Experimental Investigations of Osmotic-and-Diffusive Free Energy Conversion

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Abstract. A practical method of analysis of osmotic-and-diffusive conversion of free energy of solutions with different concentrations in membrane systems, which was elaborated previously (Kargol 1990) is experimentally verified in this work. A proper membrane system was chosen for examination. Equations for power and efficiency were obtained in a mathematically simple way for this system as an example of application of the method. Next, experimental investigations were made, whose results show the reasonability of the method proposed.

Key words: Osmosis — Diffusion — Free energy conversion — Power — Energetic efficiency

Introduction

Internal energy, or more exactly the part called free energy, can be converted to useful work e.g. through osmosis. A concentration difference ΔC of solutions is an indispensable condition. It is an analogue, for example, of a thermal way, where temperature difference ΔT is a necessary condition. In the case of selective membrane systems, osmosis is always accompanied by diffusion of dissolved substance. This latter process can also be treated as a way of conversion of free energy, but then only dissipation of energy takes place. In a previous work, (Kargol 1990) an analytic method of investigation of osmotic-and-diffusive conversion of free energy of solutions with different concentrations in membrane systems was presented. The membrane system chosen for consideration was relatively available, but only for the description of the method. It was not useful for the purpose of experimental verification of this method (except for the possibilities of measurement of mechanical pressure). Because of this, the method was applied to another system which allowed to perform fixed experimental investigations of this method. The results of the present investigation are satisfactory.

We must also add that in our opinion this method is suitable for biophysical and technical investigations (Kargol 1985, 1990; Lee et al. 1981; Loeb 1976).

In general, a practical, easy to understand and complex method of solving energetic problems of osmotic-and-diffusive energy conversion has been developed. With regard to these properties the method can be considered as an alternative to the concepts proposed by Kedem and Caplan (1965) and Peusner (1983, 1985).

Membrane system and the results of experimental investigations

The membrane system subjected to an experimental investigation of osmotic-and-diffusive energy conversion is represented in Fig 1. It consisted of a single membrane M with filtration coefficient L_p, reflection coefficient σ and permeability ω. The active surface of the membrane was $S = 5\text{cm}^2$. The membrane separated two cylindrical compartments A and B capacity 500 cm^3 each. The compartments were filled with solutions with different concentrations fulfilling the condition: $C_1 < C_2$. Because of the concentration difference of the solutions $\Delta C = C_2 - C_1$, the osmotic volume flux J_v is generated across the membrane. This flux is pressed to compartment N against hydrostatic pressure $\Delta P = \rho gh$. Thus, the system presses the solution with concentration C_2 and density ρ to high h doing effective work in this way. This work is accumulated as a potential energy $E_p = mgh$ of solution contained in compartment N. This work (and also the effective power) can easily be determined experimentally. Because of the flux J_v across the membrane M dissipation of energy due to viscosity forces occurs. It should be noted that if the membrane is selective ($0 < \sigma < 1$), then besides osmotic conversion of free energy, its transformation (dissipation) will also be observed in the diffusive way because of flux j_D of the solute.

In accordance with what has been said in Introduction, let us first try to apply our method to the system considered and to describe the results of the experimental investigation.

Equation of Kedem-Katchalsky (Katchalsky and Curran 1965) rewritten in a suitable way:

$$J_v = L_p\sigma\Delta\Pi - L_p\rho gh \tag{1}$$

will be the starting point of our consideration. On the basis of this equation the following expressions for effective power (M_{uo}), dissipative power (M_{ro}) and sum of powers (M'_{co}) generated osmotically are simply obtained:

$$M_{uo} = S\rho ghJ_v \tag{2}$$

$$M_{ro} = S\frac{J_v^2}{L_p} \tag{3}$$

$$M'_{co} = S\sigma\Delta\Pi J_v = SRT\sigma(C_2 - C_1)J_v \tag{4}$$

where $\Delta\Pi = \text{R}T(C_2 - C_1)$ is the osmotic pressure difference, R is the gas constant, T is the temperature.

Proceeding further in accordance with this method and using equation of power dissipated diffusively (Kargol 1990)

$$M_{rD} = S\frac{\omega}{\bar{c}}\Delta\Pi^2 \tag{5}$$

we obtain an expression for the efficiency η_{oD} of osmotic-and-diffusive energy conversion:

$$\eta_{oD} = \frac{M_{uo}}{M'_{co} + M_{rD}} = \frac{\rho g h J_v}{\sigma\Delta\Pi J_v + \frac{\omega}{\bar{c}}\Delta\Pi^2} \tag{6}$$

where: $\bar{c} \approx \frac{C_1+C_2}{2}$ is the average concentration.

The above equations allow a detailed insight into the energetic possibilities of the system. To partly substantiate this conclusion we calculated and constructed the following diagrams of the dependences: $J_v(h)$ based on Eq. (1); $M_{uo}(h)$ based on Eq. (2); and $\eta_{oD}(h)$ based on Eq. (6). (Figs. 2,3,4). The following data were used for the calculations: $L_p = 5.10^{-12}\mathrm{m^3N^{-1}s^{-1}}$, $\sigma = 0.044$, $\omega = 6.8.10^{-8}\mathrm{molN^{-1}s^{-1}}$ (Kargol 1978), and $S = 5.10^{-4}\mathrm{m^2}$, $C_1 = 0$ M, $C_2 = 0.1$ M, $\rho = 1004$ kg m^{-3}, $T = 290$K.

Parameters σ and ω refer to glucose as the solute.

One can notice in Fig. 3 that :

a) function $M_{uo}(h) = 0$ for $h = 0$ or $h = h_1 = 1.12$ m

b) function $M_u(h) > 0$ for $0 < h < h_1$.

The curve shows that this function has a maximum point for $h = h^{max}$. Using Eqs. (1) and (2) it is easy to calculate that

$$h^{max} = \frac{\rho\Delta\Pi}{2\rho g} = 0.556 \text{ m} \tag{7}$$

$$h_1 = \frac{\rho\Delta\Pi}{\rho g} = 1.12 \text{ m} \tag{8}$$

At the maximum point the value of function $M_u(h)$ is

$$M_{uo}(h^{max}) = \frac{1}{4}SL_p\sigma^2\Delta\Pi^2 = 7.5 \times 10^{-8} \text{ Js}^{-1} \tag{9}$$

For the purpose of the experimental verification of the method the following experiments were made with the membrane system illustrated in Fig. 1:

1. For different values of h, volume fluxes J_v were determined according to

$$J_v = \frac{\Delta m}{\rho S \Delta t}$$

where Δm is the increase of mass of solution in compartment N at time Δt.

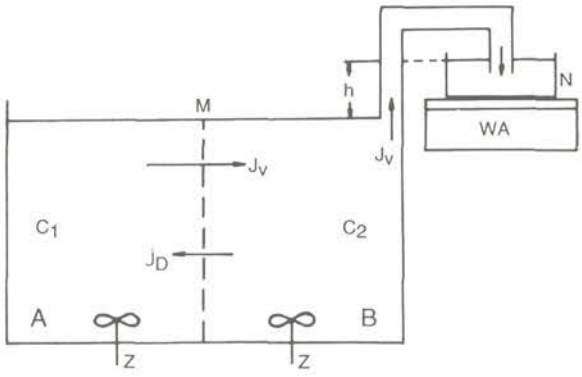

Figure 1. Membrane system used in the present analyses. M - membrane; A,B - compartments; C_1, C_2 - concentrations; N - additional vessel; J_v - volume flux; WA - analytical balance; j_D - solute flux.

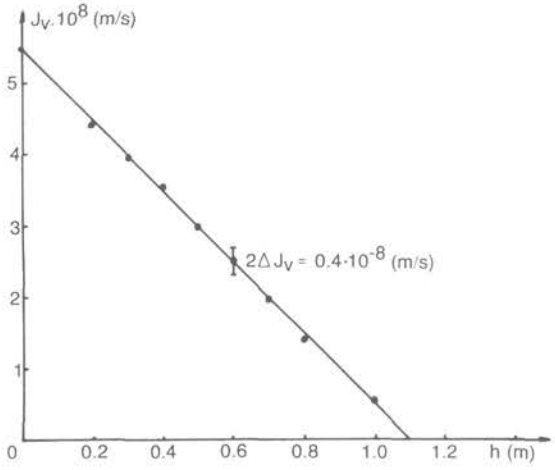

Figure 2. Plot of the dependence $J_v(h)$. See the text for explanation.

In Fig. 2 values of J_v calculated in this way are represented by points. These points lie exactly on the curve obtained from the calculations.

2. Using values Δm, weighed by analytical balance for different values of h, we calculated effective power as

$$M_{uo}^{ex} = \frac{\Delta E}{\Delta t} = \frac{\Delta mgh}{\Delta t}$$

where Δt is time.

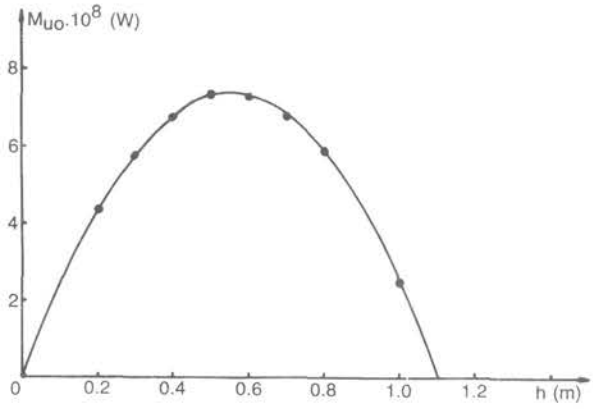

Figure 3. Plot of the dependence $M_{uo}(h)$. See the text for explanation.

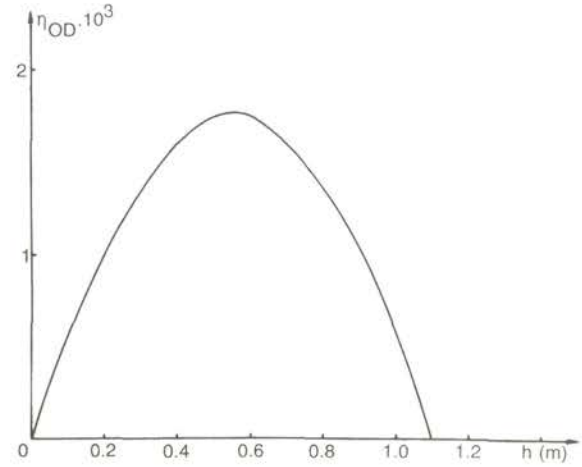

Figure 4. Plot of the dependence $\eta_{oD}(h)$. See the text for explanation.

The values of effective power obtained in this way were plotted in Fig. 3. The values neatly fit to the curve obtained from the calculations using Eqs. (1) and (2). Deviations are in the range of the measurement error. The experimentally obtained values for h_d^{max}, h_{1d} (see Fig. 2) and $M_{uo}^d(h^{max})$ are, respectively, 0.5 m, 1.1 m and 7.4×10^{-8} Js^{-1}. These values are effectively identical with those obtained from the calculations.

The above results of the experimental investigation suggest that the proposed method is correct. Unfortunately, the experimental system considered in the present work (Kargol 1990) does not allow to measure the powers M_{ro}, M'_{co}

and M_{rD}. These quantities can be calculated from Eqs. (3), (4) and (5). Using these possibilities we calculated efficiency η_{oD} as a function of h. The dependences obtained in this way are shown in Fig. 4.

Comparing curves in Figs. 3 and 4 we can notice that the membrane system emits maximal effective power working with maximal energetic efficiency.

Conclusion

This work, as well as the previous one, have dealt with a practical method of analysis of membrane systems concerning osmotic-and-diffusive energy conversion of free energy of solutions with different concentrations. This method is rather easy to understand and has a wide range of applications. This method can be used to investigate effective power, dissipative power, total power and efficiency of osmotic-and-diffusive energy conversion η_{oD}.

The reasonability of this method has partly been verified experimentally: a satisfactory agreement was obtained between the results of theoretical considerations and experiments.

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