Journal of Membrane Science 489 (2015) 299–307

Contents lists available at ScienceDirect

Journal of Membrane Science

journal homepage: www.elsevier.com/locate/memsci

Iso-watt diagrams for evaluation of membrane performance in pressure retarded osmosis

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ARTICLE INFO

Article history:
Received 20 October 2014
Received in revised form
17 April 2015
Accepted 18 April 2015
Available online 2 May 2015

Keywords:
Osmotic power
Pressure retarded osmosis (PRO)
Specific power
Iso-watt diagrams

ABSTRACT

Pressure retarded osmosis (PRO) is one feasible technology that can be used to exploit the mixing energy from salt gradients which is commonly referred to as salinity gradient power or osmotic power. This paper focuses on the construction of iso-watt diagrams and their application for detailed evaluation of specific power in PRO on basis of membrane characteristics and site specific design parameters. Iso-watt diagrams are demonstrated to be a useful tool for investigation of the effect of variation in the membrane parameters, *i.e.* the water permeability, the salt permeability and the structure parameter, and how mutual changes in the characteristic parameters will impact the PRO performance. Thus, iso-watt diagrams can be considered an effective aid for goal-oriented membrane development. In addition, iso-watt diagrams can be considered to be useful also with respect to design related aspects, such as *e.g.* site selection. Further, membrane performance data are reported in the literature for various experimental conditions, which makes direct comparison difficult. The use of iso-watt diagrams enables an efficient way of presenting and comparing the efficiency of different membranes. This is demonstrated in the current paper for ten states of the art membranes.

1. Introduction

Pressure retarded osmosis (PRO) is one feasible technology that can be used to exploit the mixing energy from salt gradients which is commonly referred to as salinity gradient power or osmotic power [1,2]. In PRO the transport of water through the membrane is caused by the difference in osmotic pressure across the membrane skin, and the net volume increase on the high saline side due to mass transport against a pressure gradient can be utilised to run a turbine.

In order to optimise the specific power output (W/m^2) a PRO power plant will be operated close to half the osmotic pressure difference between the two solutions. Thus, the maximum energy that can be utilised is limited to 50% of the theoretical reversible mixing energy, which is estimated to 2.7 kJ per kg of freshwater mixed with an excess of seawater [1,3]. Additional frictional losses in membranes, piping, pressure exchangers and pumps will reduce the exploitable energy further to approximately 40% of the theoretical value. The exploitable power from mixing of river water with seawater is estimated to approximately 1700 TW h worldwide per year [4]. The power potential from other PRO concepts utilising different feed sources will add to this figure. Closed loop PRO and PRO based on seawater and brine from RO desalination plants are examples of concepts that will contribute to the total exploitable potential of the technology.

The semipermeable membrane controlling the osmotic mixing process can be considered the heart of the PRO process. The PRO membrane is characterised by three parameters, the water permeability, *A*, the salt permeability, *B*, and the structure parameter, *S* [1]. The parameters need to be optimised in order to maximise produced power, implying that the water permeability should be high and both the salt permeability and the structure parameter should be low. However, as both the water and salt permeabilities are skin properties they cannot be optimised independently. The structure parameter reflects the thickness, porosity and tortuosity of the support (and backing) of the membrane, which are properties that will affect both the mechanical strength of the membrane as well as the transport resistance through the support structure.

In earlier work [5] we briefly presented the concept of iso-watt diagrams in relation to investigations of the interplay between the characteristic membrane parameters *A*, *B* and *S*. The objective of the present work is to present the concept of iso-watt diagrams in more details and how such diagrams can be easily constructed in order to visualise the mutual impact of *A*, *B* and *S* on the PRO

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http://dx.doi.org/10.1016/j.memsci.2015.04.042
0376-7388/

performance. The resulting effect on membrane performance by changing each of the membrane parameters will be discussed. Furthermore, the paper illustrates the benefit of using iso-watt diagrams as an aid to membrane development.

2. Theory

The produced power, P, in a PRO process can be calculated as the product of the volume flux J_V through the membrane multiplied with the hydraulic pressure difference over the membrane Δp, where the volume flux can be assumed to be identical to the water flux, J_w.

$$P = J_w \Delta p \quad (1)$$

The water flux in PRO will decrease as the pressure difference increases, whereas Eq. (1) shows that the produced power increases with increasing pressure difference. Thus, an optimum pressure difference exits and it can be shown that the theoretical optimum correspond to a pressure difference equal to half the osmotic pressure difference [1].

Several model frameworks describing the transport of salt and water through the PRO membrane have been developed [1,6–10]. The present work is based on the transport model developed by Thorsen and Holt [1], where the mass transport through the membrane skin is described by the flux equations

$$J_w = A(\Delta\pi_{skin} - \Delta p) \quad (2)$$

and

$$J_s = -B\Delta c_{skin} = -B(c_{sm} - c_p) \quad (3)$$

where J_s is the salt flux, $\Delta\pi_{skin}$ is the osmotic pressure that corresponds to the concentration difference ($\Delta c_{skin} = c_{sm} - c_p$) of salt over the membrane skin, A is the water permeability, B is the salt permeability, and c denotes the concentration of salt.

The osmotic pressure can be expressed using van't Hoff relationship, *i.e.*

$$\pi = iRTc \quad (4)$$

where R is the ideal gas constant and T is the absolute temperature. The factor i includes deviations from ideal NaCl solutions, and have been determined from the literature data to 1.9 for NaCl solutions in the concentration rage relevant for river water/seawater PRO [11].

A typical concentration profile over a thin film composite membrane is shown in Fig. 1. The water flux is defined to be positive in the direction from the feed side to the draw side, whereas the salt flux is defined to be negative in the same direction. The mass transport of salt in the membrane support and the boundary layers will equal the sum of the convective and diffusive transport of the salt. By integrating the resulting mass balances for each of the boundary layers and the membrane support, it can be shown that the concentration over the skin can be expressed by [1,5,12]:

$$\Delta c_{skin} = \frac{c_s - c_f e^{((S + d_s + d_f)J_w/D)}}{e^{(d_s J_w/D)} + \frac{B}{J_w}\left[e^{((S + d_s + d_f)J_w/D)} - 1\right]} \quad (5)$$

where c_s is the bulk concentration on the draw side, c_f is the bulk concentration on the feed side, D is the salt diffusion coefficient, d_s is the boundary layer thickness on the draw side, d_f is the boundary layer thickness on the feed side. The structure parameter, S, is defined as:

$$S = \frac{\tau}{\phi}\Delta x_{mem} \quad (6)$$

where φ is the porosity, τ is the tortuosity and Δx_{mem} is the thickness of the support membrane [1]. It should be noted that the structure parameter resembles the effective diffusion length through the membrane support and will reflect the resistance to mass transfer caused by the membrane support. Further, an important aspect with Eq. (5) is that it relates the salt concentration difference over the membrane skin to the bulk concentration in both water sources, as well as to the mass transfer resistance in both boundary layers and in the membrane support.

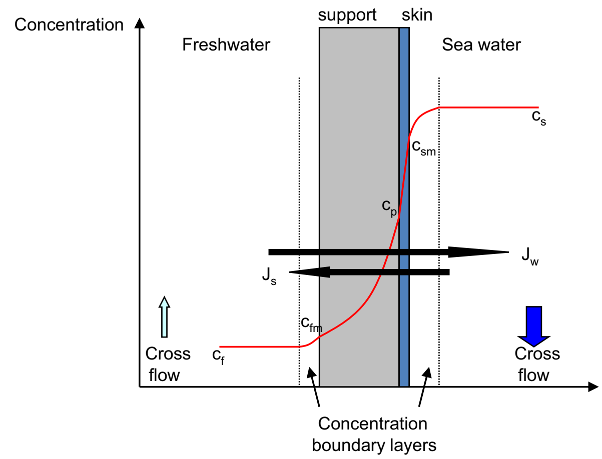

Fig. 1. Concentration profile over the membrane and boundary layers [1].

A similar transport model was developed for radial geometry aiming to take into account the circular cross section of a hollow fibre membrane [5]. It was shown that the model for a radial geometry converged with the model developed for a flat geometry (the one presented here) when the radius of the fibre increased. Further, it was shown that the flat sheet model could also be used for hollow fibres if an equivalent thickness of the fibre was used in the determination of the structure parameter. Hence, even though the presented iso-watt diagrams in this study are based on the flat sheet model only, they will be applicable for hollow fibre membranes as well.

3. Results and discussion

3.1. Construction of iso-watt diagrams

3.1.1. Iso-watt diagram

The overall objective with iso-watt diagrams is to enable a rapid and simple evaluation of the performance of different PRO membranes just by knowing the characteristic membrane parameters. An iso-watt diagram displays the mutual relationship between the membrane parameters, and the resulting effect in power performance by changing any of the parameters can be easily illustrated. Each diagram will be valid for a given condition defined by temperature as well as the salt concentration in the draw solution and feed solution, respectively. Further, since interpretation of three dimensional plots can be challenging, we have additionally chosen to keep the structure parameter constant for each iso-watt diagram. The resulting diagram displays the different combinations of water (A) and salt (B) permeabilities corresponding to a certain power performance, which are indicated by contour lines.

Fig. 2 shows an example of a iso-watt diagram with three contour lines, representing combinations of A and B that correspond to a power performance of 2.0, 4.0 and 6.0 W/m^2, respectively. The iso-watt diagram is constructed for a structure parameter equal to 0.6 mm, a draw solution concentration equal to 0.48 M, no salt in the feed solution and a temperature of 20 °C.