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Coupled Phenomena Membrane Distillation and Osmotic Distillation through a Porous Hydrophobic Membrane*

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ABSTRACT

Water transport in the vapor phase through a porous hydrophobic membrane has been studied in different experimental situations. Pure water and/or different aqueous solutions of sodium chloride, ranging from 0.5 to 5 mol/L, were employed on both sides of the membrane. The experiments were carried out under temperature differences varying between 5 and 30 K, and at mean temperatures varying between 20 and 40°C. The stirring rate was varied between 0 and 350 rpm. The results were interpreted based on the existence of unstirred polarization layers.

INTRODUCTION

Temperature-driven transport of water in the vapor phase through microporous hydrophobic partitions has been studied since the mid-1960s. The process is called "membrane distillation" (1–13). Later, in the 1980s, it was found that the same kind of membranes could be applied to an isothermal composition-driven process termed "osmotic distillation" (14–16). In all cases the membrane material is water repellent, so liquid

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water cannot enter the membrane pores unless a hydrostatic pressure exceeding the so-called "liquid entry pressure of water, LEPW" is applied. In the absence of such a pressure difference, a liquid–vapor interface is formed on either side of the membrane pores.

In some aspects both phenomena may be considered closely related, although there are some remarkable differences between them. In the two cases it is strictly necessary to maintain a water vapor pressure difference across the membrane pores in order to get a difference in water chemical potential, which is the thermodynamic force causing the transport process. However, the physical origin of that vapor pressure difference is quite different. It is a temperature difference in the case of membrane distillation, whereas it is a composition difference in the case of osmotic distillation.

In the literature there are several papers on the subject. Most of them (1–16) refer to pure water or to different aqueous solutions, as well as to various hydrophobic membrane materials such as PTFE (polytetrafluorethylene), PVDF (polyvinylidene), or PP (polypropylene).

In the present paper the simultaneous existence of both phenomena is considered. A hydrophobic membrane separates pure water from an aqueous solution, and a transmembrane temperature difference is established, synergic or antagonistic to the concentration difference. A water flux is observed through the membrane, partially due to membrane distillation and partially due to osmotic distillation. The flux has been measured in different experimental conditions by varying some parameters such as solute concentration, stirring rate, mean temperature, and bulk temperature difference. The results are discussed by taking into account the existence of the unstirred liquid layers that adhere to the membrane at both sides.

THEORY

The system to be studied consists of a porous hydrophobic membrane held between two liquid phases. The liquids may be pure water or aqueous solutions of some nonvolatile component. The stirring rate (common for both liquid phases), solute concentration, and temperature may be varied independently.

When differences in temperature and/or composition are maintained between both subsystems, a transport of water in the vapor phase takes place through the membrane. The water transport is due to the water vapor pressure difference created between the edges of each pore. The transport mechanism is called membrane distillation or osmotic distillation when the physical origin of that pressure difference is simply a temperature difference or simply a composition difference. When the two differences coexist, the two transport mechanisms act simultaneously.

The mass transfer may be explained on the basis of three different models: Knudsen-type flux, Poiseuille-type flux, and diffusive flux. In any case, the three models suggest a linear relationship between the volume flux per unit surface area of the membrane, J, and the transmembrane water vapor pressure difference, ΔP (11):

$$J = A\Delta P \tag{1}$$

where A is a phenomenological coefficient valid for the system.

The water vapor pressure at each interface depends on composition and temperature. This dependence may be expressed as a function of the value corresponding to pure water and the solution activity:

$$P(c,T) = a(c)P^{\circ}(T) \tag{2}$$

where a is the activity and the superscript "o" means pure water. On the other hand, the dependence of the vapor pressure on temperature is of the form:

$$P^{\circ}(T) \propto \exp\left(-\frac{L}{\mathrm{R}T}\right) \tag{3}$$

where L is the heat of vaporization of water and R is the gas constant.

Let T_1 and T_2 be the temperatures at the corresponding liquid–vapor interfaces, ΔT the transmembrane temperature difference, and $\bar{T}$ the mean temperature. In this case, $T_1 = \bar{T} + \Delta T/2$ and $T_2 = \bar{T} - \Delta T/2$. In what follows, it will be assumed that

$$\frac{\Delta T}{2\bar{T}} \ll 1; \qquad \frac{L\Delta T}{2\mathrm{R}\bar{T}^2} \ll 1 \tag{4}$$

If one develops the corresponding series expansion and considers only the first order, one finally arrives at the following relationship:

$$\Delta P = P^{\circ}(\bar{T})\Delta a + P^{\circ}(\bar{T})\bar{a}\frac{L}{\mathrm{R}\bar{T}^2}\Delta T \tag{5}$$

where Δa is the transmembrane activity difference and $\bar{a}$ is the mean activity. It is worth mentioning that this equation is valid when the two thermodynamic forces act individually (ΔT alone or Δc alone) or simultaneously. In this last case there are three possibilities: the two forces act in a synergistic way; the forces are antagonistic to each other (the "osmotic" contribution being the greatest); and, finally, the forces act in an antagonistic way (the "thermal" contribution being the greatest).

The literature (1–17) shows that in the case of pure water and aqueous solutions, the volume flux depends on solute concentration (c), stirring rate (ω), and temperature (mean temperature, $\overline{T}$, and bulk temperature difference, ΔT_b).

The dependence of the volume flux on mean temperature has been considered for the cases of pure membrane distillation or pure osmotic distillation by several authors (3, 11, 13, 16, 17), and most of them have found an Arrhenius-type dependence between the phenomenological coefficient and the absolute temperature to be adequate. This simple dependence must not be expected in cases where the two contributions, thermal and osmotic, take place simultaneously.

On the other hand, the dependence of J on ω has been extensively studied in Refs. 11, 16, and 17, and the experimental results have been interpreted on the basis of the concept of "unstirred polarization layers." According to this idea, the measured fluxes are affected by the presence of unstirred liquid layers adjoining the membrane on both sides. In other words, the temperature and concentration differences between the two membrane surfaces, ΔT and Δc, are not the same as the ones corresponding to the well-stirred bulk phases, ΔT_b and Δc_b. Part of these externally applied differences are dissipated through the unstirred liquid layers. Thus, we can write

$$J = A\Delta P = A'\Delta P_b \tag{6}$$

where ΔP_b is the water vapor pressure difference corresponding to the composition of the bulk phases and A' is another phenomenological coefficient. It is worth noting that coefficients A and A' have specific names for the cases of pure membrane distillation and pure osmotic distillation. In fact, in the case of pure membrane distillation experiments, the vapor pressure differences, ΔP and ΔP_b, are related to the temperature differences, ΔT and ΔT_b, and coefficients A and A' turn into B (net membrane distillation coefficient) and B' (apparent membrane distillation coefficient), respectively, while in the case of pure osmotic distillation experiments, coefficients A and A' are called C (net osmotic distillation coefficient) and C' (apparent osmotic distillation coefficient), respectively.

In previous papers concerning separated membrane distillation and osmotic distillation experiments (13, 16, 17), it was stated that, in all cases, the volume flux increases with stirring rate. Some semiempirical considerations permit a linear dependence between the inverse of the above-mentioned quantities to be postulated. In what follows it will be assumed that the same dependence exists when combined experiments are being considered:

$$\frac{1}{J_\omega - J_0} = X + \frac{Y}{\omega} \tag{7}$$

where J_ω and J_0 are the volume fluxes measured with stirring rate ω and in absence of stirring, respectively, and X and Y are adjustment parameters. Obviously, the validity of this assumption must be confirmed by experiments.

There is a very interesting case to be considered; the case of steady state which is defined by the condition $J = 0$. The steady state is obtained when the two thermodynamic forces act simultaneously and in an antagonistic way, and when both contributions, thermal and osmotic, have the same magnitude. In this case, if one considers that ΔT is proportional to ΔT_b, it is possible to find the following relationship between the activity difference corresponding to an arbitrarily chosen concentration difference and its "equivalent" bulk temperature difference, ΔT_b^{st}:

$$\Delta T_b^{st} \propto \frac{R\overline{T}^2}{L} \frac{\Delta a}{\bar{a}} \tag{8}$$

It is worth mentioning that the solute concentration has the same value on either side of the membrane and in the corresponding bulk phase in a steady state. That means that the presence of the unstirred liquid layers affects only the temperature distribution in a steady state. Consequently, in a steady state the bulk temperature difference "equivalent" to a given concentration difference, $\Delta T_b^{st}(\omega)$, is proportional to the inverse of the apparent membrane distillation coefficient, B'.

EXPERIMENTAL

Materials

A Millipore FHLP membrane has been studied. Its composition and principal characteristics, as specified by the manufacturer, are: composition, PTFE (polytetrafluorethylene); pore radius, 0.25 μm; thickness, 175 μm; empty volume fraction, 80%. The materials employed in the experiments were water and aqueous solutions of sodium chloride. Pure pro-analysis grade chemicals and pure water (deionized and distilled) were used.

Apparatus and Experimental Method

The experimental setup used (see Fig. 1) was essentially similar to that described previously (13, 16, 17). The central part of the experimental

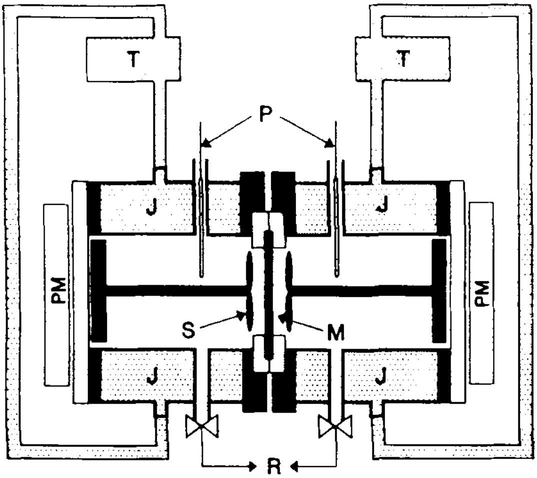

FIG. 1 Experimental assembly: (M) membrane, (J) thermostatized jackets, (S) stirrer, (P) Pt-100 probes, (T) thermostat, and (PM) propelling magnet.

device is a cell which basically consists of two equal cylindrical chambers having lengths of 20.5 cm and made of stainless steel. The membrane was fixed between the chambers by means of a PVC holder. Three Viton O-rings were employed to ensure there were no leaks in the whole assembly. The membrane surface area exposed to the flow was 2.75 × 10 ^{3} m^{2}.

The temperature requirements were set by connecting each chamber through the corresponding water jacket to a different thermostat. In order to improve the uniformity of temperatures and concentrations inside each chamber, the liquid was stirred by a chain-driven cell magnetic stirrer assembly. Temperatures were measured with platinum resistance thermometers placed near both sides of the membrane. Under these conditions, the temperature was constant within ±0.1°C.

The value of the volume flux was obtained in each case by adjusting the experimental data (volume flowing into the corresponding chamber versus time) to a linear function by a χ^2-minimization procedure. As a consequence, the water flux causes an increase in time of the solute concentration at one side of the membrane and a decrease at the other side. That means a superimposed contribution to the original flux. In the present paper the water fluxes will only be considered at the initial times, in such a way that the new contribution may be considered negligible. As an example of the calculations carried out, we shall quote the values of the slope (with its estimated standard deviation) in a particular case (stirring rate, 200 rpm; mean temperature, 40°C; solute concentration, 3 mol/L; and bulk temperature difference, 10 K): $(6.149 \pm 0.007) \times 10^{-5}$ m/s. The value of the correlation coefficient obtained in the most unfavourable case was 0.99999 for runs of at least 12 points. This confirmed that the assumptions made were correct within the ranges of measuring time, temperature, solute concentration, and stirring rate used.

RESULTS AND DISCUSSION

Determination of the fluxes was made in two sets of experiments in which the values of solute concentration, mean temperature, bulk temperature difference, and stirring rate were varied. In the first set the mean temperature was fixed at 40°C and the remaining parameters were varied independently. The solute concentration values were 0, 0.5, 1, 2, 3, 4, and 5 mol/L. The bulk temperature differences were 0, 3, 6, 10, 15, and 20 K (the bulk temperature differences were set for both synergistic or antagonistic direction with the concentration difference). The stirring rate was varied between 0 and 350 rpm, with steps of 50 rpm. The purpose of this set was to study separately the influence of solute concentration, bulk temperature difference, and stirring rate on the phenomenon. In the second set of measurements, the mean temperature was varied between 30 and 50°C, with steps of 5 K. The solute concentration values were 0, 1, 3, and 5 mol/L, and the stirring rates were 0, 50, 150, 250, and 350 rpm. The bulk temperature difference was 6 K (synergistic or antagonistic with the concentration difference). The purpose of this set was to study the influence of mean temperature on the phenomenon. The results corresponding to both sets of measurements appear in the Tables 2–18.

The influence of stirring rate on the phenomenon may be seen for some illustrative cases in Fig. 2. This figure shows the existence of polarization layers in our system. In all cases the pairs of experimental data $\{\omega; J_\omega\}$ were fitted to Eq. (7) by a least-squares procedure, and a visual inspection permits us to state that the fitting procedure is adequate. In some cases the volume flux decreases when the stirring rate increases. For this decrease to occur, it is necessary that the two thermodynamic forces act in an antagonistic manner.

Figure 3 shows the flux value as a function of the bulk temperature difference in some representative cases. The results refer to a fixed bulk concentration of 3 mol/L and various values of the stirring rate. In each case the experimental points may be satisfactorily fitted by a straight line. The intercepts of these straight lines with the vertical axis represent the pure osmotic distillation fluxes. The intercepts with the horizontal axis correspond to the steady states represented by Eq. (8). In other words,

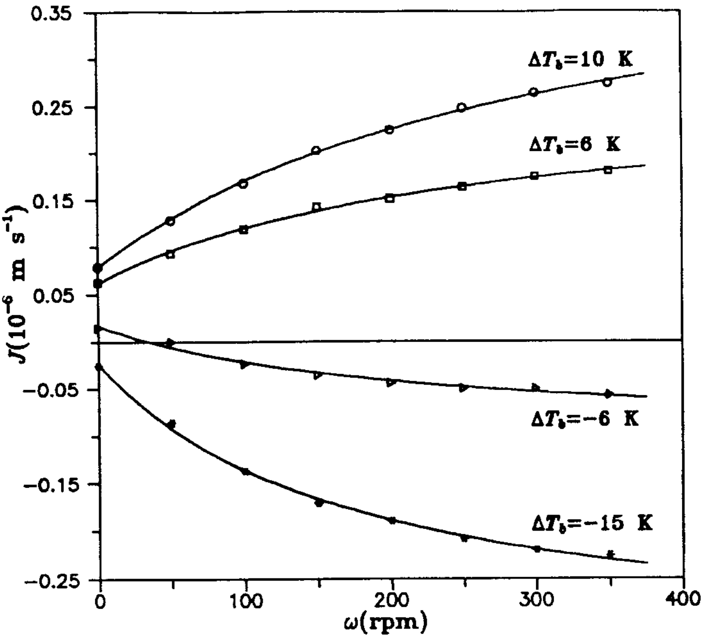

FIG. 2 Volume flux versus stirring rate for a concentration difference of 3 mol/L NaCl at four bulk temperature differences.

these intercepts are the bulk temperature differences which are equivalent to the chosen bulk concentration difference (3 mol/L) at the corresponding values of the stirring rate. Tables 1–18 show the values of the equivalent bulk temperature difference in a steady state for different values of concentration difference and stirring rate. The ΔT_b^{st} value increases, as expected, with concentration difference, but decreases with stirring rate. This fact may be explained if one considers that an increase in the stirring rate means a decrease in the effects of the polarization layers and, consequently, a smaller bulk temperature difference is required to counteract the previously chosen concentration difference. Taking into account that coefficient B' has been measured independently, the proportionality proposed in the Theory Section between $\Delta T_b^{st}(\omega)$ and the inverse of the coefficient B' may be confirmed (see Fig. 4). A visual inspection allows us to state that the agreement may be considered satisfactory.

Figure 5 shows the flux value as a function of the bulk concentration difference in some representative cases. The volume flux increases with

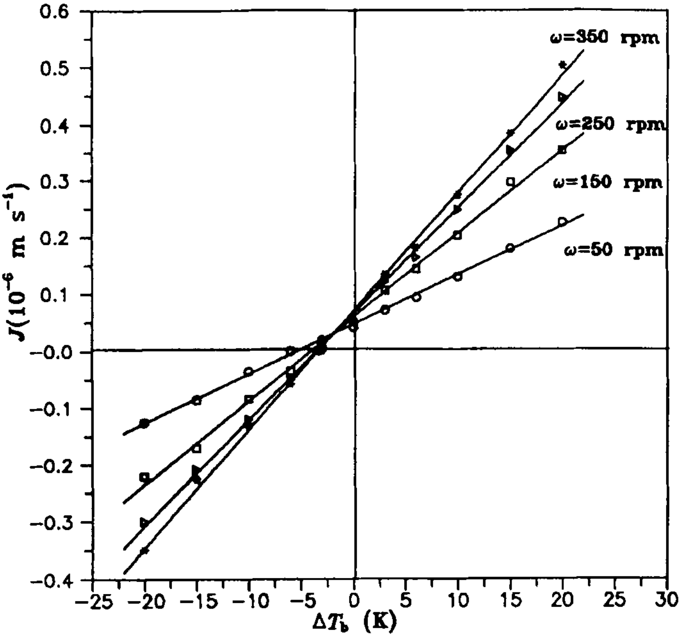

FIG. 3 Volume flux versus bulk temperature difference for a concentration difference of 3 mol/L NaCl and at various stirring rate values.

TABLE 1
Bulk Temperature Difference at Stationary State as a Function of Concentration Difference and Stirring Rate

Concentration difference (mol/L)	Stirring rate (rpm)							
	0	50	100	150	200	250	300	350
1	−3.09	−1.68	−1.27	−1.16	−1.08	−1.04	−0.92	−0.74
2	−6.01	−3.30	−2.63	−2.35	−2.23	−2.10	−2.04	−1.87
3	−8.36	−5.56	−4.09	−3.70	−3.33	−3.13	−3.10	−2.97
4	−14.28	−7.86	−6.04	−5.46	−4.85	−4.95	−4.72	−4.62
5	−16.11	−10.70	−7.40	−6.81	−6.512	−6.56	−6.66	−6.54

TABLE 2
Volume Flux as a Function of Temperature Difference and Stirring Rate[a]

Temperature difference (K)	Stirring rate (rpm)							
	0	50	100	150	200	250	300	350
20	0.135	0.218	0.312	0.345	0.365	0.442	0.476	0.515
15	0.085	0.165	0.228	0.278	0.312	0.334	0.357	0.364
10	0.057	0.108	0.161	0.183	0.205	0.220	0.236	0.234
6	0.0279	0.062	0.095	0.080	0.116	0.123	0.127	0.136
3	0.0123	0.033	0.050	0.056	0.061	0.068	0.069	0.081
−3	−0.010	−0.032	−0.050	−0.051	−0.051	−0.124	−0.140	−0.062
−6	−0.031	−0.065	−0.094	−0.110	−0.123	−0.131	−0.036	−0.147
−10	−0.052	−0.108	−0.053	−0.186	−0.181	−0.219	−0.236	−0.241
−15	−0.085	−0.169	−0.234	−0.279	−0.307	−0.330	−0.373	−0.365
−20	−0.138	−0.233	−0.328	−0.395	−0.431	−0.459	−0.502	−0.514

[a] The results correspond to a mean temperature of 40°C and pure water.

TABLE 3
Volume Flux as a Function of Temperature Difference and Stirring Rate[a]

Temperature difference (K)	Stirring rate (rpm)							
	0	50	100	150	200	250	300	350
20	0.145	0.218	0.305	0.357	0.391	0.447	0.467	0.492
15	0.098	0.173	0.232	0.281	0.308	0.318	0.363	0.334
10	0.063	0.065	0.095	0.180	0.201	0.225	0.234	0.248
6	0.032	0.065	0.095	0.106	0.201	0.136	0.144	0.147
3	0.021	0.043	0.055	0.065	0.074	0.086	0.086	0.092
−3	−0.003	−0.021	−0.030	−0.038	−0.045	−0.055	−0.064	−0.055
−6	−0.016	−0.055	−0.076	−0.093	−0.102	−0.117	−0.118	−0.127
−10	−0.039	−0.094	−0.127	−0.153	−0.177	−0.190	−0.211	−0.224
−15	−0.069	−0.147	−0.210	−0.252	−0.291	−0.307	−0.336	−0.350
−20	−0.098	−0.196	−0.284	−0.368	−0.368	−0.415	−0.440	−0.462

[a] The results correspond to a mean temperature of 40°C and a concentration difference of 0.5 mol/L.

TABLE 4
Volume Flux as a Function of Temperature Difference and Stirring Rate[a]

Temperature difference (K)	Stirring rate (rpm)							
	0	50	100	150	200	250	300	350
20	0.144	0.212	0.302	0.351	0.401	0.436	0.468	0.495
15	0.071	0.173	0.227	0.267	0.312	0.340	0.373	0.380
10	0.071	0.111	0.155	0.187	0.206	0.224	0.237	0.246
6	0.054	0.071	0.094	0.110	0.128	0.140	0.149	0.155
3	0.026	0.045	0.062	0.072	0.081	0.089	0.089	0.101
−3	0.000	−0.041	−0.021	−0.027	−0.032	−0.038	−0.040	−0.056
−6	−0.009	−0.041	−0.021	−0.081	−0.092	−0.100	−0.110	−0.114
−10	−0.032	−0.077	−0.118	−0.144	−0.159	−0.174	−0.183	−0.191
−15	−0.065	−0.132	−0.188	−0.235	−0.258	−0.279	−0.300	−0.311
−20	−0.094	−0.180	−0.268	−0.324	−0.358	−0.384	−0.408	−0.437

[a] The results correspond to a mean temperature of 40°C and a concentration difference of 1 mol/L.

TABLE 5
Volume Flux as a Function of Temperature Difference and Stirring Rate[a]

Temperature difference (K)	Stirring rate (rpm)							
	0	50	100	150	200	250	300	350
20	0.128	0.224	0.312	0.374	0.418	0.441	0.488	0.499
15	0.121	0.174	0.242	0.289	0.317	0.348	0.373	0.411
10	0.070	0.121	0.179	0.205	0.221	0.234	0.252	0.261
6	0.049	0.081	0.109	0.127	0.143	0.152	0.163	0.186
3	0.052	0.064	0.076	0.089	0.198	0.110	0.115	0.116
0	0.021	0.028	0.031	0.034	0.038	0.039	0.040	0.041
−3	0.018	0.006	−0.005	−0.009	−0.012	−0.018	−0.020	−0.023
−6	0.003	−0.027	−0.042	−0.059	−0.068	−0.077	−0.082	−0.089
−10	−0.021	−0.064	−0.095	−0.118	−0.128	−0.148	−0.158	−0.152
−15	−0.049	−0.114	−0.167	−0.195	−0.224	−0.246	−0.268	−0.275
−20	−0.081	−0.158	−0.235	−0.293	−0.356	−0.369	−0.369	−0.388

[a] The results correspond to a mean temperature of 40°C and a concentration difference of 2 mol/L.

TABLE 6
Volume Flux as a Function of Temperature Difference and Stirring Rate[a]

Temperature difference (K)	Stirring rate (rpm) 0	50	100	150	200	250	300	350
20	0.158	0.226	0.299	0.356	0.400	0.447	0.468	0.500
15	0.124	0.179	0.245	0.296	0.321	0.354	0.376	0.384
10	0.079	0.128	0.167	0.203	0.223	0.248	0.264	0.274
6	0.062	0.093	0.119	0.143	0.151	0.163	0.174	0.180
3	0.053	0.070	0.086	0.105	0.113	0.121	0.122	0.133
0	0.032	0.041	0.046	0.050	0.052	0.053	0.054	0.054
−3	0.029	0.018	0.013	0.007	0.005	0.000	0.000	0.000
−6	0.014	0.000	−0.024	−0.036	−0.045	−0.050	−0.050	−0.058
−10	0.000	−0.036	−0.069	−0.085	−0.106	−0.120	−0.128	−0.133
−15	−0.026	−0.086	−0.137	−0.171	−0.190	−0.208	−0.219	−0.275
−20	−0.054	−0.126	−0.193	−0.220	−0.274	−0.299	−0.322	−0.348

[a] The results correspond to a mean temperature of 40°C and a concentration difference of 3 mol/L.

TABLE 7
Volume Flux as a Function of Temperature Difference and Stirring Rate[a]

Temperature difference (K)	Stirring rate (rpm) 0	50	100	150	200	250	300	350
20	0.207	0.248	0.340	0.370	0.417	0.453	0.499	0.522
15	0.123	0.211	0.255	0.300	0.352	0.379	0.393	0.413
10	0.120	0.144	0.201	0.224	0.250	0.263	0.275	0.286
6	0.073	0.122	0.142	0.161	0.174	0.189	0.192	0.196
3	0.065	0.090	0.111	0.124	0.136	0.141	0.154	0.155
0	0.048	0.059	0.068	0.078	0.078	0.079	0.083	0.085
−3	0.042	0.038	0.036	0.035	0.034	0.032	0.031	0.030
−6	0.033	0.0166	0.000	−0.006	−0.014	−0.017	−0.021	−0.027
−10	0.018	−0.017	−0.045	−0.063	−0.071	−0.082	−0.0946	−0.099
−15	−0.044	−0.060	−0.108	−0.134	−0.167	−0.178	−0.190	−0.202
−20	−0.029	−0.103	−0.171	−0.212	−0.249	−0.266	−0.281	−0.299

[a] The results correspond to a mean temperature of 40°C and a concentration difference of 4 mol/L.

TABLE 8
Volume Flux as a Function of Temperature Difference and Stirring Rate[a]

Temperature difference	Stirring rate (rpm)							
(K)	0	50	100	150	200	250	300	350
20	0.199	0.240	0.333	0.378	0.425	0.462	0.489	0.514
15	0.145	0.211	0.267	0.323	0.357	0.383	0.405	0.418
10	0.120	0.157	0.201	0.230	0.287	0.287	0.296	0.312
6	0.082	0.120	0.147	0.177	0.197	0.203	0.220	0.222
3	0.080	0.103	0.133	0.143	0.157	0.165	0.175	0.180
0	0.058	0.073	0.083	0.094	0.101	0.104	0.111	0.113
−3	0.050	0.056	0.055	0.058	0.000	0.051	0.056	0.056
−6	0.057	0.032	0.014	0.007	0.000	0.005	0.007	0.004
−10	0.030	0.007	−0.030	−0.042	−0.050	−0.052	−0.050	−0.058
−15	0.005	−0.032	−0.086	−0.113	−0.129	−0.133	−0.143	−0.149
−20	−0.016	−0.072	−0.142	−0.179	−0.209	−0.213	−0.235	−0.257

[a] The results correspond to a mean temperature of 40°C and a concentration difference of 5 mol/L.

TABLE 9
Volume Flux as a Function of Concentration Difference and Stirring Rate[a]

Concentration	Stirring rate (rpm)				
(mol/L)	0	50	150	250	350
0	0.021	0.046	0.079	0.092	0.102
1	0.033	0.054	0.085	0.098	0.110
3	0.048	0.070	0.102	0.115	0.124
5	0.070	0.092	0.120	0.138	0.146

[a] The results correspond to a mean temperature of 30°C and a bulk temperature difference of 6 K.

TABLE 10
Volume Flux as a Function of Concentration Difference and Stirring Rate[a]

Concentration	Stirring rate (rpm)				
(mol/L)	0	50	150	250	350
0	−0.017	−0.047	−0.073	−0.085	−0.089
1	−0.007	−0.033	−0.052	−0.070	−0.078
3	0.014	−0.006	−0.025	−0.035	−0.040
5	0.042	0.023	−0.010	−0.004	0.000

[a] The results correspond to a mean temperature of 30°C and a bulk temperature difference of −6 K.

TABLE 11
Volume Flux as a Function of Concentration Difference and Stirring Rate[a]

Concentration (mol/L)	Stirring rate (rpm)				
	0	50	150	250	350
0	0.024	0.059	0.099	0.117	0.129
1	0.048	0.068	0.104	0.134	0.145
3	0.067	0.097	0.126	0.148	0.161
5	0.086	0.119	0.169	0.193	0.211

[a] The results correspond to a mean temperature of 35°C and a bulk temperature difference of 6 K.

TABLE 12
Volume Flux as a Function of Concentration Difference and Stirring Rate[a]

Concentration (mol/L)	Stirring rate (rpm)				
	0	50	150	250	350
0	−0.022	−0.070	−0.104	−0.116	−0.128
1	−0.011	−0.041	−0.069	−0.088	−0.099
3	−0.016	−0.017	−0.038	−0.047	−0.053
5	0.073	0.029	−0.006	0.000	−0.004

[a] The results correspond to a mean temperature of 35°C and a bulk temperature difference of −6 K.

TABLE 13
Volume Flux as a Function of Concentration Difference and Stirring Rate[a]

Concentration (mol/L)	Stirring rate (rpm)				
	0	50	150	250	350
0	0.027	0.062	0.107	0.123	0.135
1	0.053	0.071	0.109	0.140	0.155
3	0.063	0.093	0.143	0.163	0.180
5	0.082	0.120	0.177	0.287	0.312

[a] The results correspond to a mean temperature of 40°C and a bulk temperature difference of 6 K.

TABLE 14

Volume Flux as a Function of Concentration Difference and Stirring Rate[a]

Concentration (mol/L)	Stirring rate (rpm)				
	0	50	150	250	350
0	−0.031	−0.005	−0.110	−0.132	−0.148
1	−0.009	−0.040	−0.081	−0.100	−0.115
3	0.040	0.000	−0.085	−0.120	−0.275
5	0.057	0.007	−0.042	−0.052	−0.058

[a] The results correspond to a mean temperature of 40°C and a bulk temperature difference of −6 K.

TABLE 15

Volume Flux as a Function of Concentration Difference and Stirring Rate[a]

Concentration (mol/L)	Stirring rate (rpm)				
	0	50	150	250	350
0	0.031	0.066	0.114	0.140	0.153
1	0.048	0.106	0.141	0.165	0.174
3	0.070	0.113	0.157	0.196	0.213
5	0.119	0.144	0.194	0.235	0.255

[a] The results correspond to a mean temperature of 45°C and a bulk temperature difference of 6 K.

TABLE 16

Volume Flux as a Function of Concentration Difference and Stirring Rate[a]

Concentration (mol/L)	Stirring rate (rpm)				
	0	50	150	250	350
0	0.028	−0.071	−0.121	−0.142	−0.161
1	0.012	−0.049	−0.089	−0.114	−0.126
3	0.031	−0.005	−0.033	−0.051	−0.059
5	0.052	0.039	−0.020	0.013	0.010

[a] The results correspond to a mean temperature of 45°C and a bulk temperature difference of −6 K.

TABLE 17
Volume Flux as a Function of Concentration Difference and Stirring Rate[a]

Concentration (mol/L)	Stirring rate (rpm)				
	0	50	150	250	350
0	0.048	0.088	0.152	0.184	0.208
1	0.053	0.106	0.152	0.187	0.222
3	0.084	0.128	0.190	0.223	0.252
5	0.117	0.156	0.232	0.272	0.311

[a] The results correspond to a mean temperature of 50°C and a bulk temperature difference of 6 K.

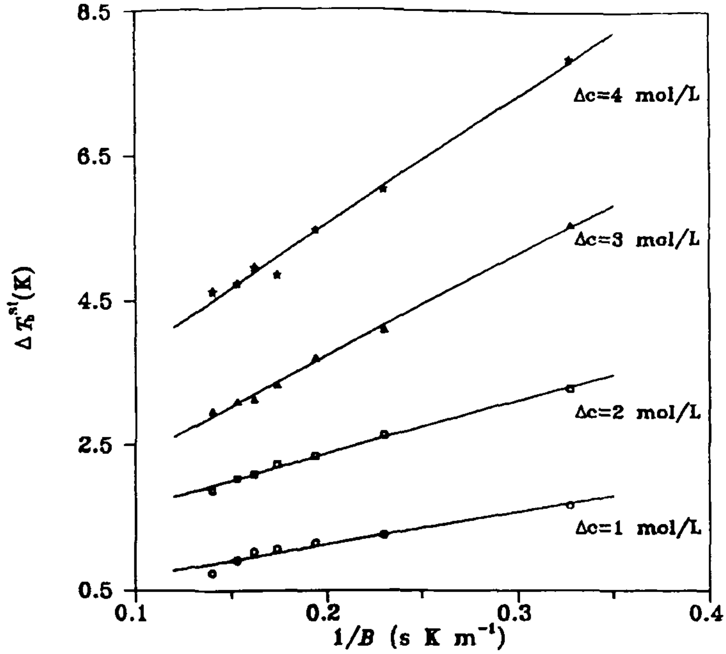

FIG. 4 Steady-state bulk temperature difference for various sodium chloride concentration differences versus the inverse of the apparent membrane distillation coefficient.

TABLE 18
Volume Flux as a Function of Concentration Difference and Stirring Rate[a]

Concentration (mol/L)	Stirring rate (rpm)				
	0	50	150	250	350
0	−0.031	−0.074	−0.128	−0.153	−0.176
1	−0.014	−0.051	−0.096	−0.124	−0.139
3	0.009	−0.010	−0.036	−0.055	−0.072
5	0.063	0.046	0.027	0.019	0.013

[a] The results correspond to a mean temperature of 50°C and a bulk temperature difference of −6 K.

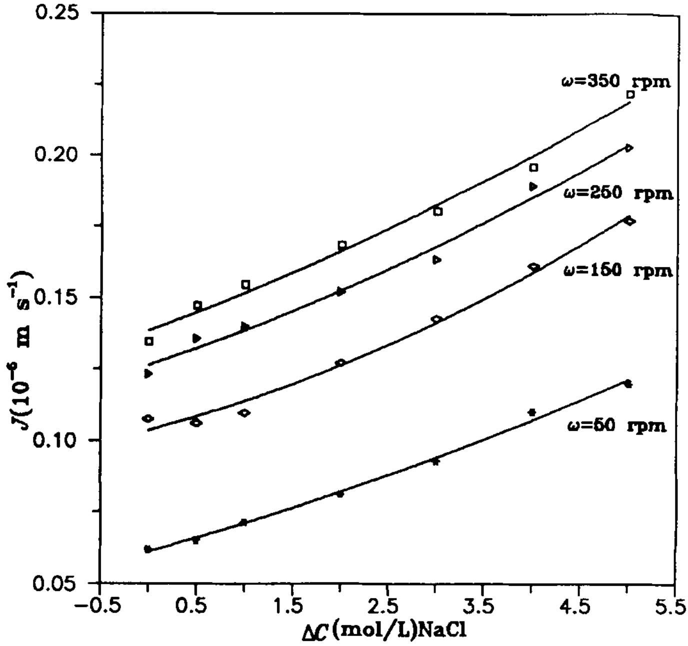

FIG. 5 Volume flux versus bulk sodium chloride concentration difference at four stirring rates and at a bulk temperature difference of 6 K.

the concentration difference. The dependence separates from linearity for the greatest concentration differences. This result is not unexpected and had been previously checked (16) in pure osmotic distillation experiments.

The dependence of the volume flux on mean temperature is more complicated. As it was discussed in the Theory Section, the simple Arrhenius type of dependence is only fulfilled in "pure" cases, not when the two thermodynamic forces act simultaneously.

NOTATIONS

a	activity
A	phenomenological coefficient
A'	phenomenological coefficient
B	net membrane distillation coefficient
B'	apparent membrane distillation coefficient
c	solute concentration
C	net osmotic distillation coefficient
C'	apparent osmotic distillation coefficient
J	volume flux
J_0	volume flux without stirring
L	heat of vaporization
P	vapor pressure
R	gas constant
T	absolute temperature
X	adjustment parameter
Y	adjustment parameter
ω	stirring rate

Superscripts

o	pure water

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