47.5-59.9 %

Modelling of the coalescence filtration – detachment of droplets

Two independent criteria for droplets detachment from fibres are considered:

1. stable size of a droplet in local hydrodynamic conditions
2. balance of adhesion and drag forces

Ad. 1.

Walstra 1993: $$We_{crit} = \frac{\mu_c \dot{\gamma} d_{\max}}{\sigma} = 2$$

For the plug flow in fibrous bed: $$\dot{\gamma} = \cancel{\frac{4u(1-\varepsilon)}{d_f \varepsilon^2}}$$

Shear rate in saturated bed: $$\dot{\gamma} = \frac{2u_{local}}{l_{pore}^{eq}}$$

Ad. 2.

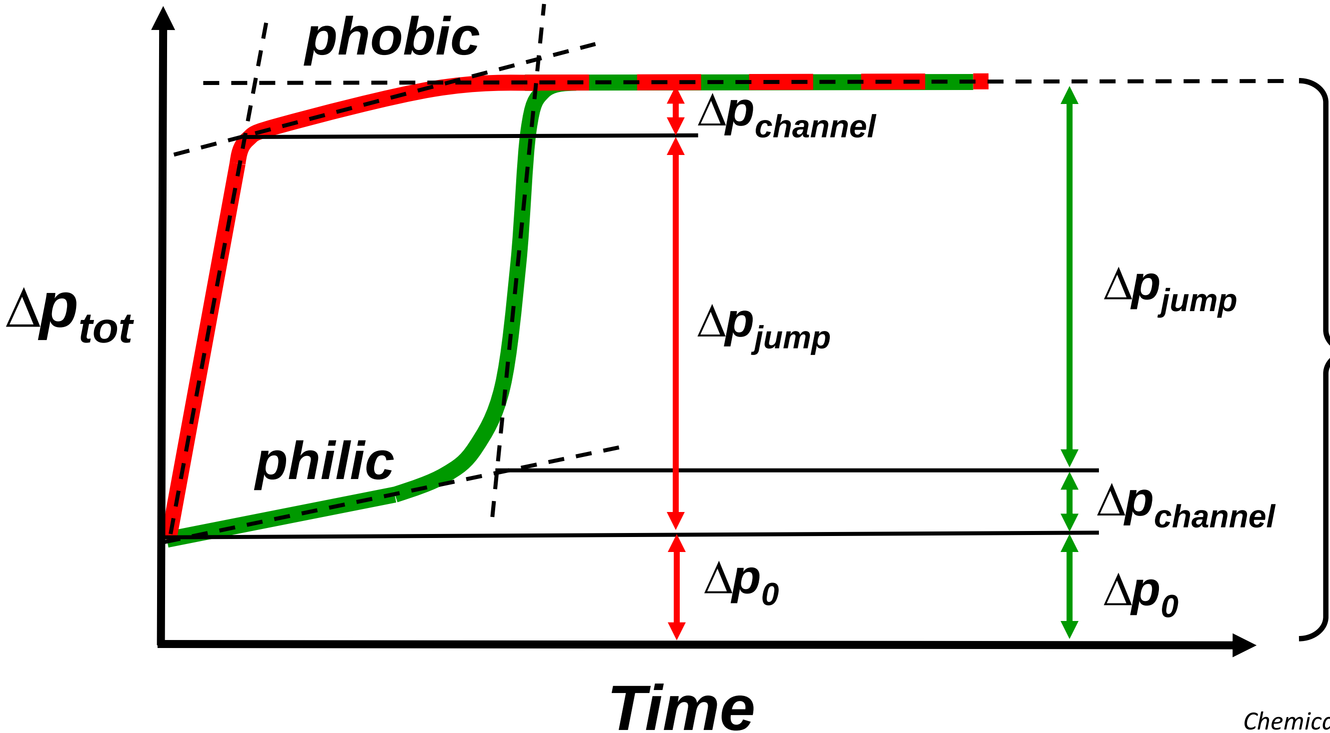
$$F_D = \frac{\frac{15}{2}\pi d_{df} u_{local} \mu_c \left[1 + \frac{2}{3}\frac{\mu_c}{\mu_d}\right]}{1 + \frac{\mu_c}{\mu_d}}$$

vs. $$F_A = \sigma \cos(\theta) P$$

	d_f	5 µm	10 µm	25 µm	50 µm	100 µm
θ	30°	52.7_{S}	108_{S}	263_{S}	496_{S}	1063_{S}
	75°	$73.2_{D\text{-}A}$	$146_{D\text{-}A}$	$366_{D\text{-}A}$	$729_{D\text{-}A}$	$1457_{D\text{-}A}$

Mean size of detached droplets (in µm) as a function of fibre diameter and contact angle;
calculations for superficial velocity 10 mm/s, packing factor 0.001, $l_p = 10\, d_f$;
Superscripts indicate the detachment criterion: S – stable size of droplets, D-A – drag to adhesion force ratio.

Film and channel model



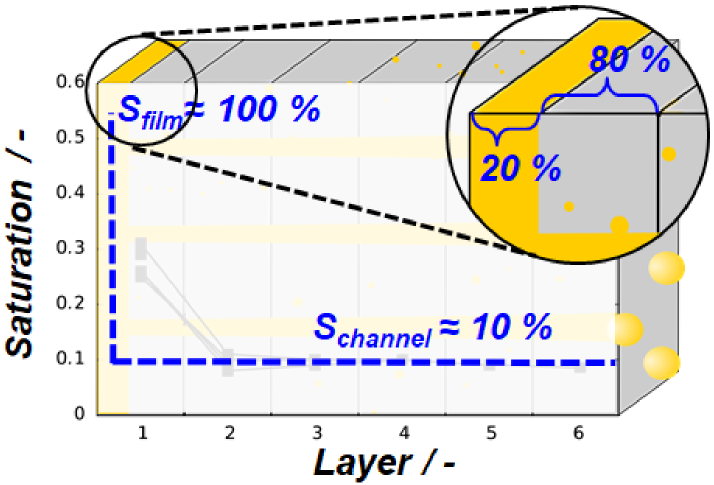
$$\Delta p_{tot,wet} = \sum_i \Delta p_i$$

Chemical Engineering Science 2015 , 122, 150-160

Δp_{jump} : associated with film *(capillary phenomenon depending only on media properties)*

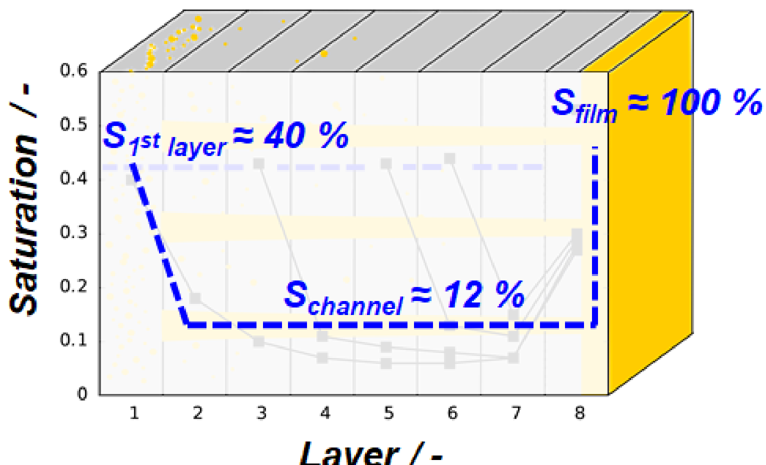
$\Delta p_{channel}$: associated with oil channels *("flow phenomenon" depending on viscosity, droplets load, face velocity,…)*

Film and channel model – saturation profiles



Sections of const. saturation in phobic media:

- Film (thickness f ≈ 20% of 1st layer)
- Channels

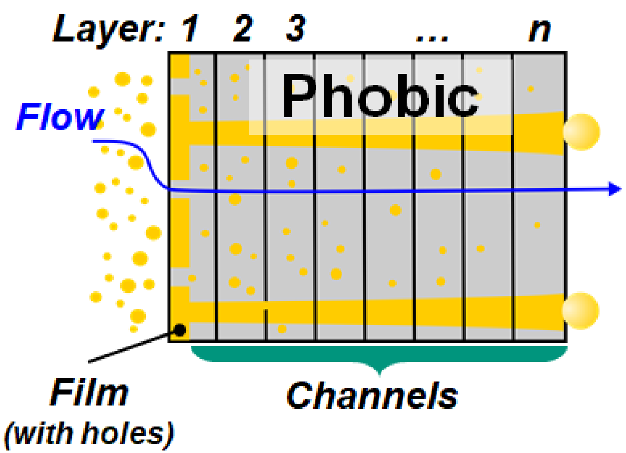


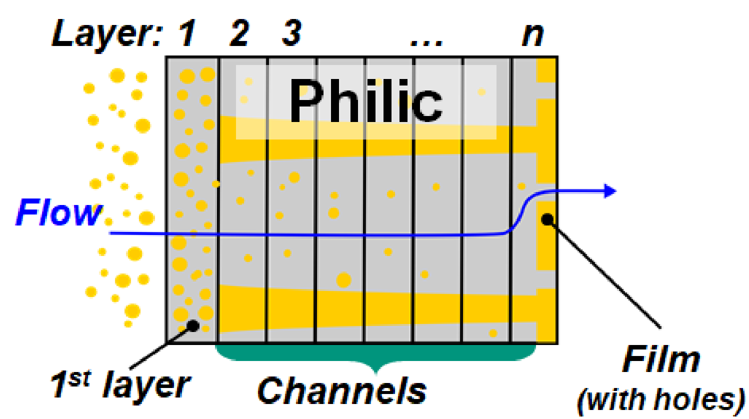
Sections of const. saturation in philic media:

- 1st Layer
- Channels
- Film (f ≈ 20% of last layer)

E. Kolb, Transitional phenomena in oil mist filtration , EYEC, 2018

Film and channel model – efficiency of multilayer filter





Penetration (1 – efficiency) depends on:
- properties of fibrous structure
- saturation

For the sandwich of filtration layers (the same media) the total penetration:

$$P = P_1 \cdot P_2 \cdot P_3 \dots P_n$$

P_i's : "sectional penetrations"

→ Phobic sandwich of n layers:

$$P = P_{\mathrm{film}} \left(P_{\mathrm{channel}}\right)^{n-f}$$

→ Philic sandwich of n layers:

$$P = P_{1^{\mathrm{st}}\ \mathrm{layer}} \left(P_{\mathrm{channel}}\right)^{n-1-f} P_{\mathrm{film}}$$

where f is film thickness in % of single layer

E. Kolb, Transitional phenomena in oil mist filtration , EYEC, 2018

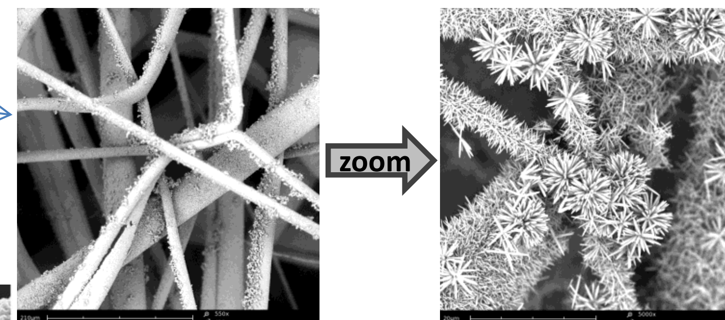
Modification of the filter media

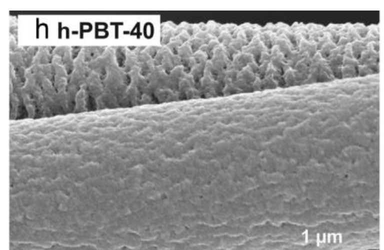
Methods (for polymer media):
- primary, i.e. at the stage of fibre formation
- secondary, i.e. coating of fibrous structure

Aim:
- change of wettability (obtain desired afinity with a liquid)
- antimicrobial properties (bacteria, algae, molds)
- catalytic/photocatalytic properties
- sorption (organics, metal ions)
- improve electric conductivity

Examples:

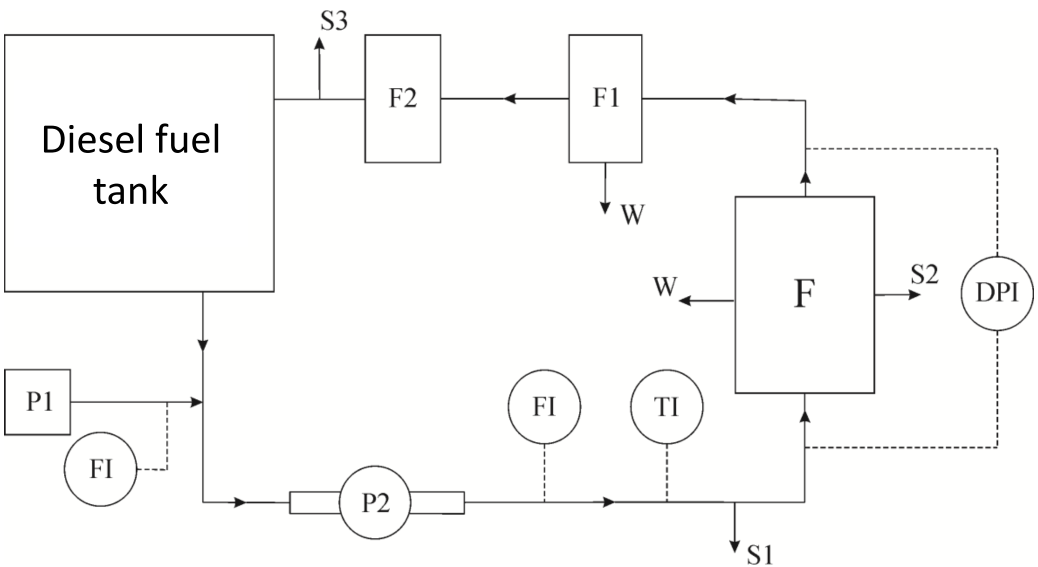
- Chemical additives to polymer matrix – prepare masterbatch or twin screw extrude (e.g. Halar®1400LC oraz FluoroLink® added to PP)
- ZnO needles deposited on the fibres (CBD)
- High-voltage electric field treatment of the molten polymer (during the production)
- Low temperature plasma treatment
- Hydrolysis of polyester fibre surface

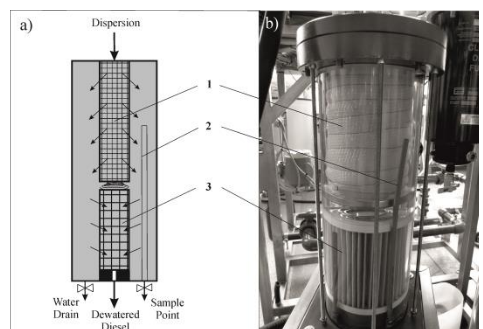




Chemical Engineering Science 2016, 146 , 104-114

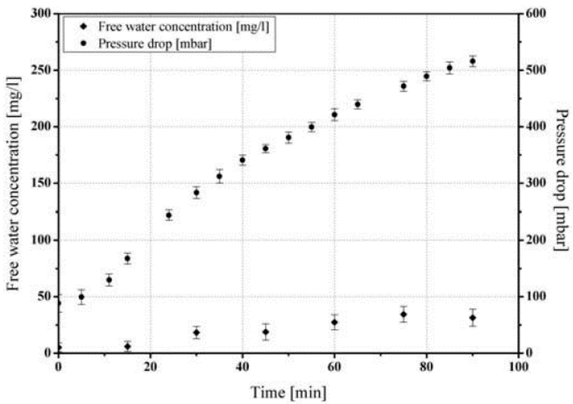
Experimental – test rig





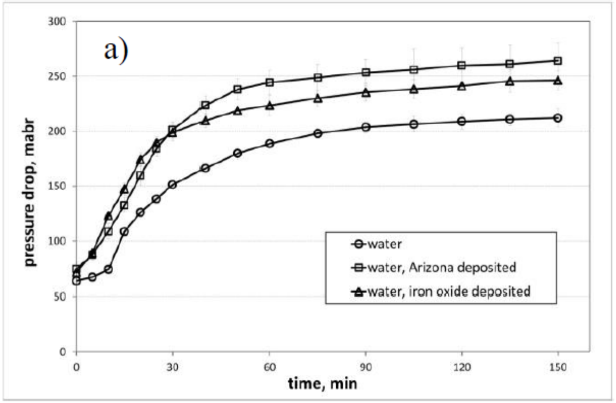
Experimental – some results

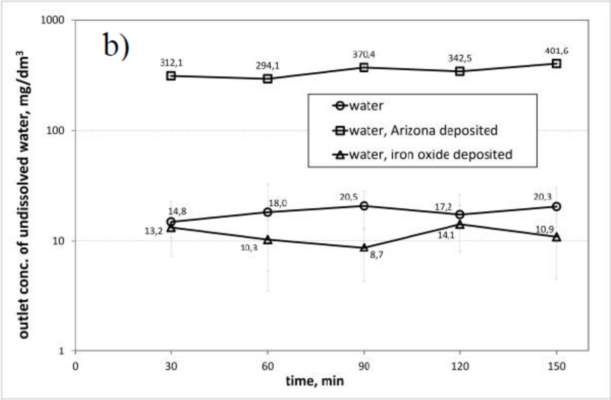
Perfectly water wetted fibreglass media



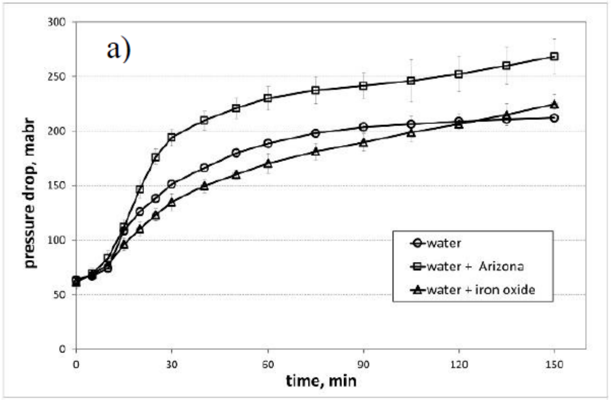
Effect of solids

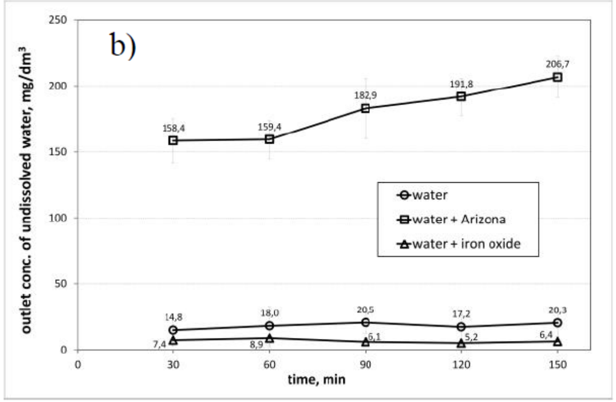
particles deposited in fibrous media before experiment





particles present in the emulsion (filtered during the process)



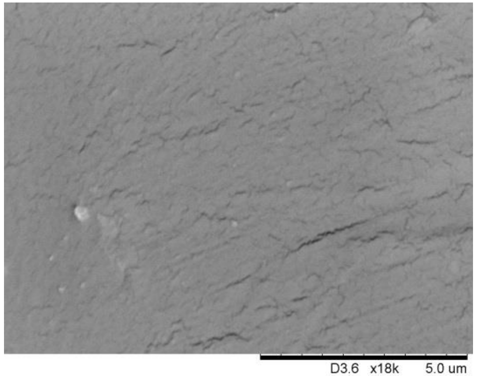


Experimental – some results

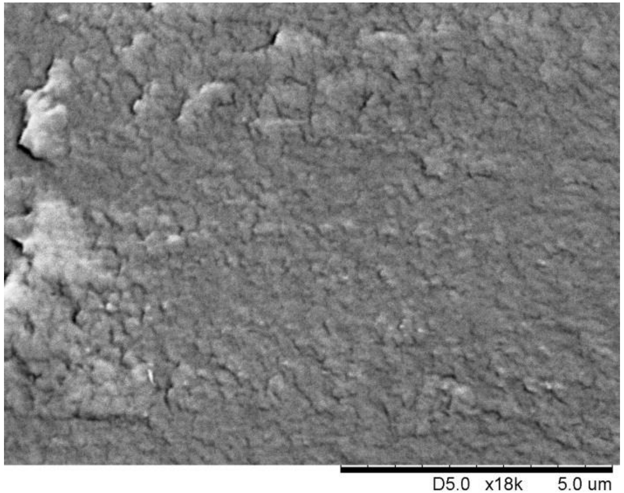
Effect of surface treatment (PBT native and modified with Ar/O_2 plasma)

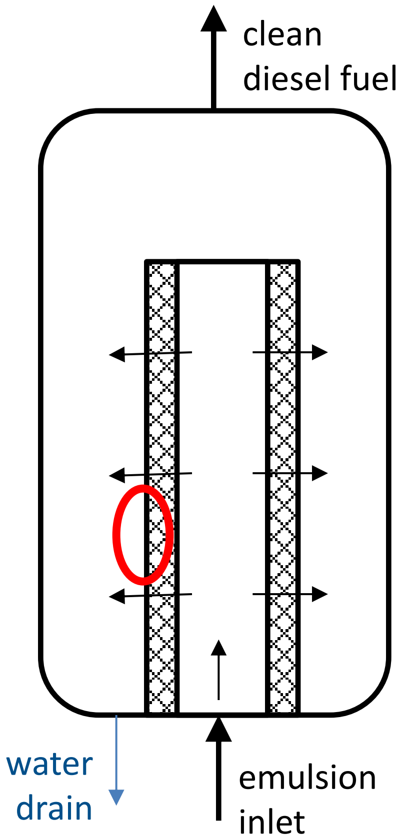
SEM images of the PBT fibers surface:

native (untreated)

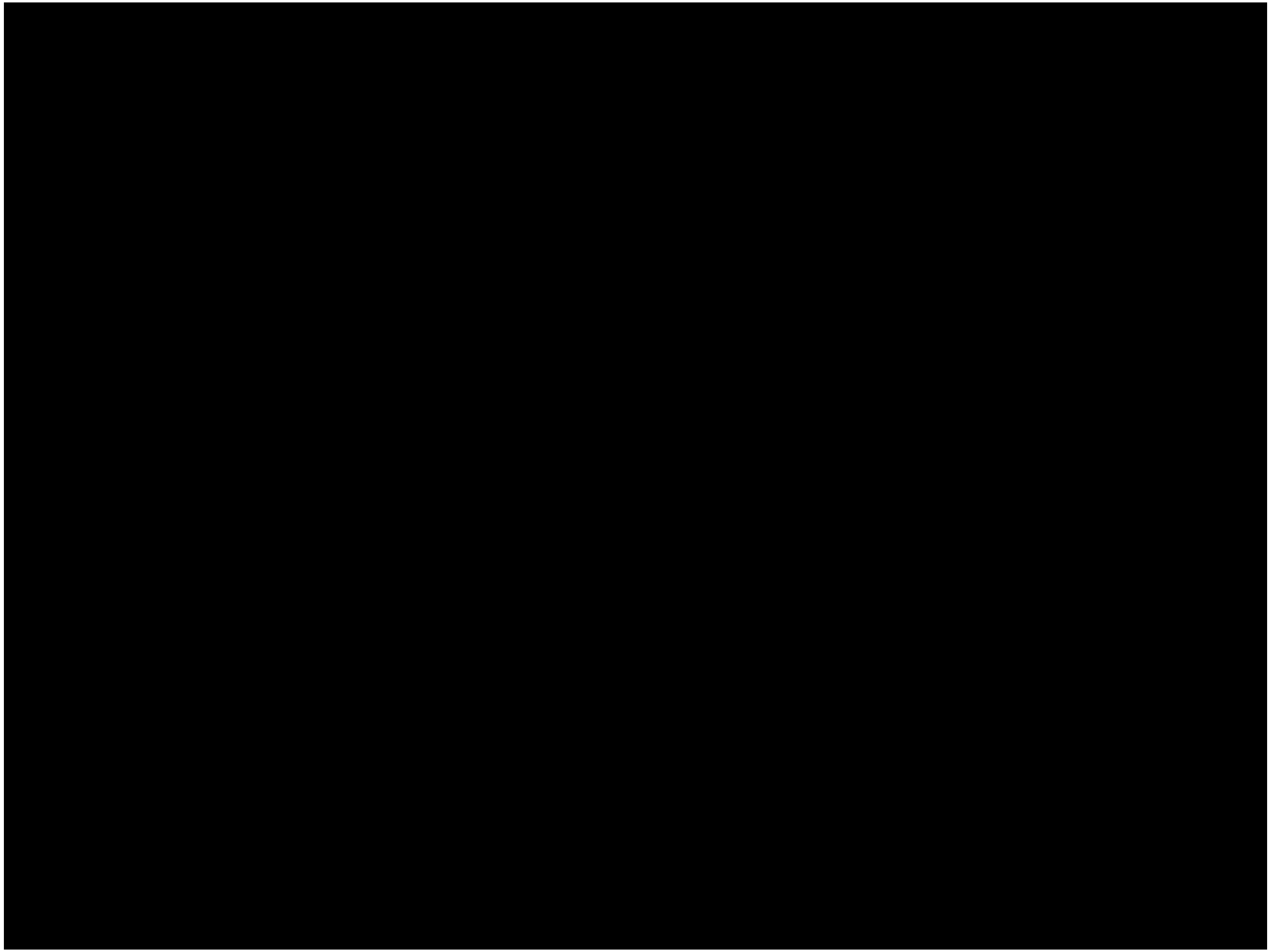


after plasma process in the O_2/Ar = 40/60 vol. gaseous mixture
(treat. time 1.5 min,
discharge power 50 W,
voltage -550V,
abs. pressure 1 mbar)

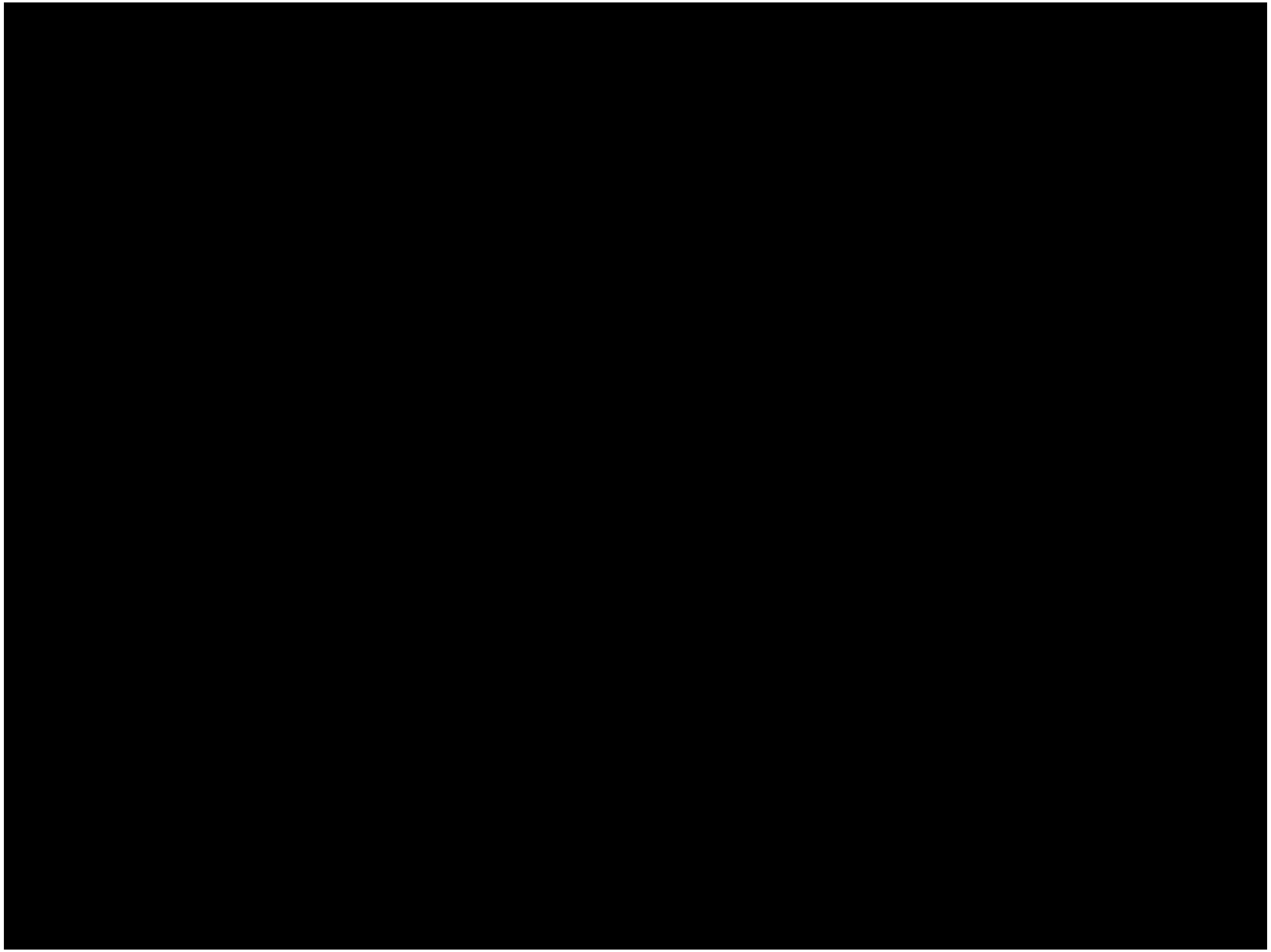




Experimental – untreated PBT



Experimental – plasma modified PBT



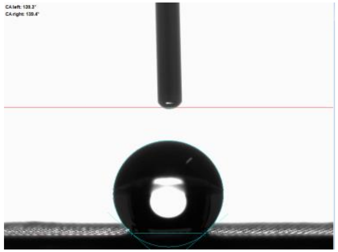
Experimental – drain layer design

Water deoiling (separation of O/W emulsion) – PP versus PA

Surface coalescence

COALESCER (I) **1. Increase size of droplet size upstream the separation**

SEPARATOR (II) **2. Separate the droplets by gravity or using te separation filter** (capillary forces)**:**



- apparent pore size, packing density, fibers size (specific surface area)
- phobicity of filter media with the dispersed phase (no wettability: superhydrophobicity for dewatering applications)
- improvement of self-cleaning abilities of separators (e.g. low adhesion to the surface + hydrodynamics)
- very low face velocity

dP < „capillary pressure”

Specific process: water removal from diesel fuel

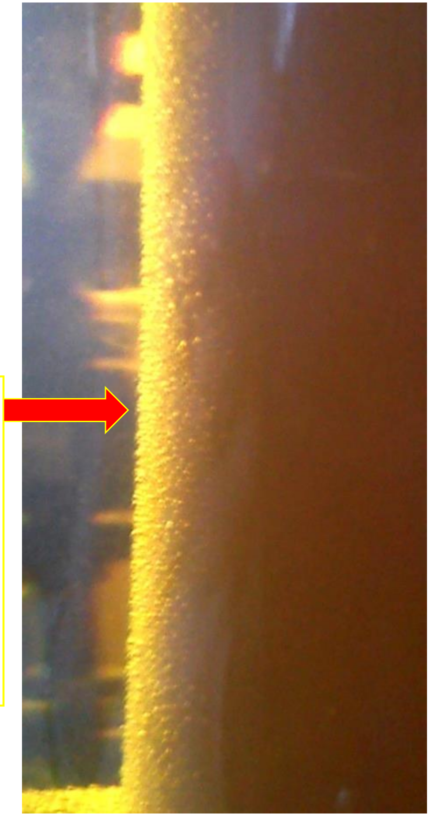
Origin of problems in recent years:

- ULSD
- FAME
- additives
- high quality of fuel necessary for CR injection systems

These led to:

- decrease of IFT value
  (clearly less than e.g. 15-19 mN/m as per SAE J1488)
- increase of viscosity
  (biodiesel blends – also vulnerability to bacteria growth)
- increase of water solubility

hydrophobic filtration surface „coated" by water droplets

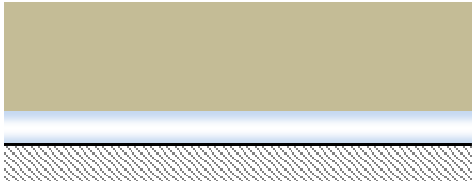


Hindered coalescence of water droplets, no drainage –

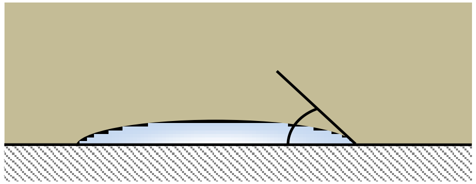
– accumulation of water on surface, above certain dP filter breakthrough

Wettability – surface properties determination

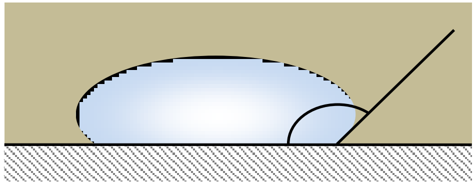
Static contact angle



High surface energy (and σ_{crit})
Good wetting (0º contact angle)

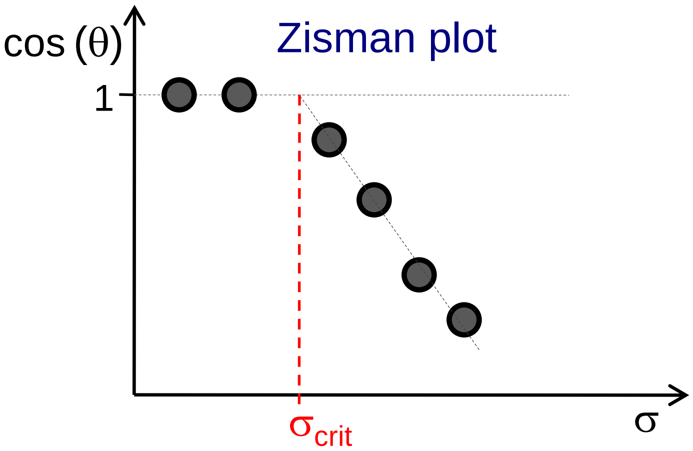


Wetting
(0º < contact angle < 90º)



Low surface energy (and σ_{crit})
No wetting (contact angle > 90º)

Critical surface tension



Serie of test liquid – homologs, e.g. n-alkanes, alcohols

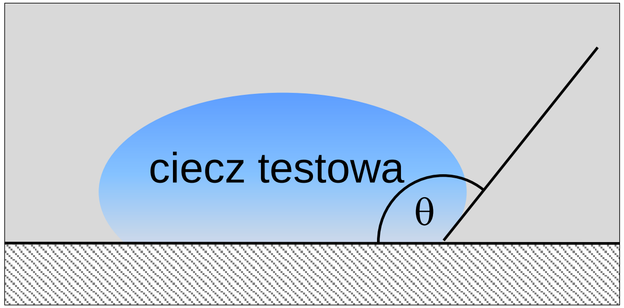
Free surface energy can be determined using one of following methods:

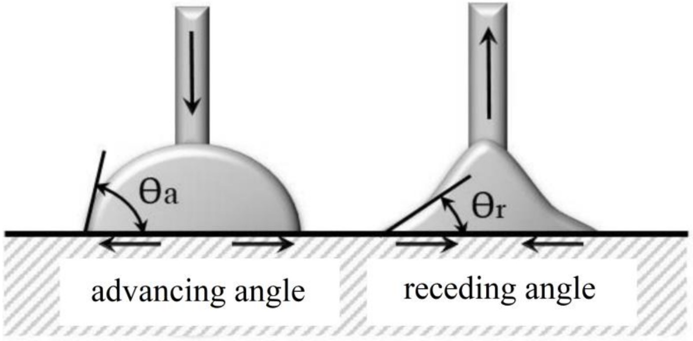
- geometric mean (based on *Fowkes eqn*)
- harmonic mean (method derived by *Wu*)
- acid-base method (*van Oss* and *Good*)

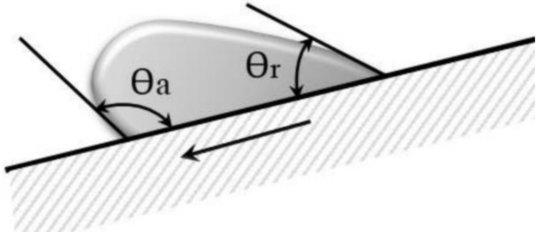
and few other methods

Wettability – determination of surface properties

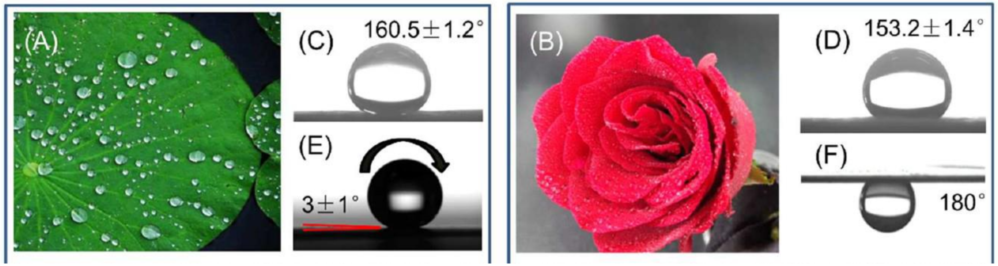
For water separators applied for dewatering of diesel fuel:
- hydrophobic surface (superhydrophobic θ > 150°)







A look into nature – superhydrophobic surfaces



Lotus leaf – low adhesion Rose petal – high adhesion

Ind. Eng. Chem. Res. 2017, 56, 907–919

$$\rho_k g V_k \sin(\alpha) = 2 R_{zw} k$$

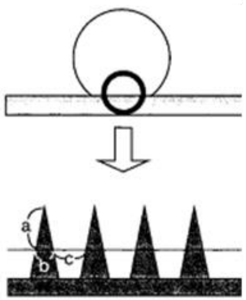
$$k = \sigma\left[\cos(\theta_r) - \cos(\theta_a)\right]$$

Modification of filter media applied for diesel fuel dewatering

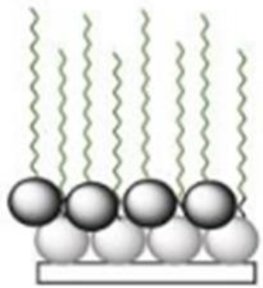
HIGHER HYDRPHOBICITY

Surface morphology (roughness)

Chemical composition



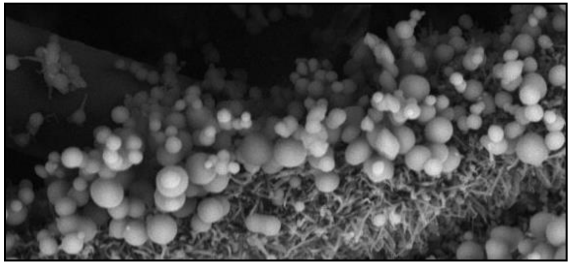
(Miwa et al., 2000)



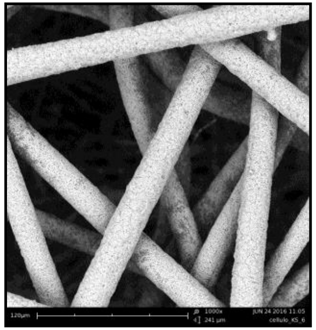
(Xue et al., 2011)

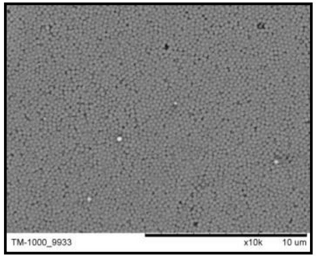
Chemical compounds with low surface energy,
e.g.: fluorocarbons, silicones, silanes.

Wenzel and Cassie-Baxter models – effect of the morphology



Fiber coated with aerogel particles

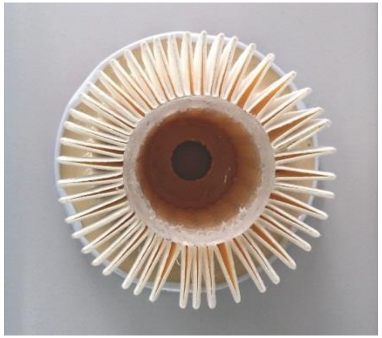




Fibers coated with silica particles

ACS Omega 2021, 6, 28, 18065-18073

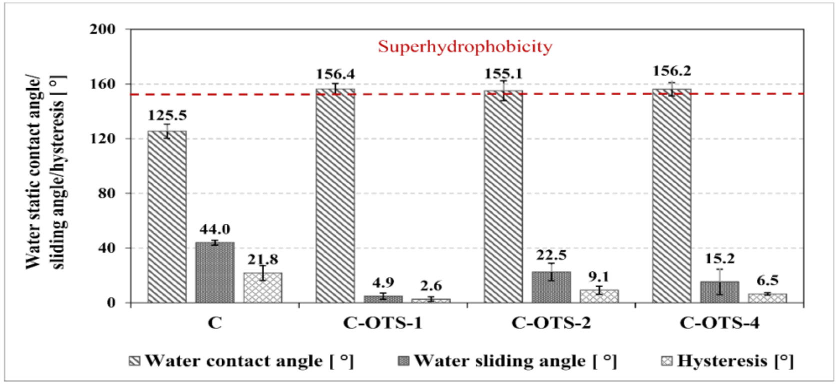
Some experimental results for OTS-coated separation media

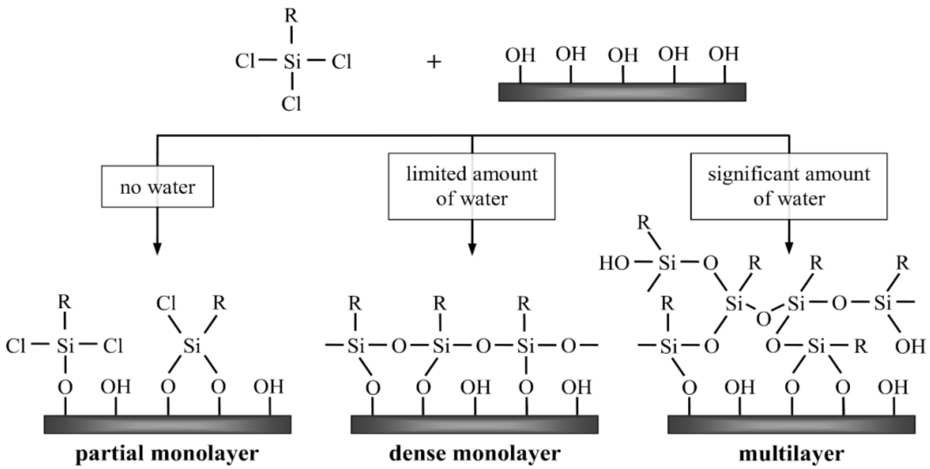


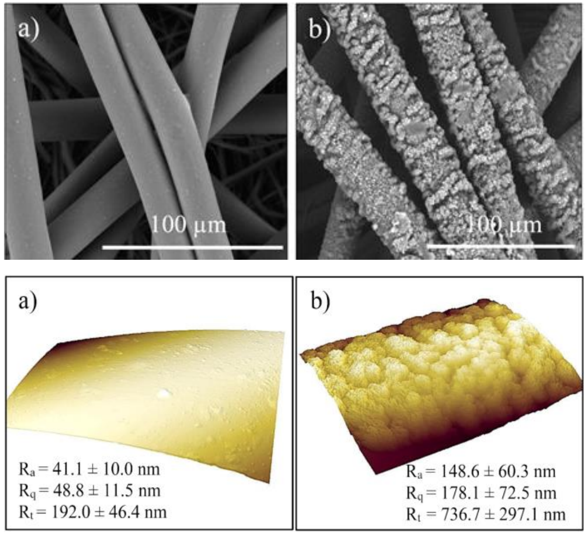
350 H/SM50 (Ahlstrom)

2 polyester prefiltration layerson the cellulose:
1) spun-bond PET
2) melt-blown PBT

Top view of the pleated separator







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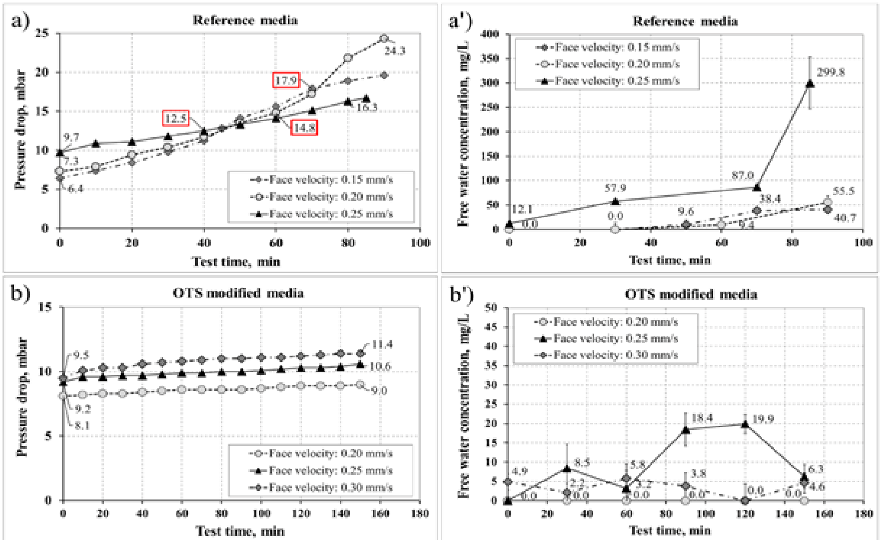
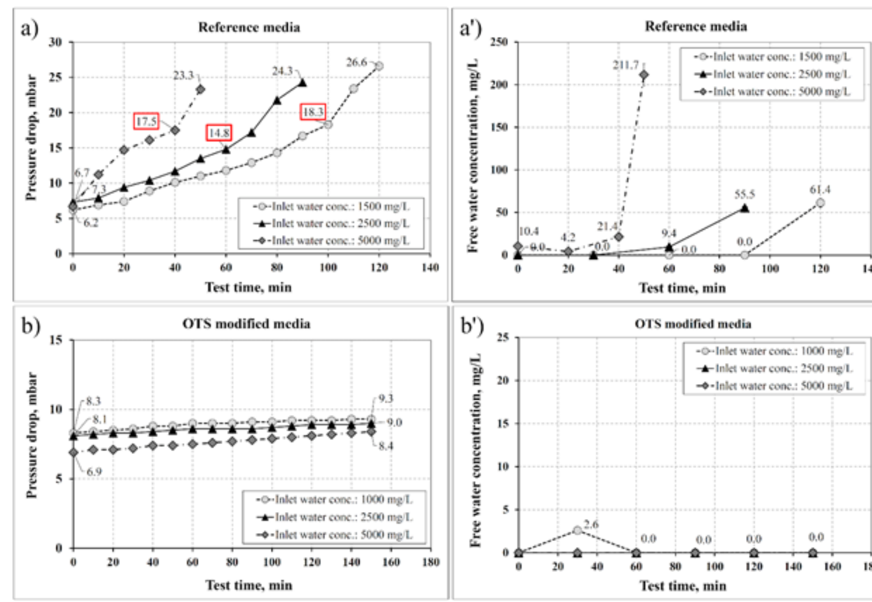
Some experimental results for OTS-coated separation media



The effect of the face velocity on the pressure drop and free water concentration on the outlet

The effect of the inlet water concentration



ACS Omega 2021, 6, 28, 18065-18073

Modelling the dynamic contact angles and droplet movement using CFD

Ongoing work of PhD student – Patrycja Jachimczyk (Wierzba)

Introducing a new relation for dynamic contact angles depending on force acting upon the „pinned” droplet

↓

Comparing the force (gravity component or drag) at the onset of motion

↓

Analysis of the droplets mobility depending on surface properties of filter media, droplet size and hydrodynamics at the surface

Measurements of CAs and roll-off angle for surface modified media

Development of UDF code, which will include:

- defining CAs at the interface
- pinning (i.e. immobilizing) the droplet
- extracting the CAa at the droplet symmetry plane
- calculating the total force acting upon the droplet

Modelling the dynamic contact angles and droplet movement using CFD

Thank you for your attention