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Water Filtration with Carbon Nanomembranes

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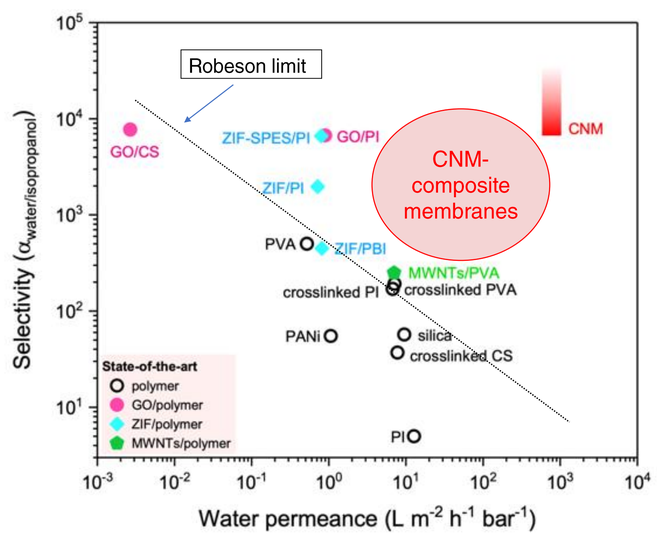
Motivation

Recently scientists at Bielefeld University demonstrated that nanometer-thin carbon nanomembranes (CNMs) made by cross-linking of self-assembled monolayers of aromatic molecules possess an extremely high pore density of one sub-nm channel per square nanometer [1]. Thus, this two-dimensional (2D) material combines an exceptionally high water permeance (~ 800 LMH) with close to full rejection of salts [2] and small organic molecules like urea.

The introduction of CNMs in composite membranes promises a hitherto non-attainable separation efficiency (high water flux, low operation pressure, removal of difficult materials, and high concentration factors in forward osmosis).

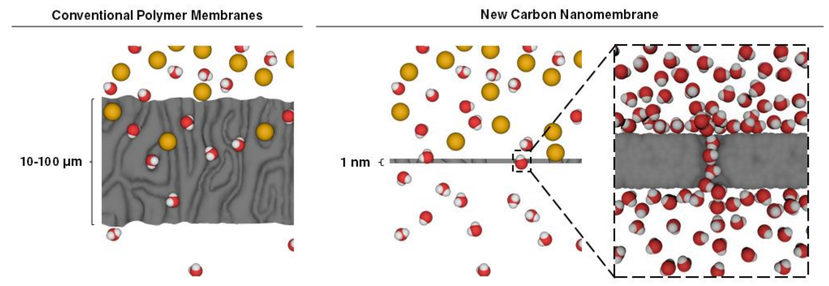


CNMs compare favourably to other membranes, which are limited by the trade-off between selectivity and permeance ("Robeson-limit").

Carbon Nanomembranes [3] - Basics and Principles

Properties of CNMs

- Carbon-based, polymeric 2D sheet material
- Approx. 1 nm thickness
- Intrinsic sub-nanometer porosity (1 pore per nm² or 40 % of membrane area)
- Controllable chemical functionalisation (even differently on both sides)
- Mechanically stable and withstand harsh conditions
- Manufacturing (from large area membranes to CMOS-compatible integration)
- CNMs are complementary to graphene, but can be transformed into high-quality sheet graphene



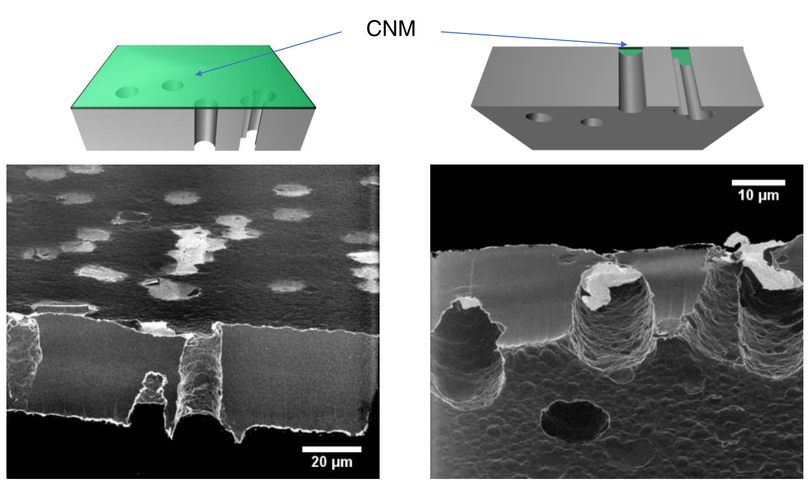
Separation uses differences in solubility and diffusivity between water molecules and solutes leading to dissimilar migration speeds resulting in different flux rates.
Problem:

- Trade-off between permeance and selectivity
- For effective filtration (high selectivity): low permeance
- Needs high pressures to achieve reasonable water fluxes

Water is transported - like in biological membranes - in a collective single file motion through sub-nanometer wide channels, which are then blocked for other species.
Advantage:

- Up to 1.000 times higher permeance
- Close to full rejection of all other species
- Less fouling due to low operational pressures

CNM-Composite Membranes

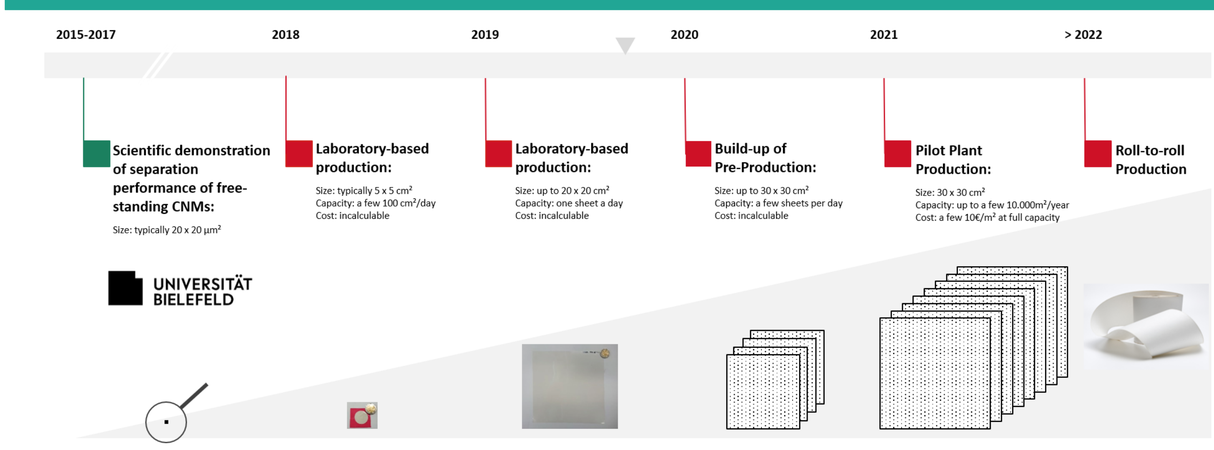


Helium Ion Micrographs of cross-sections of CNM-composite membranes.

We have succeeded in implementing nanometer-thin CNMs as active layers in large-area composite membranes These consist of a track-etched polymer (e.g. PET) support layer with pores in the micrometer-range giving access to the free-standing active CNM-layer.

These composite membranes are mechanically stable and can be mounted in modules. Depending on the pore size of the support layer, they can withstand pressure differences of more than 10 bar.

Membrane Production



Currently, we can produce membrane sheets with areas of up to 20 x 20 cm² in the laboratory. A concept for a batch-based pre-industrial pilot production with a capacity of up to several 10.000 m² is in place. We have conducted tests with equipment manufacturers to show the viability of the manufacturing approach, which can ultimately be expanded to a roll-to-roll production

Forward Osmosis with CNM-Composite Membranes

In this model experiment, we demonstrate the use of our CNM-based composite membranes in cold concentration of watery solutions by forward osmosis. The two volumes are separated in the middle by a CNM-based composite membrane. A concentrated NaCl solution (5M) is on the right-hand side. Nature's quest for balance causes water to flow from the low-concentrated liquid on the left-hand side and concentrate it - without any further energy input.

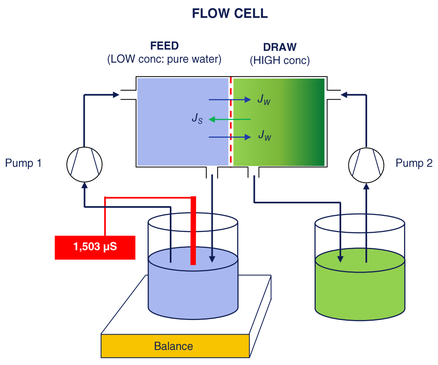
The time-lapse videos (duration between 30 min and a few hours) show some examples of the multitude of mixtures that can be concentrated with this technique in an energetically favourable way and without significant changes to their ingredients. For this simple demonstration we used no convection of the liquids on the two sides and no optimised draw solution.

See the full movie on
http://www.cnm-technologies.com/en/applications/membrane-technology/osmosis.html

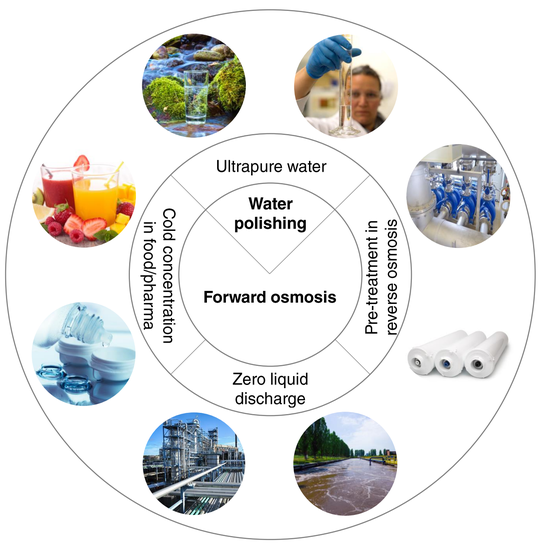
Setup for quantitative characterisation

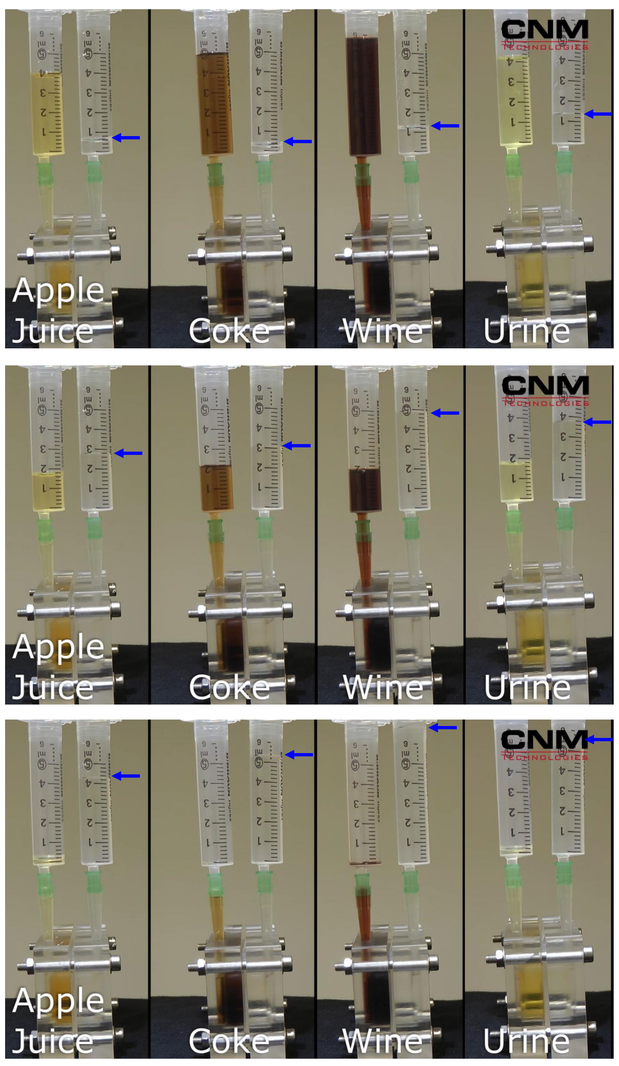
The water flow J_W is determined via the weight loss of the feed reservoir. The salt flow J_S is determined by the change of conductivity of the feed solution.

- Permeation: ~ 20 lm^{-2}h^{-1} at 1M NaCl
- Reverse salt flow: < 1 gl^{-1}



Applications





Further Applications of CNMs

Carbon Nanomembranes are a platform technology with a huge variety of applications

Electronics
- Sensor technology
- Semiconductor manufacturing
- Flexible electronics
- Displays

Energy
- Capacitors
- Batteries
- Fuel cells
- Electrolysis

Medicine
- Diagnostics, lab-on-a-chip
- Dialysis
- Tissue engineering
- Next generation sequencing

Nanotechnology
- TEM-/SPR-sample holder
- Nano tribology
- Nano fluidics
- Nano electromechanical systems (NEMS)

Please don't hesitate to contact us with your ideas.

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[2] Y. Yang, R. Hillmann, Y. Qi, R. Korzetz, N. Biere, D. Emmrich, M. Westphal, B. Büker, A. Hütten, A. Beyer, D. Anselmetti, A. Gölzhäuser, *Ultrahigh Ionic Exclusion through Carbon Nanomembranes*, Advanced Materials 32, 1907850 (2020).
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