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A new concept for an osmotic energy converter

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SUMMARY

A new concept for an osmosis power generation system is presented. While the power production of a conventional system is based on continuous, increasing volumetric flow of solution directed to a turbine, the new concept is based on the pressurizing of fluids by osmosis. Two different new concepts were studied. In the first case, the osmotic module consists of the osmotic membranes, fresh water and solution. In the second case, gas is included in the solution part of the module. Consequently, the new system without gas was found to result in more than 2.5 times higher power values than the conventional concept. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS: osmosis; power generation; thermodynamics; flow inside hollow fibres

1. INTRODUCTION

Available energy can be extracted by the mixing of fluids of different composition. If the mixing occurs at a constant temperature and pressure, the maximum theoretical work delivered by an energy converter equals the difference in Gibbs energy between the initial and final states of the fluids. One possible way to extract this energy is based on the usage of an osmotic membrane. An application frequently considered is the placing of an ocean–river water plant at an estuary, enabling the use of large reservoirs of solution (salty ocean water) and fresh water (river water).

In an osmosis power generating system, solution and fresh water are directed to different sections of an osmotic module. The solution and fresh water are separated from each other by a semi-permeable membrane. Owing to osmosis, the fresh water penetrates through the membrane and mixes with the solution. In a conventional model, the solution is first pressurized, for instance by pump, and directed into the module. The pressurized, continuous volume flux of solution increases due to osmosis and is directed to a turbine. Owing to the losses in the module, the pressure drops. As the flow past the turbine is higher than the flow past the pump, it is

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possible, despite the pressure losses, to achieve net power from the conventional system. In contrast to the conventional model, in the new model presented in this paper, the solution is first pressurized in a constant volume by osmosis and then released to the energy converter (turbine).

Different concepts of osmosis power generation systems have been previously compared by Loeb *et al.* (1990) and Seppälä and Lampinen (1999). Levenspiel and de Nevers (1974) have proposed a model based on reverse-osmosis. Economical aspects have been considered by Loeb (1976, 1998), Wick (1978) and Lee *et al.* (1981).

2. PREVIOUS CONCEPT OF OSMOSIS POWER GENERATING SYSTEM

The power generating systems based on osmosis (often named as pressure-retarded osmosis power generation systems) considered in literature, so far, are more or less based on scheme presented Figure 1.

This kind of continuously operating osmosis power generation system (COS) contains:

1. A pump which pumps the needed solution flow steadily at the needed pressure.
2. An osmotic module which consists mainly of osmotic membranes. In this work we compare the results of the new system (described in Section 3) to COS when the membranes of the COS are hollow cylindrical fibres. The module contains numerous densely packed fibres providing a high membrane surface area compared to the module volume. The walls of the fibres are considered as semi-permeable, i.e. impermeable to the solute, membranes. The solution is directed to flow inside the hollow fibres and the freshwater outside the fibres. Owing to the lower chemical potential of

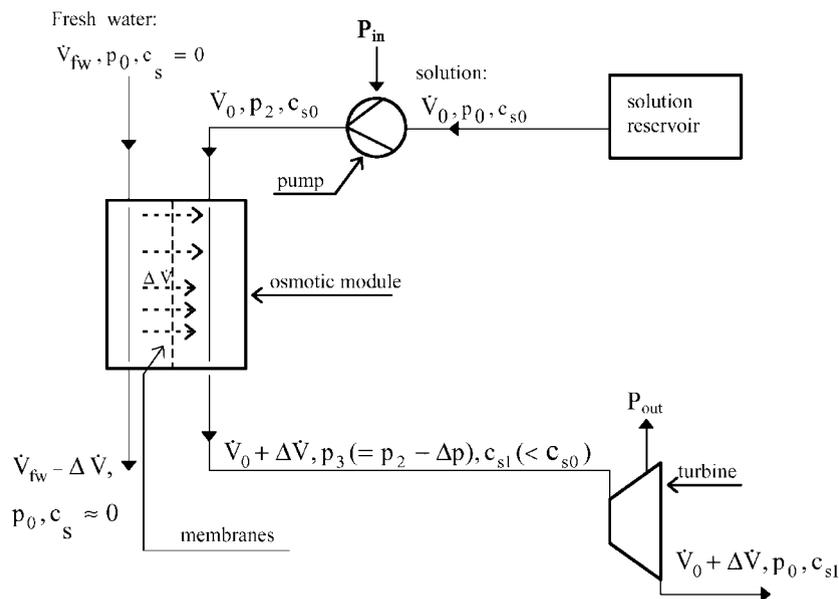


Figure 1. Continuously operating osmosis power generation scheme (COS).

water in the solution than of fresh water, the fresh water permeates through the semi-permeable surface to the solution. So, the solution flow increases and dilutes. The solution is pressurized, retarding the permeating flow. The hydrostatic pressure drops in the module.

3. The fresh water side. In this study, fresh water is directed to flow outside the fibres and it may also need some pumping but in general, the pressure loss will be considerably lower than on the solution side.
4. A turbine which transforms the momentum of the solution flow into work.

The volume flow through the turbine is higher than through the pump, enabling the possible net power generation despite the pressure losses. The COS can be made more efficient by recycling the same volume flow than pumped to the osmotic module, back into a reservoir (or reservoirs) from which the solution is originally pumped (Loeb *et al.*, 1990; Seppälä and Lampinen, 1999). Thus, we can considerably reduce the power needed for pumping. However, if we consider ideal pump and turbine which efficiencies are set to unity, there is no difference in net power output of the recycling COS and the COS presented in Figure 1.

When the efficiencies are neglected, the power demand of a pump is $\dot{V}_{\text{pump}} \Delta p_{\text{pump}}$ and the power delivered by a turbine is $\dot{V}_{\text{turb}} \Delta p_{\text{turb}}$, where \dot{V} is the volume flow and Δp the hydrostatic pressure change. The hydrostatic pressure changes are regarded as negligible everywhere except at the solution side of the osmotic module, at the pump and at the turbine. Using the notations of Figure 1, the net power obtained is then

$$P = (\dot{V}_0 + \Delta \dot{V})(p_3 - p_0) - \dot{V}_0(p_2 - p_0) \quad (1)$$

As the pressure of the fresh water is assumed to remain at constant p_0 , Equation (1) may be carried forward into a form

$$P = \dot{V}(z=L)\Delta p(z=L) - \dot{V}(z=0)\Delta p(z=0) \quad (2)$$

where $\Delta p(z=0)$ and $\Delta p(z=L)$ are the hydrostatic pressure differences over the membrane at the beginning ($z=0$) and at the end ($z=L$) of the osmotic module, respectively.

To estimate the net power of the system from Equation (2) we had to determine the pressure difference (Δp) and the volume flow (\dot{V}) in function of the distance from the entrance of the module (z). The derivation of the transport equation for a solution flow inside a hollow cylindrical fibre that estimates the changes in pressure and volume flow is presented in the appendix. It follows closely the derivation in Seppälä and Lampinen (1999) except we apply in the appendix a non-linear model for the osmotic water flux through the membrane instead of linear.

3. THE PRESSURIZING OSMOSIS POWER GENERATION SYSTEM (POS)—THE NEW CONCEPT

The new osmotic power production system (Figure 2) based on the pressurizing of fluids (POS) consist of an osmotic module, an energy converter and fresh water and solution reservoirs. The fresh water and solution reservoirs may be understood as well to be for instance river and sea, respectively. Inside the osmotic module, an osmotic membrane separates the fresh water and the solution. The osmotic membrane is selective, prohibiting the solute to penetrate the membrane.

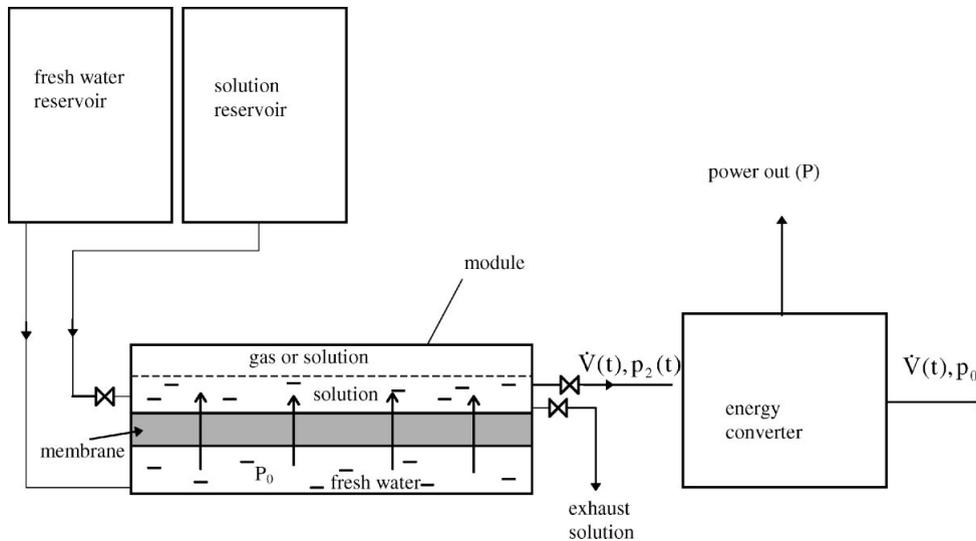


Figure 2. The new concept.

The chemical potential of water will be higher on the fresh water than on the solution until certain hydrostatic pressure head is exerted over the membrane. In theory, as long as the chemical potential of the fresh water is higher than the chemical potential of water in the solution, the water moves from the fresh water into the solution.

The energy conversion cycle consist of the following processes:

- (A) At the initial state the pressure of the solution equals the pressure of the fresh water. All valves are kept closed. Water moves from the fresh water to the solution side of the module pressurizing the solution. The solution dilutes during this process. The solution part of the module may also include gas providing more compressibility than if the solution were alone. This will increase the amount of penetrating water and the time needed to reach the needed pressure during the process A.
- (B) When a certain value of pressure of solution is reached the valve connecting the module and energy converter is opened. The pressurized solution passes the energy converter, which converts the pressure into work.
- (C) If gas exists at the solution side of the module, the gas must possibly be changed or otherwise transformed to the initial state.
- (D) The diluted solution is changed by opening the exhaust valve and the valve connecting the solution reservoir and the module.

An advantage of this kind of osmosis energy converting system is assumed to be that the pressure losses are considerably lower compared to the continuous flow in narrow channels or fibres of the COS. Another advantage is that the osmotic flow starts at the zero pressure difference over the membrane enabling a maximum flow rate (see Equation (3)) at the beginning of the pressurizing. On the other hand, the dilution of the solution and concentration boundary layers inside the solution may be more harmful compared to the COS.

For the permeating molar flux per surface area of a membrane J_w (mol/m²s), we use the equation suggested for osmosis in Seppälä (2001)

$$J_w = \frac{A_w \Delta x_s - B_w \Delta p_r}{1 + \Phi \bar{x}_s} \quad (3)$$

where Δx_s is the difference of molar fraction of the solute over the membrane, Δp_r the dimensionless pressure difference over the membrane. The dimensionless pressure is defined as

$$p_r = \frac{p}{c \mathfrak{R} T} \quad (4)$$

where \mathfrak{R} is the universal gas constant, c the total concentration of the solution and T absolute temperature. A_w (mol/m²s), B_w (mol/m²s) and Φ (dimensionless) are the transport coefficients. The volume flux of the water (\dot{V}_w) through the membrane can be determined from

$$\dot{V}_w = \frac{J_w}{c} A_{\text{surf}} \quad (5)$$

where A_{surf} is the surface area of membrane.

3.1. No gas inside the module

First we study the system where gas is absent from the osmotic module (POSSs). The compressibility (κ) of the solution is defined by

$$\kappa = -\frac{1}{v} \left(\frac{\partial v}{\partial p} \right)_T \quad (6)$$

where v is the specific volume of the solution. When we consider an isothermal process and keep the compressibility as constant, integrate Equation (6), the pressure at time t can be expressed as a function of specific volume $v(t)$ and known pressure (p_f) and specific (v_f) volume

$$p(t) = p_f - \frac{\ln(v(t)/v_f)}{\kappa} \quad (7)$$

3.1.1. Process \mathcal{A} —pressurizing. All valves are kept closed during the process. By applying Equation (3) and neglecting the changes on the total concentration in Equation (4), the change in the number of moles of solution (n_L) inside the module can be expressed by the equation

$$\frac{dn_L}{dt} = A_{\text{surf}} J_w = A_{\text{surf}} \frac{A_w \Delta x_s - B_w ((p - p_0)/c \mathfrak{R} T)}{1 + \Phi \bar{x}_s} \quad (8)$$

As solute flux through the membrane is assumed to be zero, the molar fraction of solute on the membrane surface on the fresh water side is then zero, and the number of moles of solute (n_s)

remains constant. The solution part of the module is assumed to be rigid, that is the volume remains constant ($v = V_0/n_L$). By substituting Equation (7) for Equation (8), setting the initial pressure to p_0 , and assuming the effect of solute boundary layer inside the solution to be negligible, we get

$$\frac{dn_L}{dt} = A_{\text{surf}} \frac{A_w(n_s/n_L) - (B_w/\kappa c \mathcal{R} T) \ln(n_L/n_{L_0})}{1 + (\Phi n_s/2n_L)} \quad (9)$$

where n_{L_0} is the initial number of moles of solution. The number of moles of solution (n_L) can be numerically solved from Equation (9) for example by applying the following formula

$$n_L^n = n_L^{n-1} + r \left[A_{\text{surf}} \frac{A_w(n_s/n_L^n) - (B_w/\kappa c \mathcal{R} T) \ln(n_L^n/n_{L_0})}{1 + (\Phi n_s/2n_L^n)} \Delta t \right] \\ + (1-r) \left[A_{\text{surf}} \frac{A_w(n_s/n_L^{n-1}) - (B_w/\kappa c \mathcal{R} T) \ln(n_L^{n-1}/n_{L_0})}{1 + (\Phi n_s/2n_L^{n-1})} \Delta t \right]$$

where r is the weighting factor to be chosen between 0 and 1. If $r = 0$, the formula is explicit and if $r = 1$, it is fully implicit.

3.1.2. Process \mathcal{B} —release. This process starts when the valve separating the module and the energy converter is opened and the solution is released to the energy converter. During the release, the specific volume v_L of the solution changes from the value v_{L_1} to the value that is close to the original value $v_{L_2} \approx v_{L_0}$, as at the beginning of process \mathcal{A} . The work ($W_c(\mathcal{B})$) delivered by the energy converter during the release is

$$\frac{W_c(\mathcal{B})}{n_L} = \int_{v_{L_1}}^{v_{L_0}} (p - p_0) dv_L \quad (10)$$

where n_L is the total number of moles of solution during the release. By substituting Equation (7) into Equation (10) ($p_f = p_{L_1}$ and $v_f = v_{L_1}$) and integrating results in

$$\frac{W_c(\mathcal{B})}{n_L} = \left(\frac{1}{\kappa} - \Delta p \right) \Delta v_L + \frac{v_{L_0}}{\kappa} \ln \left(\frac{v_{L_1}}{v_{L_0}} \right) \quad (11)$$

where $\Delta p = p_0 - p_1$ and $\Delta v = v_{L_0} - v_{L_1}$.

3.2. Gas included

In the second case, we study the system whereby a layer of ideal gas occurs inside the module (POS_g). In general, gases compress considerably more than liquid solutions. Therefore, the solution is regarded as incompressible compared to the gas. As a result of compression of gas, a far greater amount of water is allowed to permeate through the membrane before the pressure exceeds the value at which the release should be performed. The pressure of the solution can well be approximated to be same as the pressure of the gas.

3.2.1. *Process A—pressurizing.* All valves are kept closed during the process. The gas is assumed to compress isothermally due to the increasing solution volume caused by the osmotic flow through the membrane. According to the law of ideal gas, then

$$p(t) = \frac{p_0 V_{g_0}}{V_g(t)} \quad (12)$$

where V_g is the volume of the gas. As the total volume is constant, the change in the volume of the gas equals the change (in the opposite direction) in the volume of solution

$$dV_g = -dV_L \quad (13)$$

As the solute flux is assumed to be zero, and if we neglect the changes in total concentration in Equation (4), we get, from Equations (3)–(5), for the change of the solution volume

$$\frac{dV_L}{dt} = \dot{V}_w = \frac{A_{\text{surf}}}{c} \frac{Ax_s - (B_w/c\mathcal{R}T)(p - p_0)}{1 + (\Phi x_s/2)} \quad (14)$$

The change in molar fraction of the solute can be expressed during the pressurizing as

$$dx_s = d\left(\frac{c_s}{c}\right) = x_{s_0} V_{L_0} d\left(\frac{1}{V_L}\right) \quad (15)$$

because the number of moles of solute remains constant and it is assumed that $c = \text{constant}$. Equations (12)–(15) can be set for numerical calculation to the following form:

$$\begin{aligned} V_L^n &= V_L^{n-1} + r \left[\frac{A_{\text{surf}}}{c} \frac{A_w x_s^n - (B_w/c\mathcal{R}T)(p^n - p_0)}{1 + (\Phi x_s^n/2)} \right] \Delta t \\ &+ (1 - r) \left[\frac{A_{\text{surf}}}{c} \frac{A_w x_s^{n-1} - (B_w/c\mathcal{R}T)(p^{n-1} - p_0)}{1 + (\Phi x_s^{n-1}/2)} \right] \Delta t \end{aligned}$$

$$V_g^n = V_{g_0} - (V_L^n - V_{L_0})$$

$$x_s^n = x_s^{n-1} + x_{s_0} V_{L_0} \left(\frac{1}{V_L^n} - \frac{1}{V_L^{n-1}} \right)$$

$$p^n = \frac{p_0 V_{g_0}}{V_g^n}$$

3.2.2. *Process B—release.* The gas is assumed to expand either isothermally or isentropically. The expansion of gas is dominant compared to the expansion of the solution. The work obtained

from the energy converter is thus

$$W_c(\mathcal{B}) = \int_{V_{g_i}}^{V_{g_f}} (p - p_0) dV_g \quad (16)$$

where V_{g_i} and V_{g_f} are the initial and final volumes of gas, respectively.

Isothermal release: The state of the gas after isothermal process \mathcal{B} is the same as before process \mathcal{A} . Thus, the cycle undergone by the gas is

$$(p_0, V_{g_0}, T_0) \xrightarrow{\mathcal{A}} (p_1, V_{g_1}, T_0) \xrightarrow{\mathcal{B}} (p_0, V_{g_0}, T_0)$$

By inserting Equation (12) into Equation (16) and performing the integration, the work delivered by the energy converter during the isothermal release is represented as

$$W_c(\mathcal{B}) = p_0 V_{g_0} \ln \left[\frac{V_{g_0}}{V_{g_1}} \right] - p_0 (V_{g_0} - V_{g_1}) \quad (17)$$

Isentropic release: If the gas expands polytropically during the release of the solution, the pressure is obtained from

$$p V_g^k = \text{constant} \quad (18)$$

For an isentropic process $k = c_p/c_v$, where c_p and c_v are the specific heat of the gas in constant pressure and constant volume, respectively. For known values of volume V_{g_1} and pressure p_1 , the pressure p can be determined from Equation (18) in function of the volume V_g

$$p = p_1 \left(\frac{V_{g_1}}{V_g} \right)^k \quad (19)$$

After the isentropic expansion, the temperature and the volume of the gas are below the initial values T_0 and V_{g_0} and therefore the gas must be either heated or replaced by a new gas (process \mathcal{C}) to return to the original state. The cycle that the gas experiences is

$$(p_0, V_{g_0}, T_0) \xrightarrow{\mathcal{A}} (p_1, V_{g_1}, T_0) \xrightarrow{\mathcal{B}} (p_0, V_{g_2}, T_2) \xrightarrow{\mathcal{C}} (p_0, V_{g_0}, T_0)$$

Substituting Equation (19) for Equation (16) and integrating results in

$$W_c(\mathcal{B}) = \frac{p_1 V_{g_1}}{1-k} \left[\left(\frac{p_1}{p_0} \right)^{(1-k)/k} - 1 \right] - p_0 V_{g_1} \left[\left(\frac{p_1}{p_0} \right)^{1/k} - 1 \right] \quad (20)$$

from which the work gained from the energy converter according to the isentropic (or polytropic) release can be estimated.

3.3. Power delivered by the energy converter

The total time of the energy conversion cycle is estimated to be close to the time needed for pressurizing the solution (process \mathcal{A}), i.e.

$$\Delta t = \Delta t(\mathcal{A}) + \Delta t(\mathcal{B}) + \Delta t(\mathcal{C}) + \Delta t(\mathcal{D}) \approx \Delta t(\mathcal{A}) \quad (21)$$

In practice, so that the release of gas can occur isothermally, release should be relatively slow. Therefore, the approximation of Equation (21) is less accurate for isothermal release of gas than for isentropic release. The average power (P) delivered by the energy converter during the cycle is then

$$P = \frac{W_c(\mathcal{B})}{\Delta t(\mathcal{A})} \quad (22)$$

4. RESULTS AND DISCUSSION

We shall first study separately the functioning and the power output of both systems, POS_s and POS_g . Subsequently, we shall compare these results to those of power output of the COS described in Section 2. For all calculated results, we apply measured values of transport coefficients A_w , B_w , and Φ of the cellulose acetate membrane SS10 produced by Osmonics Inc. According to the measurements by Seppälä (2001), the coefficients are for NaCl solution $A_w = 29 \text{ mol m}^{-2} \text{ s}$, $B_w = 45 \text{ mol m}^{-2} \text{ s}$ and $\Phi = 836$. The gas in the present study is air. The effect of a solute boundary layer inside the solution has been disregarded. In all calculations, we shall apply a ratio between solution volume and membrane surface area, resulting in a $100 \mu\text{m}$ thickness of the solution layer. With such a thin layer, while clearly still present, the concentration differences inside the solution should not play a decisive role in estimating the osmotic flow through the membrane from Equation (3). Furthermore, it should be noted that, in a real system, there should be a very large membrane surface area to obtain power of economical interest. Therefore, to retain the system in finite size, the ratio between volume and membrane surface area should be kept small.

4.1. POS_s

In Figure 3(a), the evolution of pressure during process \mathcal{A} is shown for the POS_s . In Figure 3(b) the average power during one cycle (Equation (22)) in function of pressurising time $\Delta t(\mathcal{A})$ is plotted. For each chosen initial parameter (solute concentration, membrane surface area, solution volume etc.), there is a corresponding point of time when the release should be performed to result in a maximum average power (maximum positions of each curve in Figure 3(b)). The corresponding optimum pressure deviates from the equilibrium pressure, i.e. from the maximum value that the pressure approaches in time. The maximum values of pressure and power depicted in Figures 3(a) and (b) become independent of the chosen values of surface area and volume. Volume and surface area influence only the time taken to reach maximum values. To reach continuously the average power shown in Figure 3(b), the solution should be changed after each release. Otherwise, the solution dilutes and the average power during a cycle diminishes in time. As can be seen from Figure 3(b), the optimum time taken to reach maximum power is very short, from 0.02 to 0.16 s,

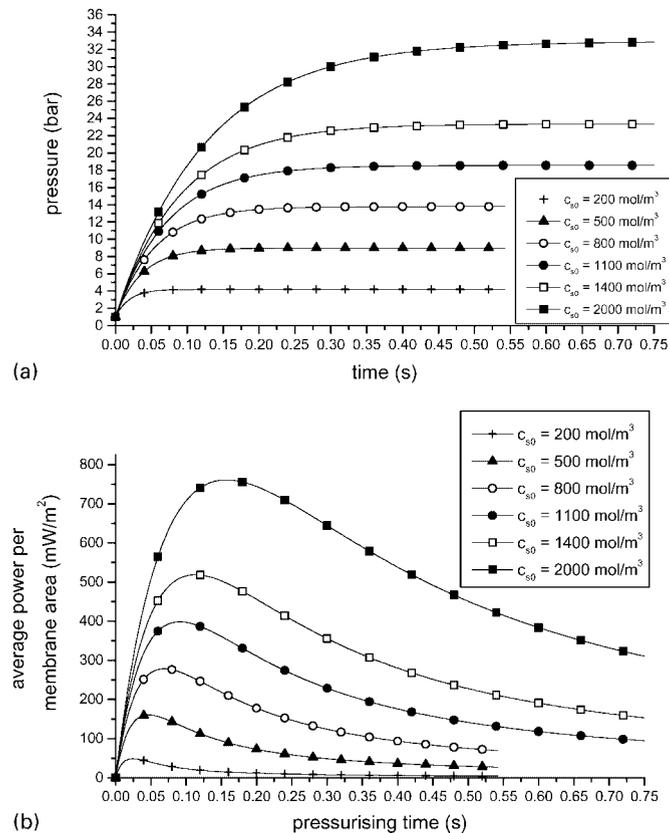


Figure 3. (a) The evolution of pressure of POS_s in time for different initial solute concentrations (c_{s0}). (b) Corresponding average power per surface area of the membrane in function of pressurizing time $\Delta t(\mathcal{A})$. For both parts: $A_{\text{surf}} = 1 \text{ m}^2$, $V_L = 0.0001 \text{ m}^3$, $T = 298 \text{ K}$, $\kappa = 4.6 \times 10^{-10} \text{ 1/Pa}$, $p_0 = 1 \text{ bar}$, $c = 55\,555 \text{ mol/m}^3$.

depending on the initial-solute concentration. Therefore, the disregarded work that is needed to replace the solution may become important. Consequently, the behaviour of average power when the solution is not changed after the releases (a combined process $\mathcal{A} \oplus \mathcal{B}$ is repeated) is also examined. In Figure 4(a), the cumulative work is shown after successive processes $\mathcal{A} \oplus \mathcal{B}$. The effect of dilution of solution can be seen in the convexity of the curves. From Figure 4(b) it can be seen how the average power during one combined process $\mathcal{A} \oplus \mathcal{B}$ decreases as a function of time due to the repetition of the process.

4.2. POS_g

The evolution of pressure during process \mathcal{A} is shown in Figure 5 for the POS_g. In Figures 6(a) and (b) the average power delivered by POS_g is plotted as a function of pressurizing time $\Delta t(\mathcal{A})$ for isothermal and isentropic releases, respectively. Again, the optimal point of time (optimal $\Delta t(\mathcal{A})$) for the release to reach the maximum average power can be found. This optimal time appears to be considerably larger in the case of the POS_g compared to the POS_s. The values of maximum

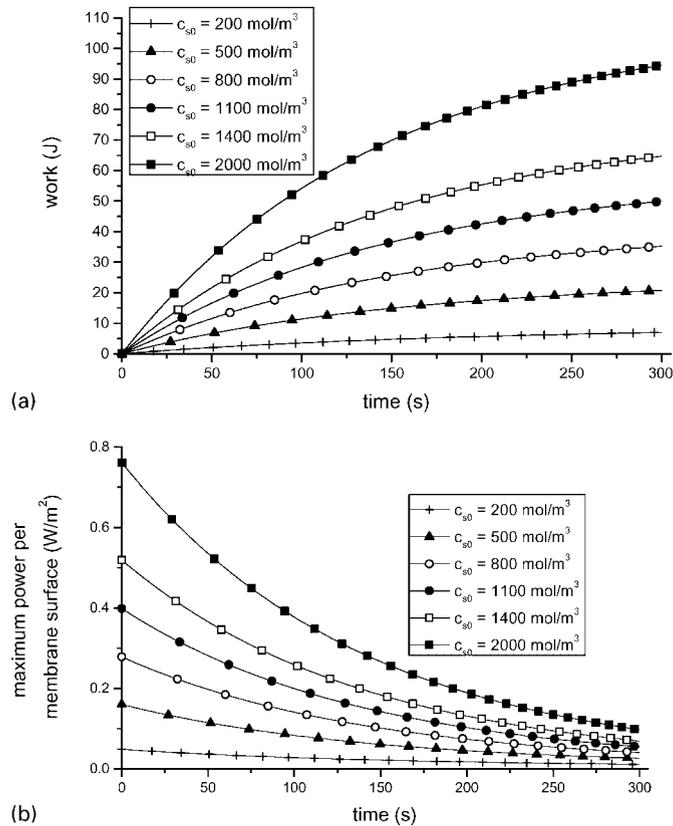


Figure 4. (a) The work (cumulative in time) delivered by POS, after successive releases without replacing the solution (combined process $\mathcal{A} \oplus \mathcal{B}$ is repeated) (b) Corresponding maximum power during a process $\mathcal{A} \oplus \mathcal{B}$ at a point of time t . For both parts: $A_{\text{surf}} = 1 \text{ m}^2$, $V_L = 0.0001 \text{ m}^3$, $T = 298 \text{ K}$, $\kappa = 4.6 \times 10^{-10} \text{ 1/Pa}$, $p_0 = 1 \text{ bar}$, $c = 55\,555 \text{ mol/m}^3$.

average power of isothermal release are approximately 1.6–1.9 times higher than the corresponding values of isentropic release. The value of the maximum average power does not depend on the surface area of the membrane, and remains constant for different solution and gas volumes when the ratio between them, V_L/V_g , is maintained constant. Figure 7 depicts the dependence of the maximum power on the ratio V_L/V_g . The maximum power increases as this ratio increases. However, the increase decelerates considerably after a certain value of the ratio V_L/V_g . For instance, the increase of the ratio V_L/V_g from a value of 100 to 10 000 increases the power by approximately 0.5 per cent. By contrast, the optimal time $\Delta t(\mathcal{A})$ for the ratio $V_L/V_g = 10\,000$ is 100 times shorter than for the value $V_L/V_g = 100$. Thus, in the case of a high ratio V_L/V_g , considerably more work should be done to replace the solution with a new one.

4.3. Comparison of models

In Figure 8, the power delivered by different concepts of osmosis energy converters is compared. The work required to replace the solution with a fresh one (process \mathcal{D}) from POS has been

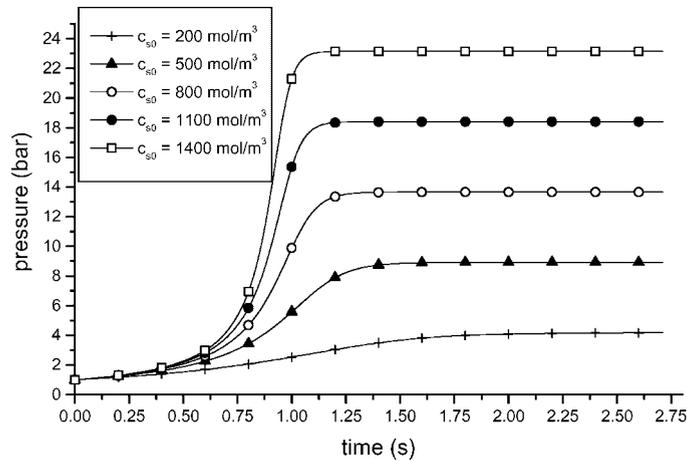


Figure 5. Evolution of pressure during the pressurizing of POS_g . Parameters: $k = 1.4$, $p_0 = 1$ bar, $c = 55555 \text{ mol/m}^3$, $V_{g0} = 10^{-6} \text{ m}^3$, $V_{L0} = 10^{-4} \text{ m}^3$, $A_{\text{surf}} = 1 \text{ m}^2$.

neglected. Therefore, in order to compare the POS_g and POS_s , the total time between two solution removals is maintained identical in both systems. The selected time interval for removal is that required for one cycle of POS_g . To obtain the same total time for POS_s , the process $\mathcal{A} \oplus \mathcal{B}$ is repeated as often (m -times, solution dilutes all the time because it is not changed) as that required for one cycle of POS_g . A complete power generating cycle of POS_g and POS_s can be represented as processes $\mathcal{A} \oplus \mathcal{B} \oplus \mathcal{C} \oplus \mathcal{D}$ and $m \otimes (\mathcal{A} \oplus \mathcal{B}) \oplus \mathcal{D}$, respectively.

Since, in the case of POS_g the power depends on the fraction between the volume of solution and gas, a ratio that results in 99 per cent of the maximum power possible to achieve was selected. This resulted in a considerably longer period of cycle than if the 100 per cent power value had been applied (see Section 4.2). The usage of 99 per cent of the maximum power resulted in V_L/V_g fractions between 34 to 68, depending on the initial concentration. The time needed to obtain 99 per cent of the maximum power values, that is the time of one cycle, was between 2 and 3 s.

The power values of COS were calculated according to the theory in appendix. Consequently, for each initial solute concentration entering the fibres, an optimal initial hydrostatic pressure, an optimal initial mean velocity of the solution (or initial volume flow), and an optimal fibre length can be found. These optimal values correspond to the maximum power delivered by the COS. The curves in Figure 8 present these maximum values. The optimising of COS has been previously demonstrated in more detail in Seppälä and Lampinen (1999). The power per fibre surface area becomes independent of the selected fibre radius.

With most dilute solutions, both POS_s and POS_g result in higher power compared to COS. However, as the applied solution becomes stronger, COS is more preferable to POS_g . POS_s produces the highest power output (2.5–2.8 times more than COS) for all studied concentrations. In a comparison of COS with POS, it should be remembered that the time needed for work production of POS is assumed to approach the time to pressurize the solution, and thus both the time and work needed for the removal of the solution are ignored. The effect of the solute boundary layer inside the solution of POS is similarly disregarded. However, a rather thin layer of solution, 100 μm , was included in the calculations and the continuous releases of the POS_s may act more or less as mixing of the solution.

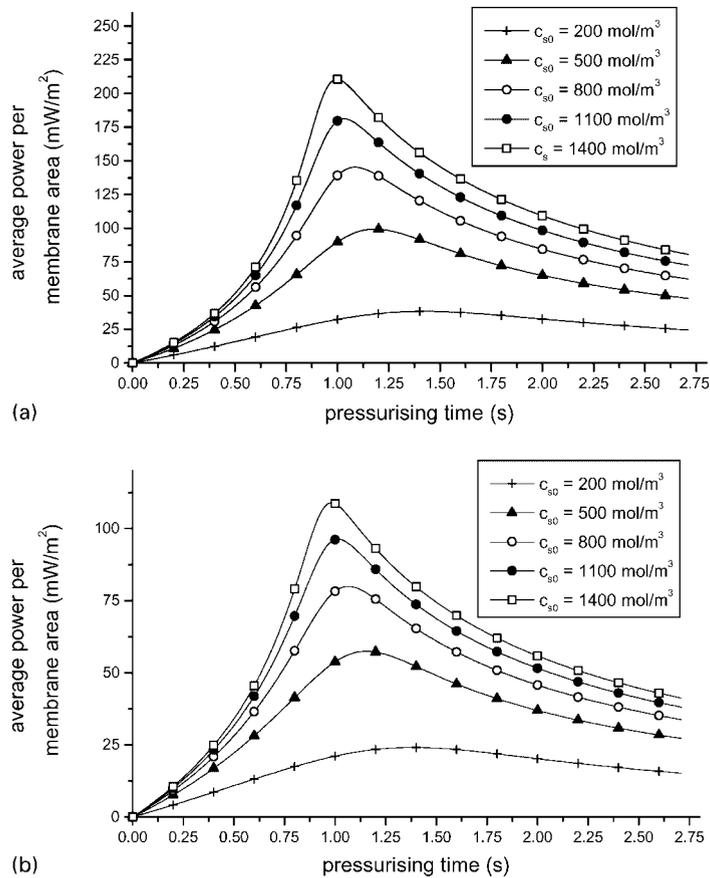


Figure 6. Average power per surface area of the membrane delivered by POS_g during one cycle in function of pressurizing time $\Delta t(\infty)$. (a) Isothermal release, (b) isentropic release. Parameter values as in Figure 5.

As was found by Loeb (1976) and Ludwig *et al.* (2001) the power delivered by osmotic energy converters utilising reverse-osmosis membranes (such as the SS10 membrane, which transport coefficients in osmotic region were utilized in this study) is low. This is due to the poor performance of present day membranes, whose main application is the extraction of species by reverse-osmosis (in reverse osmosis, the pressure of solution is so high that the solvent moves from the solution to the other side of the membrane where the solute concentration is lower or zero). In fact, the performance of these membranes in the region of reverse osmosis is considerably higher than in the region of osmosis.

5. CONCLUSIONS

A new concept for an osmotic power generation system is presented. This concept differs from previous concepts in that it is based on the pressurizing of fluids. Two variations of the new

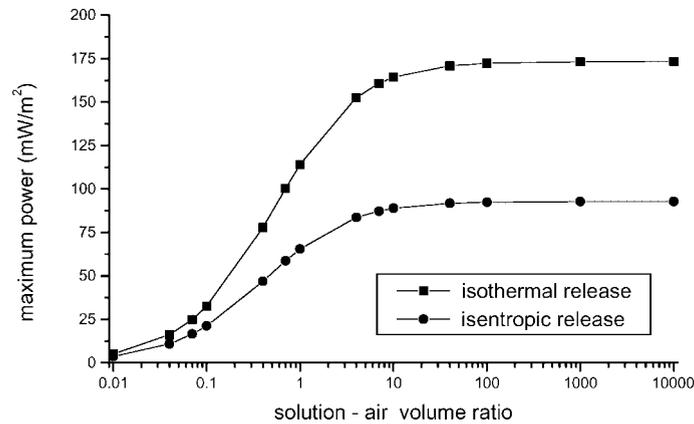


Figure 7. The maximum power of POS_g in function of the ratio between the solution and air volumes (or between the thickness of layers). Parameters: $k = 1.4$, $p_0 = 1$ bar, $A_{\text{surf}} = 1$ m², $c = 55\,555$ mol/m³, $c_{s_0} = 1020$ mol/m³.

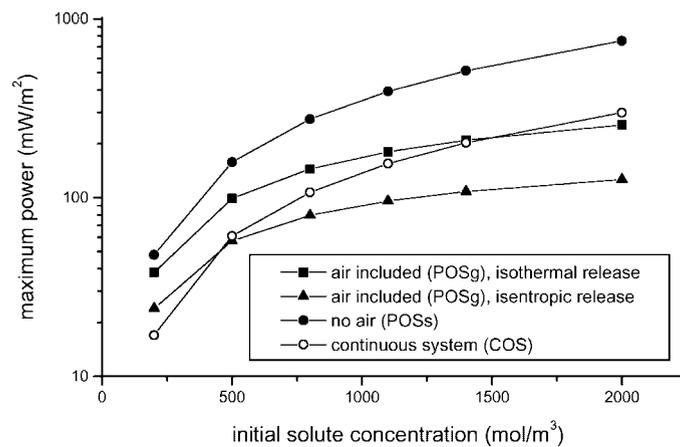


Figure 8. Comparison of power delivered by different osmotic energy production concepts. $A_{\text{surf}} = 1$ m², $c = 55\,555$ mol/m³, $V_L = 0.0001$ m³, $\mu = 0.000855$ Ns/m².

concepts were studied. In the first case, the osmotic module consisted of osmotic membranes, fresh water and solution (POS_s). In the second case, both gas and solution existed at the solution part of the module (POS_g). The work was simplified by disregarding the solute boundary layers inside the module and the work and time needed for replacing the diluted solution. The solute flux through membrane was similarly disregarded.

Consequently, the power delivered by POS_s is considerably higher than POS_g , particularly with the highest concentrations studied. On the other hand, the advantage of POS_g over POS_s is that it allows considerably longer periods between successive releases of solution to the converter. This period can be controlled by adjusting the amount of gas in the module.

The results were compared with the net power of the conventional concept of the osmosis power production system, which is based on continuous, increasing flow of solution past membranes (COS). With a solute concentration below 500 mol m^{-3} , both new concepts, POS_s and POS_g , appear to be more efficient compared with the COS. However, when the solute concentration is increased, the COS is to be preferred to the POS_g . The POS_s resulted in the highest power in all systems (2.5–2.8 times higher power values than COS) for the studied concentrations of solute from 200 to 2000 mol m^{-3} .

Whereas the new systems (POS_s , POS_g) pressurize the solution by osmosis starting from environmental pressure, the COS operates continuously at a solution pressure that is remarkably above the environmental pressure (the value of pressure depends on the solute concentration), thereby retarding the permeating flow through the membrane. Furthermore, the continuous flow of the solution inside narrow space causes pressure losses in COS. These are the main advantages of the new system compared with the COS. On the other hand, in POS_s and POS_g , the dilution of the solution, particularly when high solute concentrations are applied, may be more significant than in COS.

Despite more than 2.5 times higher power values in the POS_s system than in the conventional model (COS), the power delivery of the osmosis energy converter remains uneconomically low. Considerable emphasis should be given to the question of how to improve the performance of the membranes, or possibly alternative ways could be researched, without the usage of the membranes, to extract the available energy of the mixing process.

APPENDIX. TRANSPORT EQUATION FOR A SOLUTION FLOW (INCREASING DUE TO OSMOSIS) INSIDE A HOLLOW CYLINDRICAL FIBRE

The determination of the hydrodynamic conditions inside a hollow cylindrical fibre follows closely the derivation in Seppälä and Lampinen (1999). The difference with the derivation of Seppälä and Lampinen is that, in the present paper, a non-linear equation for water flux through the membrane is applied.

In a stationary state, the equation for continuity for a solute s in a flow of solution inside a hollow cylindrical fibre can be set as a convection–diffusion problem

$$\nabla \cdot \mathbf{n}_s = 0 \quad (\text{A1})$$

where \mathbf{n}_s is the mass flux (vector) of solute relative to stationary co-ordinates

$$\mathbf{n}_s = \rho_s \mathbf{v} + \mathbf{j}_s \quad (\text{A2})$$

where \mathbf{v} is mass average velocity (vector) of a solution and the diffusion flux of solute

$$\mathbf{j}_s = -\rho D \nabla \left(\frac{\rho_s}{\rho} \right) \quad (\text{A3})$$

where D is the diffusion coefficient, ρ_s the partial density of the solute, and ρ total density of the solution.

We assume that in the z -direction (longitudinal direction of the fibre), the diffusion flux is meaningless compared to the convective flow ($\rho_s v_z$). At the surface of the membrane (highly selective) and at the centre of the fibre (symmetry line), the solute massflux in the r -direction $n_{s,r} \approx 0$. Assuming this is applicable, everywhere in r -direction leads to the mass average velocity in radial direction $v_r = (\rho D / \rho_s) (\partial(\rho_s / \rho) / \partial r)$. Under the above assumptions, when divided by the molar mass of solute, the continuity Equation (A1) in cylindrical co-ordinates (z, r, θ) results in

$$v_z \frac{\partial c_s}{\partial z} + c_s \frac{\partial v_z}{\partial z} = 0 \quad (\text{A4})$$

where $n_{s,\theta} = 0$ is also set for the study of a symmetrical case in θ -direction. It is still assumed that the velocity in the z -direction achieves separated solutions, i.e.

$$v_z(r, z) = F(r)G(z) \quad (\text{A5})$$

where $F(r)$ and $G(z)$ are unknown functions. Inserting this into Equation (A4) obtains

$$G(z) \frac{\partial c_s(r, z)}{\partial z} + c_s(r, z) \frac{dG(z)}{dz} = 0 \quad (\text{A6})$$

the solution of which is

$$c_s = \frac{f(r)}{G(z)} \quad (\text{A7})$$

i.e. solute concentration also satisfies a separated solution of form $c_s(r, z) = f(r)g(z)$ where $g(z) = 1/G(z)$ and $f(r)$ is an unknown function.

At the entrance, the flow is assumed to satisfy the profile of laminar fully developed flow

$$v_z(r, z = 0) = 2v_{0,\text{mean}} \left[1 - \left(\frac{r}{r_0} \right)^2 \right] \quad (\text{A8})$$

where $v_{0,\text{mean}}$ is the initial mean velocity. For the initial solute concentration at the surface of the membrane (c_{ss0}), we set a condition

$$c_s(r = r_0, z = 0) = \text{constant} = c_{ss0} \quad (\text{A9})$$

The osmotic water flux ($\text{mol m}^{-2}\text{s}$) through the membrane is estimated according to the equation proposed by Seppälä (2001)

$$J_w = \frac{A_w \Delta x_s - B_w \Delta p_r}{1 + \Phi \bar{x}_s} \quad (\text{A10})$$

where x_s is the molar fraction of the solute on the surface of the membrane, and the p_r dimensionless pressure on the surface of the membrane

$$p_r = \frac{p_s}{c\mathfrak{R}T} \quad (\text{A11})$$

where \mathfrak{R} is the universal gas constant, c the total concentration of the solution, p_s hydrostatic pressure at the surface of the membrane (i.e. $p_s = p(z, r = r_0)$) and T absolute temperature. A_w , B_w and Φ are the transport coefficients.

When the total concentration of the solution (c) and temperature (T) are constant, the solute concentration on the fresh water side of the membrane is zero, Equation (A10) can be expressed thus,

$$J_w = \frac{A_w c_{ss} - (B_w/\mathfrak{R}T) \Delta p_s}{c + (\Phi_w c_{ss}/2)} \quad (\text{A12})$$

where c_{ss} denotes the solute concentration on the inner surface of the fibre. As the permeating flow (Equation (A12)) must be equal to the change of the solution flow, the boundary condition at the surface can be written (when $\rho_{\text{water, fresh}} \approx \rho_{\text{solution}}$) as

$$\frac{1}{c} \frac{A_w c_{ss} - (B_w/\mathfrak{R}T) \Delta p_s}{c + (\Phi_w c_{ss}/2)} = \frac{1}{2\pi r_0} \frac{\partial (\int_0^{r_0} v_z(r, z) dA)}{\partial z} \quad (\text{A13})$$

where the differential cross-sectional area of fibre $dA = 2\pi r dr$. Applying the boundary condition Equation (A8) to Equation (A5), we set

$$G(z = 0) = 2v_{0,\text{mean}} \quad (\text{A14})$$

$$F(r) = 1 - \left(\frac{r}{r_0}\right)^2 \quad (\text{A15})$$

Inserting Equation (A15) into Equation (A5) and substituting the result into Equation (A13), after solving the integral and applying Equation (A7), results in the form

$$\frac{1}{c} \frac{A_w c_{ss} - (B_w/\mathfrak{R}T) \Delta p_s}{1 + (\Phi_w c_{ss}/2)} = \frac{r_0}{4} \frac{dG(z)}{dz} \quad (\text{A16})$$

The constant value of $f(r = r_0)$ can be obtained from the boundary condition Equation (A9)

$$c_{ss0} = \frac{f(r = r_0)}{G(z = 0)} = \frac{f(r = r_0)}{2v_{0,\text{mean}}}$$

then

$$f(r = r_0) = 2v_{0,\text{mean}} c_{ss0} \quad (\text{A17})$$

Substituting this into Equation (A7) and substituting the result into Equation (A16) we get

$$\frac{dG(z)}{dz} = \frac{A_1 + A_2 \Delta p_s(z) G(z)}{A_3 + G(z)} \quad (\text{A18})$$

where the constants A_1 , A_2 and A_3 are

$$A_1 = \frac{8A_w v_{0,\text{mean}} c_{\text{ss}0}}{c^2 r_0}, \quad A_2 = -\frac{4B_w}{r_0 c^2 \mathfrak{R}T}, \quad A_3 = \frac{\Phi_w v_{0,\text{mean}} c_{\text{ss}0}}{c}$$

Equation (A18) may be solved analytically if the hydrostatic pressure difference $\Delta p_s(z) = 0$. Two results are obtained for $G(z)$:

$$G(z) = -A_3 + \sqrt{A_3^2 + 4A_3 v_{0,\text{mean}} + 4(v_{0,\text{mean}})^2 + 2A_1 z}$$

or

$$G(z) = -A_3 - \sqrt{A_3^2 + 4A_3 v_{0,\text{mean}} + 4(v_{0,\text{mean}})^2 + 2A_1 z}$$

As the second solution gives only negative values to the function $G(z)$ (when we choose $v_{0,\text{mean}}$ to be positive into positive z -direction), it is omitted as a non-physical solution ($G(z) \leq 0 \Rightarrow v(r, z) \leq 0$ because $F \geq 0$).

The velocity in the z -direction is thus

$$v_z(r, z) = \left[1 - \left(\frac{r}{r_0} \right)^2 \right] \left[-A_3 + \sqrt{A_3^2 + 4A_3 v_{0,\text{mean}} + 4(v_{0,\text{mean}})^2 + 2A_1 z} \right]$$

Integrating the above velocity profile over the cross-sectional area of the fibre, we get for the mean volume flow

$$\dot{V}_{\text{mean}} = \frac{\pi r_0^2}{2} \left(-A_3 + \sqrt{A_3^2 + 4A_3 v_{0,\text{mean}} + 4(v_{0,\text{mean}})^2 + 2A_1 z} \right) \quad (\text{A19})$$

This equation may be used in other cases but here it means that the power generation of the system vanishes (see Equation (2) in Section 2, when $\Delta p(z) = 0$).

The pressure drop of the solution flow is solved from the z -component of the Navier–Stokes equation of motion for an incompressible fluid with constant viscosity (μ) in radial co-ordinates:

$$\rho \frac{dv_z}{dt} = \mathcal{F}_z - \frac{\partial p}{\partial z} + \mu \left[\frac{\partial^2 v_z}{\partial r^2} + \frac{1}{r} \frac{\partial v_z}{\partial r} + \frac{1}{r^2} \frac{\partial^2 v_z}{\partial \theta^2} + \frac{\partial^2 v_z}{\partial z^2} \right] \quad (\text{A20})$$

For symmetry $\partial^2 v_z / \partial \theta^2 = 0$ and the acceleration term (the left-hand side of Equation (A20)) and the external force \mathcal{F}_z terms can be considered as meaningless. The concern here is with the pressure at the surface where, due to the friction, also $v_z = 0$ (assuming no-slip condition). In the light of the above statements and when substituting Equations (A5) and (A15) into

Equation (A20), the result is

$$\frac{\partial p_s}{\partial z} = \left(\frac{\partial p}{\partial z} \right)_{r=r_0} = \frac{-4\mu G(z)}{r_0^2} \quad (\text{A21})$$

The numerical integration of Equations (A18) and (A21) is carried through using the following procedure:

$$\Delta p_s^n = \Delta p_s^{n-1} - \frac{4\mu \Delta z G^{n-1}}{r_0^2} \quad (\text{A22})$$

$$G^n = G^{n-1} + \left\{ \frac{A_1 + A_2 \Delta p_s^n G^{n-1}}{A_3 + G^{n-1}} \right\} \Delta z$$

Each time a new value of G^n is solved from Equation (A22), the corresponding volume flow is evaluated from $\dot{V}^n = \int_0^{r_0} G^n F(r) dA = r_0^2 G^n / 4$ and the net power from Equation (2) can be written in the form

$$P^n = \dot{V}^n \Delta p^n - \dot{V}^0 \Delta p^0 \quad (\text{A23})$$

Note that in the energy production equation (Equation (A23)), it was assumed that the pressure on the surface wall is equal to the pressure applied in the power equation. Thus, the pressure is assumed constant in radial direction and actually the fully developed condition is utilized for the power equation. If we study only the flow inside the fibre according to Equation (A22), the fully developed condition is not applied. For example, the pressure distribution in radial direction is present, although it was not necessary to solve it (the second derivative of the velocity v_z , i.e. $\partial^2 v_z / \partial z^2$, is set to zero only at the fibre wall, not everywhere).

NOMENCLATURE

$\mathcal{A}, \mathcal{B}, \mathcal{C}, \mathcal{D}$	= processes
A	= cross-sectional area of fibre (m^2)
A_{surf}	= surface area (m^2)
A_w	= transport coefficient for water flow ($\text{mol m}^{-2} \text{s}$)
A_1, A_2, A_3	= constants
B_w	= transport coefficients for water flow ($\text{mol m}^{-2} \text{s}$)
c	= total concentration (mol m^{-3})
c_s	= solute concentration (mol m^{-3})
c_{s_0}	= initial solute concentration (mol m^{-3})
c_{ss}	= solute concentration at the membrane surface (mol m^{-3})
COS	= continuously operating osmosis power generation system
d	= total differential
D	= diffusion coefficient ($\text{m}^2 \text{s}^{-1}$)
\mathbf{j}	= diffusion flux (vector) ($\text{kg m}^{-2} \text{s}$)
J_w	= molar flux of water ($\text{mol m}^{-2} \text{s}$)

k	= polytropic exponent
L	= length of a fibre (m)
\mathbf{n}	= mass flow relative to stationary co-ordinates (vector) ($\text{kg m}^{-2} \text{s}$)
n_L	= number of moles of (liquid) solution (mol)
N	= molar flow (mol s^{-1})
p	= hydrostatic pressure, bar or Pa in equations
p_r	= dimensionless pressure
P	= power delivered by the energy converter (W)
POS	= pressurizing osmosis power generation system
POS _g	= pressurizing osmosis power generation system, gas included
POS _s	= pressurizing osmosis power generation system, only solution inside module (no gas)
\mathfrak{R}	= universal gas constant (J molK^{-1})
r	= weighting factor, co-ordinate
r_0	= fibre radius, μm , or m in equations
t	= time (s)
T	= temperature (K)
v	= specific volume of solution ($\text{m}^{-3} \text{mol}^{-1}$)
\mathbf{v}	= mass average velocity (m s^{-1})
$v_{0,\text{mean}}$	= initial mean velocity (m s^{-1})
v_z	= velocity in z -direction (m s^{-1})
\dot{V}	= volume flow ($\text{m}^3 \text{s}^{-1}$)
V_g	= volume of gas (m^3)
V_L	= volume of solution (m^3)
W_c	= work delivered by the energy converter (J)
x_s	= mole fraction of solute

Greek letters

Δ	= difference
κ	= compressibility ($1/\text{Pa}$)
μ	= dynamic viscosity (Ns m^{-2})
ρ	= total density of a solution (kg m^{-3})
ρ_s	= partial density of solute (kg m^{-3})
Φ	= transport coefficient for water flow (dimensionless)
∂	= partial differential
\mathcal{F}	= external force (N m^{-3})
∇	= gradient
\oplus	= combination of processes
\otimes	= repeat of a process

Subscripts/Superscripts

fw	= fresh water
g	= gas
mean	= mean value over the cross-sectional area of the fibre
n	= iteration number

r	= radial direction
s	= solute, surface
turb	= turbine
w	= water
z	= longitudinal direction
0	= initial value

REFERENCES

- Lee KL, Baker RW, Lonsdale HK. 1981. Membranes for power generation by pressure-retarded osmosis. *Journal of Membrane Science* **8**:141–171.
- Levenspiel O, de Nevers N. 1974. The osmotic pump. *Science* **183**:157–160.
- Loeb S. 1976. Production of energy from concentrated brines by pressure-retarded osmosis, I. Preliminary technical and economic correlations. *Journal of Membrane Science* **1**:49–63.
- Loeb S. 1998. Energy production at the Dead Sea by pressure-retarded osmosis: challenge or chimera? *Desalination* **120**:247–262.
- Loeb S, Honda T, Reali M. 1990. Comparative mechanical efficiency of several plant configurations using a pressure-retarded osmosis energy converter. *Journal of Membrane Science* **51**:323–335.
- Ludwig W, Seppälä A, Lampinen MJ. 2001. Experimental studies on osmotic behaviour of reverse osmosis membranes for different NaCl solutions and hydrostatic pressure differences. *Journal of Membrane Science*. Submitted for publication.
- Seppälä A. 2001. On the non-linearity of osmotic flow. *Journal of Membrane Science*. Submitted for publication.
- Seppälä A, Lampinen MJ. 1999. Thermodynamic optimizing of pressure-retarded osmosis power generation systems. *Journal of Membrane Science* **161**:115–138.
- Wick GD. 1978. Power from salinity gradients. *Energy* **3**:95–100.