Efficiency Rate Optimization of Osmotic Energy Power Plants

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Abstract. In a context of world energetic mix diversification and greenhouse effect reduction, attention is focusing on renewable and carbon free sources. Amongst them marine sources are attractive ones by their huge potential today globally evaluated at world scale as high as 120.000TWh/ year. They include osmotic energy one, which has been up-to-now left aside because of technological constraints and prohibitive exploitation cost. Reduction of their impact implies two possible actions : to operate the plants at a maximum efficiency rate, and to improve membrane technology in order to significantly lower exploitation costs. These two actions can be developed independently and it is proposed in the present study to concentrate on the first point to maximize theoretical osmotic plant efficiency rate. The output is a set of relations between system parameters defining the "optimized" line along which the system ought to be operated. This first study opens for a parallel study the technical feasibility of such optimally designed membranes to be installed in the plants.

1 Introduction

The very large amount of energy to produce for human kind development and its exponential growth worldwide is leading countries to investigate alternative renewable sources aside classical fossil ones, in order to also reduce the carbon dependence of present energy mix with its high greenhouse environmental impact. On top of solar, wind, geothermal and river exploitation, interest is now shifting toward new sources from the oceans, in relation with the considerable potential it implies. So is osmotic energy which takes advantage of the pressure difference between waters of different salinity [1], and is now under development. This energy is transformed into electrical ones by the process of Pressure Retarded Osmosis (PRO) [2].

This technique uses semi-permeable membranes to separate the different solutions with their different concentrations. (for instance fresh water and salted water, a solution and another more concentrated one). The membrane lets the solution enter the next compartment and increase its pressure. Water can then be depressurized and be used to move a hydro-turbine generating electricity.

On the base of ocean distribution on Earth's surface, the production potential for osmotic energy is today estimated to 180 TWh for Europe. On a world scale about 1700 TWh could be yearly produced if extended to all river mouths [3], which could theoretically cover a tenth of electricity world demand. To make it worth, it is necessary as for other alternative sources, to make it competitive by lowering both construction constraints and operating costs. In the present case of osmotic energy plants, the fundamental element is the semi-permeable barrier quality which creates the pressure differential between the compartments. Evidently, the higher is the concentration, the larger is the free energy extracted, and the more power can be generated. Along this line, osmotic power looks a promising alternative renewable energy source provided the conversion factor from pressure difference is large enough [3]. However, this technical element ought also to be operated in the best conditions, in the same way as in the past steam engines were gaining from improvement of steel, but also from optimization calculations defining best efficiency rate, which were leading to Carnot cycle. Here it is intended in a similar way to find the best operating line for any osmotic power plant, defined by the highest power output, it can formally deliver. This is based on analysis of a system of equations representing osmotic plant dynamics, from which power optimization is developed and explicit expression of best operating points is given in terms of system parameters. So without calculation, it is now possible to determine a priori if an osmotic power plant is competitive with its given set of nominal parameters, or what should be their modification to reach competitiveness level.

2 Osmotic Power System Production

Let a schematic osmotic power system with J_V , J_S (ms^{-1}) the volume and solute fluxes across the membrane, the solute reflection coefficient, A $(mPa^{-1}s^{-1})$ the membrane fluid permeability, and $E_m = \exp\left(-\left[(1-\sigma)J_V L_\omega{}^{-1}\right]\right)$ with the solute permeability, see Figure 1.

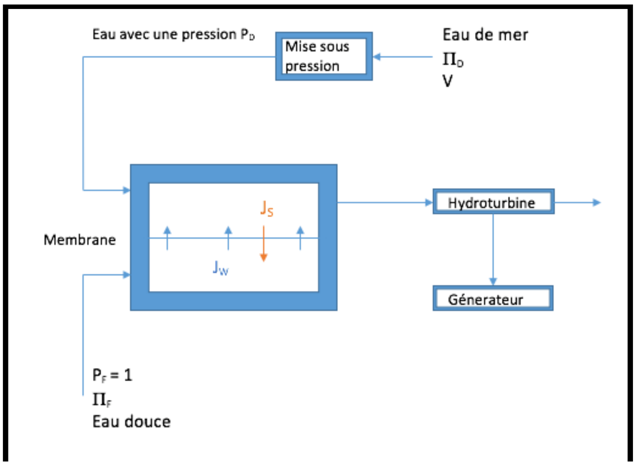

Fig. 1. Osmotic Plant Balance, J_S the Salt Flux across the Membrane

Flux equations for this system [4] can be integrated to get fluxes J_v and J_s flowing through the membrane with pressure retarded osmosis

$$J_V = A(\sigma\Delta\pi - \Delta P)\,;\, J_S = -(1-E_m)^{-1}(J_V C_d E_m - C_i) \quad (2)$$

Similarly, in the support one gets

$$J_S = -(1-E_s)^{-1}(J_V C_i E_s - C_f) \quad (3)$$

with C_d, C_i and C_f the solute concentration in the draw solution, at the barrier-layer/support interface, and in the feed solution respectively, and $E_s = \exp\left(-\left[J_V \delta D_e{}^{-1}\right]\right)$ with δ the support thickness. Equality of fluxes in the barrier layer and the support gives from (1,2,3) the non-dimensional equation

$$\propto \{(1-\sigma)(1-E^{1-\sigma})^{-1} + E^{\rho}(1-E^{\rho})^{-1}\} = (1-r)(1-E^{\rho})^{-1} - \sigma \quad (4)$$

With $\propto = 1 - \frac{C_i}{C_d}$, σ the solute reflection coefficient, $r = \frac{C_f}{C_d}$, $\rho = \frac{\delta\omega}{D_e L}$, δ the support thickness, L the barrier layer thickness, D_e the effective diffusion coefficient of the solute, $E = \exp(-X)$, $X = F(\sigma \propto - <\Delta P>)$, $F = ART\mathrm{v}C_d L/\omega$, the salt stoichiometric coefficient and finally $<\Delta P> = (P_d - P_f)/RTvC_d$. For a given dimensionless hydrostatic-pressure difference$<\Delta P>$, (4) is a transcendental equation in $\propto$ (dimensionless concentration difference across the barrier layer) which determines the operating conditions of the osmotic plant for a given set of system parameters.
From these expressions the power produced per surface unit of installed membrane is given by $W = J_m \Delta P$ with W in Wm^{-2}, or in non-dimensional form

$$<W> = \frac{W}{A(RTvC_d)^2} = <\Delta P> (\sigma\alpha - <\Delta P>) \quad (5)$$

$<W>$ is maximum when $<\Delta P> = \sigma\alpha/2$ and is then equal to $<W> = (\sigma\alpha)^2/4$ However it should be verified that this maximum is reachable as and $<P>$ are also linked by (4) which imposes a constraint on system coefficients relating "physical" (concentration performance) to "technical" F (barrier quality). Different limits can be evaluated for possible power outputs from the system [5], but here the general optimum will be directly obtained from (4).

3 Power Plant Optimization

So far, the problem is to determine $<\Delta P>$ in terms of all system parameters from (4). To proceed, it is observed that (4) can be rewritten as

$$\alpha = (1-Y)[(1-r) - \sigma(1-Y^{\Psi})]/[(1-\sigma)(1-Y^{\Psi}) + Y^{\Psi}(1-Y)] \quad (6)$$
$$Y = \exp\,[-(1-\sigma)F(\sigma\alpha - <\Delta P>)]$$

with $\Psi = \rho/(1-\sigma)$. Taking now Y ($\in$[0,1] from its definition) as a dummy variable, (6,7) provides a parametric representation $<\Delta P> = <\Delta P>(Y)$, $\alpha = \alpha(Y)$, of the curve $<\Delta P> = <\Delta P>(\alpha)$ in terms of Y for all other system parameters fixed. If there exists an intersection between the curve $<\Delta P> = <\Delta P>(\alpha)$ and the maximum power output condition $<\Delta P> = \sigma\alpha/2$ from (5) (a straight line in the $\{<\Delta P>, \alpha\}$-plane) then evidently this point will meet all the requirements for being an optimum operating point. From (6) one gets the limits

$$\alpha(0) = 1 - r/(1-\sigma),\ \alpha(1) = (1-r)/(\rho+1) \quad (7)$$

and

$$d\alpha/dY(1) = - \quad /(1+ \quad)(1-\sigma) < 0 \quad (8)$$
$$d\alpha/dY(Y\to 0) = -(1-r)/(1-\sigma) + r \quad Y^{\Psi-1}/(1-\sigma)^3 \quad (9)$$

In the same way $<\Delta P>$ (0) $= -\infty$ and $<\Delta P>$ (1) $= \sigma\alpha < \alpha$ and both curves can be placed in $\{<\Delta P>, \alpha\}$-plane, see Figure 2

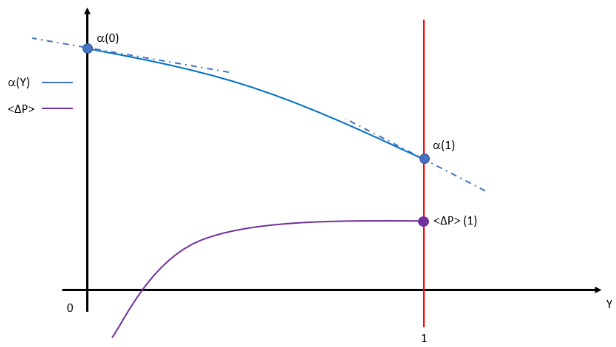

Fig. 2. Schematic Plots of $<\Delta P>$ and α vs Y for $\Psi > 1$ and $\alpha(0) > \alpha(1)$

The curve $<\Delta P> = <\Delta P>(\alpha)$ can be drawn from the two curves, see Figure 3. Next step is to get the intersection point I of this curve with the optimum power output line $<\Delta P> = \sigma\alpha/2$ from (5), which always exists in considered parametric case for all physically acceptable value of the parameters satisfying the existence constraint $\alpha. > 0$. Because $<\Delta P> = <\Delta P>(\alpha)$

starts from $\alpha(1) > \sigma\alpha(1)$ and drops asymptotically to $-\infty$ for $\alpha = \alpha(0)$, condition for existence of at least one intersection I is that $<\Delta P> = <\Delta P>(\alpha)$ cuts the abscissa line for positive α. This is always the case here because from (6) $\alpha = 0$ when $Y^{\Psi} = (r + \sigma - 1)/\sigma > 0$ by definition of Y which contradicts the existence condition at 0 $\alpha(0) > 0$, so there does not exist such 0's.

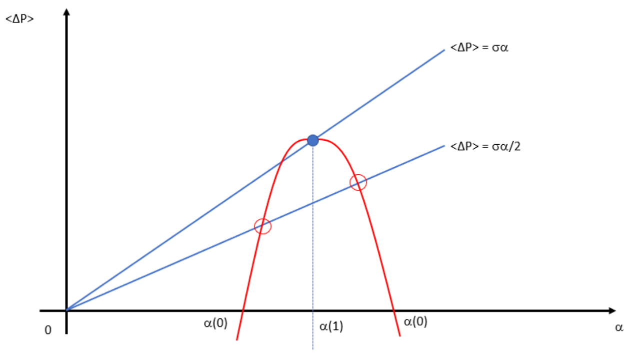

Fig. 3. Sketch of $<\Delta P>$ vs α for $\Psi > 1$: right branch $\alpha(0) > \alpha(1)$ left branch $\alpha(0) < \alpha(1)$. Optimum operating points are marked by circles

A largest power output is obtained when $\alpha(0)$ takes the largest value as shown in Figure 3 (right circle). Being identified, numerical calculation is possible and design of parameters organized to satisfy this constraint. The advantage of this condition is that it is completely explicit in terms of system parameters and is obtained without any calculation of system trajectory dynamics. If W_{lim} if the lower limit for osmotic plant profitability, one gets from (5) the viability condition

$$W_{lim} = A(RTvC_d)^2 \Delta P^2 \quad (10)$$

where pressure is evaluated at the optimum point. For typical ΔP = 1.2 MPa (for water) and usual system parameters, the limit value $A \cong 1.4$mPa ^{1}s ^{1} is still outside the reach of today membranes [6], and extension of simple barriers has been suggested [7].

4 Conclusion

Osmotic pressure systems are recognized as potentially valuable alternative renewable energy sources due in particular to their large distribution over all Earth's surface, when operated in a Pressure Retarded Osmosis mode. To define the parameter domain corresponding to profitable exploitation, the study of their dynamics has been undertaken and it is shown that, aside the improvement of important technical parameters such as semi-permeable membranes, there exists a set of conditions for which the power output is maximized at system level notwithstanding the specific value of its parameters. Their great interest is that they can in full generality be determined explicitly from formulae expressed in terms of system parameters, simplifying considerably the design of the osmotic pressure plant. The net result is that the profitability limit of 5W/m2 is more easily reached when evaluated at identified functioning points corresponding to the optimum by reducing in proportion the technical constraint.

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