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Computational fluid dynamic analysis of concentration polarization and water flux optimization in spiral wound modules

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Introduction:

In membrane separation spiral wound modules (SWMs) are a common design due to their high membrane area to volume ratio. In addition SWMs offer a good balance between ease of operation, fouling control, permeation rate and packing density and SWMs are widely used for commercial applications ranging from reverse osmosis (RO) to ultrafiltration.

A common application is RO-based desalination. Systems of SWMs scale with the number of modules, thus making them popular for large treatment plant designs. The typical module sizes, referring to the module diameter, are 2.5", 4" and 8". There is a considerable interest in making even bigger modules, as water treatment cost could be cut considerably, but experiments with 16" prototypes showed very poor performance[1]: The long membrane envelopes and the resulting large pressure drop lead to higher concentration polarization (CP), reducing the modules performance. Through the application of more membrane envelopes and turbulence promoting spacers, a module could be optimized, but due to the tight packing, local measurements of the flow field and the solute concentration distribution are very difficult to conduct[2].

SWMs have also recently attracted interest in the design of forward osmosis (FO) membrane modules, and recent progress in FO membrane development has led to a growing interest in using FO membranes in hybrid FO-RO systems. Here low salinity waste water is used as a feed solution, which dilutes sea water through FO. The subsequent RO desalination is less energy consuming and shows a smaller fouling tendency, compared to a stand-alone RO desalination. But economic assessments of the FO-RO systems show a need for more effective FO modules[3]. As FO is an osmotic driven process, the pressure drop along the module is crucial for the modules performance. The implementation of turbulence promoting spacers in the feed channel reduces the CP but also increases the module's pressure drop.

Thus for both RO and FO SWM design a complete 3D computational fluid dynamic (CFD) model would be very beneficial for the design of modules and plants[2]. However, so far no CFD models of SWM modules capable of resolving the pressure drop dependency on the choice of spacer has yet been developed[3].

In the following, we present our design of a CFD model capable of resolving the flow field and solute concentration- and pressure distribution for an entire SWM. Once fully developed, it will be applicable for optimizing performance in both RO and FO applications.

Method:

The underlying method was presented in Gruber et al.[4]. It is the implementation of a fluid solver and a boundary condition, that acts as a membrane. With the parameters water- and solute permeability and the solute resistivity of the porous layer, the model resolves the flow field, the solution concentration- and pressure distribution in the flow domain, and the boundary effects of external- and internal CP, but only for flat membrane sheets.

The first step in the development of a complete SWM is the further development of the above mentioned CFD model to also work with wound membrane boundary conditions. The major challenge in developing a complete spiral wound CFD model is the simplification of the module geometry, such that modern high performance computers can simulate the flow in reasonable time. This is met by making use of the symmetry of the model: It is sufficient to only simulate one membrane envelope and the adjacent feed channel on either side. In fact, by defining a periodic boundary in the middle of the feed channel, only half of the feed channel is simulated on either side (**Fig.1**). These periodic boundaries are crucial to model development. They copy the flow field at the boundary to their respective partner boundary, as if another membrane envelope was adjacent to it. Thus, only a small part of the whole module is simulated, without cutbacks in the resolution of the results.

The RO SWM is based on pressure driven transport in the envelope but for FO, a flow channel needs to be created. This is achieved by pressurizing the feed inlet and implementing a baffle across ~3/4 of the length of the draw channel, forcing the draw solution stream over the membrane surface (**Fig.2**).

With this model both FO and RO SWMs will be investigated and optimized with respect to spacer geometries, amount of envelops and baffle geometries.

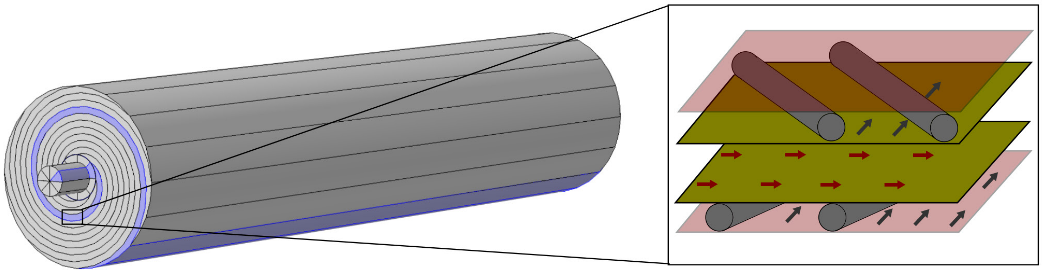

Figure 1. Sketch of the geometry of the spiral wound membrane module, with the actual computational domain highlighted in blue and a detailed sketch of the computational domain. The green surfaces are the respective membranes of the envelope. Between them, the flow field of the permeate (RO) or draw solution (FO) is indicated by the red arrows. Outside the envelope half of the feed channel is added to either side of the envelope. The grey cylinders represent the feed spacers and the black arrows indicate the feed solution flow field. The red-transparent surfaces are the crucial part of the model: They represent a pair of periodic boundaries in the middle of the feed channel.

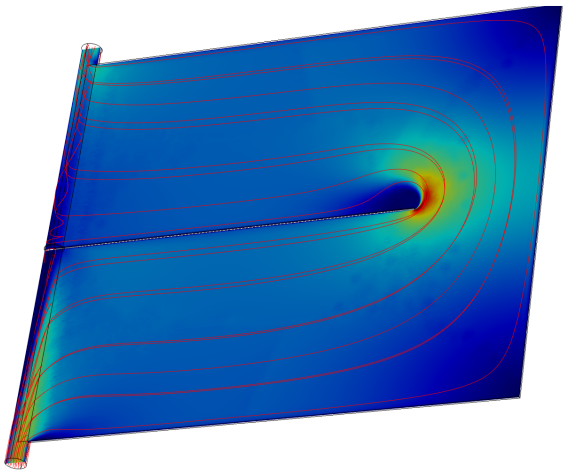

Figure 2. Flow field in the draw channel of one unrolled envelope in FO operation: Through implementing a baffle across ~3/4 of the length of the envelope and pressurizing the feed tube inlet, a channel is created and the spiral wound membrane module can be operated in FO.

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Research interests: development of computational schemes for particle transport in fluids and the application of these for the design of membrane modules