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Modelling mass transport in hollow fibre membranes used for pressure retarded osmosis

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ABSTRACT

The principle of PRO is to utilise parts of the free energy of mixing when mixing freshwater with seawater for production of electrical energy. The mixing process takes place over a semi permeable membrane that will retain salts, and ideally allow only transport of water. The transport of water will occur due to differences in chemical potential across the membrane. The PRO process will be operated with elevated pressure on the seawater side of the membrane, and the net increase in volume due to osmotic transport of water across the membrane, can be utilised to run a turbine and hence produce energy.

At present the biggest challenge in PRO is to develop membranes with sufficient specific power. This challenge involves optimisation of the basic membrane characteristics, *i.e.*, high water permeability (*A*), low salt permeability (*B*) and low structure parameter (*S*).

In this paper a transport model for water and salt in hollow fibres in PRO has been developed. Further, a structure parameter equivalent to the structure parameter for flat sheet membranes has been defined. The impact of the membrane parameters (*A*, *B* and *S*) on PRO performance in a hollow fibre element has been demonstrated by applying iso-watt diagrams. In general, for a given structure parameter *S*, increasing the *A* value and decreasing the *B* value will increase the specific power. It was also found that if the salt permeability exceeds a certain level, a further increase in the water permeability will not result in a corresponding increase in the specific power. Similarly, if the water permeability is lower than a certain level the effect of increased salt permeability will be low.

Further, the PRO performance of different hollow fibre membranes has been estimated using the iso-watt diagrams. Based upon the reported membrane characteristics the PRO performance for the selected membranes ranges from less than 1 W/m^2 to above 4.5 W/m^2. The membranes having a specific power around 4.5 W/m^2 are promising candidates for future PRO plants, given that these membranes can tolerate the typical operation pressure in a PRO plant of 12–14 bar.

1. Introduction

Osmotic power is a renewable energy resource that has gained increasing attention during the recent years. The opening of Statkraft's pressure retarded osmosis (PRO) prototype at Tofte in Norway in November 2009 can be considered an important milestone in the development of this technology [1]. The energy potential has been estimated to give a significant contribution to the power production world-wide, where the latest estimate is approximately 1700 TW h [2,3].

One major challenge for future utilisation of osmotic power is that the mixing process is encumbered with low energy density (J/m^3 freshwater). As a result, a rather large membrane area will be required even for modest capacity plants. Presuming a net specific power of 5 W/m^2 membrane area, which corresponds to the target value for spiral wound elements stated by Statkraft, a 25 MW plant will require five to six million square meters of membrane [2,4]. For the hollow fibre configuration the target values for maximum specific power can possibly be reduced by approximately 50% [4]. Another implication of the low energy density of the mixing process will be the requirement for large water volumes. For the 25 MW plant the demand of freshwater and seawater will be in the range of 25 m^3/s and up to 50 m^3/s, respectively. This obviously results in the need of high efficiency and low hydraulic losses for all process units in the PRO plant [4].

The development of membranes with sufficiently high specific power is presently assumed to be the biggest challenge in PRO. Thorsen and Holt [4] discuss that the PRO process will require a

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membrane with low structure parameter (S), in addition to high water permeability (A) and low salt permeability (B). The structure parameter is defined as the ratio between tortuosity and porosity multiplied by the thickness of the membrane, and can be regarded as a measure of the effective diffusion length in the support structure. The excessively high structure parameter which has been measured for commercial RO membranes is identified as the main explanation why they perform inadequately in PRO [4]. Today only a few membrane companies, including *e.g.,* Hydration Technology Innovations (HTI), offer commercial forward osmosis (FO) membranes. The FO membrane from HTI is an asymmetric cellulose acetate membrane supported by an embedded polyester mesh. At present, several membrane environments spend significant effort to improve performance of FO/PRO membranes [5–15].

Both hollow fibres and flat sheet membranes can be applied in PRO [16]. The two configurations have different advantages and disadvantages in consideration of *e.g.,* specific power, production costs, packing density, pressure loss, fouling propensity and cleaning ability. The preferred configuration are still under evaluation [4]. Hollow fibres comprise an interesting alternative to spirals due to several characteristics. The higher packing density normally obtained in hollow fibre elements may result in a relaxation in the target value for specific power compared to spiral wound elements. This is beneficial from a membrane development perspective, but also from an operational view where a lower flux may result in less fouling propensity. Further, PRO presupposes cross flow on both sides of the membrane. Cross flow operation will require less modification of existing hollow fibre elements compared to the modifications required for the conventional spiral wound elements.

SINTEF and Statkraft have pursued both configurations. Testing facilities for characterisation of membrane characteristics in terms of A, B and S have been developed for both flat sheet and hollow fibre membranes. The work also includes the development of a model framework for the two mentioned module configurations. This paper will however focus on mass transport in hollow fibre membranes and presents a transport model for estimating the concentration profile over such membranes. A comparison with the previously developed transport model for flat sheet membranes is also given. Further, we link the PRO performance result to the structure parameter, S, that initially was developed for a flat sheet membrane. The impact of the structure parameter on power production will be demonstrated, and the concept of iso-watt diagrams will be introduced.

Our first priority is to harvest energy using seawater, but in the following the term *salt water* will be used to emphasise that the model is general and not specific to seawater.

2. Theory

In PRO water will be transported against a pressure gradient due to difference in osmotic pressure, and the net volume increase on the salt water side can be converted to power in a turbine. A simplified flow diagram for the PRO process is shown in Fig. 1.

The produced power, P, can be expressed with the equation

$$P = J_v \Delta p \tag{1}$$

i.e., volume flux, J_v, times pressure difference, Δp, over the membrane. Since the water flux in PRO will decrease as the pressure difference increases, the produced power will have a theoretical optimum at half the osmotic pressure difference. In order to predict the power production in PRO, it will be essential to estimate the water flux through the membrane for various temperatures and salt water concentrations. Thus, a model framework describing the transport of salt and water through the membrane will be required. Further, for hollow fibres the model must account for the circular shape of the membrane and hence describe the transport in cylindrical coordinates.

2.1. Membrane mass transfer in cylindrical coordinates

Fig. 2a shows the cross section of an ideal hollow fibre bundle with identical distance between all neighbouring fibres. The hexagonal arrangement has been applied to define the free cross sectional area surrounding each fibre to correspond to the area of the hexagon minus the area of the fibre itself. Thus, the characteristic dimensions describing the fibre are the inner and the outer diameter of the fibre, the thickness of the freshwater and salt water boundary layers, and the radius of the free cross sectional area surrounding the fibre, $r_o + h_s$ ref. Fig. 2b. Further, Fig. 3 defines the concentration profile over a hollow fibre and relates the concentration to the radial position. Also note that the water flux is defined to be positive in the direction from the freshwater side to the salt water side, whereas the salt flux is defined to be negative in the same direction.

The mass transport of salt in the membrane support, and in each of the boundary layers, will equal the sum of the convective

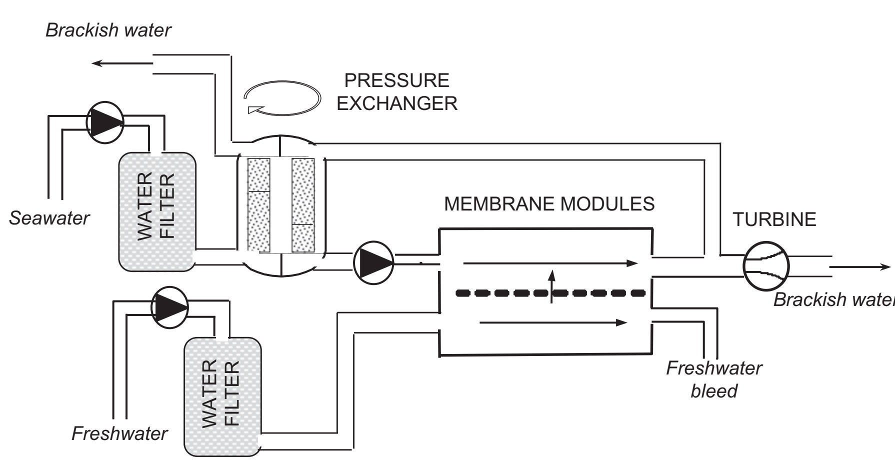

Fig. 1. The PRO process.