Supporting Information

Title Reformulating the Permselectivity-Conductivity Tradeoff Relation in Ion-Exchange Membranes

*Jovan Kamcev**

Department of Chemical Engineering
Macromolecular Science and Engineering
University of Michigan, North Campus Research Complex B28, 2800 Plymouth Rd., Ann Arbor, MI 48109 USA
E-mail: jkamcev@umich.edu

Table of Contents

S1. Properties of IEMs for electrodialysis/reverse electrodialysis

Membrane properties reported in the literature were extracted from either tables or plots via the Engauge Digitizer freeware software. The numerical values used to generate Figures 1 and 2 in the main text are tabulated below.

Table 1. Properties of anion-exchange membranes. Apparent permselectivity measurements were performed via the static method using 0.5 M NaCl solution on one side of the membrane and 0.1 M NaCl solution on the other side of the membrane. Ionic conductivity measurements were performed with membrane equilibrated with 0.5 M NaCl solutions.

Membrane	Apparent Permselectivity	Ionic Conductivity (S/m)	$\alpha_{g/c}$	$C_g^m D_g^m$ ($\times 10^{-9}$ $mol/(cm \cdot s)$)	Reference
aPPO-C6D2	0.906	0.034	20.3	0.085	1
aPPO-C16D4	0.907	0.038	20.4	0.095	1
aPPO-C6D6	0.855	0.313	12.8	0.772	1
Selemion AMV	0.927	0.270	26.2	0.692	1
Membr. Int. AMI	0.806	0.255	9.3	0.613	1
aPPO-20	0.890	0.105	17.2	0.263	1
aPPO-27	0.897	0.170	18.4	0.429	1
aPPO-24	0.900	0.190	19.0	0.480	1
aRadel-1.76	0.892	0.115	17.5	0.290	1
aRadel-1.87	0.862	0.171	13.5	0.425	1
aRadel-2.66	0.849	0.625	12.3	1.54	1
PECH A	0.902	0.376	19.5	0.953	2

PECH B-1	0.865	0.402	13.8	0.998	2
PECH C	0.792	0.675	8.6	1.61	2
PECH B-2	0.871	0.819	14.6	2.04	2
PECH B-3	0.869	0.985	14.3	2.45	2
AMX	0.907	0.570	20.5	1.45	3
AMH-PES	0.893	0.932	17.7	2.35	3
FAD	0.860	0.831	13.3	2.06	3
Qianqiu	0.863	1.03	13.6	2.56	3
AMV	0.873	0.394	14.7	0.981	3
FAS	0.894	0.320	17.9	0.807	3
AEM 1	0.956	0.227	44.5	0.59	4
AEM 2	0.956	0.432	44.5	1.12	4
AEM 3	0.95	0.673	39.0	1.75	4
AEM 4	0.948	1.06	37.5	2.75	4
AEM 5	0.946	1.23	36.0	3.19	4
AEM 6	0.949	1.54	38.2	3.99	4
AEM 7	0.948	1.83	37.5	4.74	4
AEM 8	0.943	1.87	34.1	4.83	4
AEM 9	0.944	1.76	34.7	4.54	4
AEM 10	0.943	1.55	34.1	4.01	4
AEM 11	0.939	1.46	31.8	3.77	4

AEM 12	0.93	1.82	27.6	4.67	4
AEM 13	0.925	1.93	25.7	4.94	4
AEM 14	0.922	2.01	24.6	5.14	4
AEM 15	0.917	1.46	23.1	3.72	4
AEM 16	0.917	1.89	23.1	4.82	4
AEM 17	0.919	2.32	23.7	5.92	4
AEM 18	0.92	2.38	24.0	6.08	4
AEM 19	0.919	2.46	23.7	6.28	4
AEM 20	0.915	2.35	22.5	5.99	4
AEM 21	0.915	2.32	22.5	5.91	4
AEM 22	0.913	2.24	22.0	5.70	4

Table 2. Properties of cation-exchange membranes. Apparent permselectivity measurements were performed via the static method using 0.5 M NaCl solution on one side of the membrane and 0.1 M NaCl solution on the other side of the membrane. Ionic conductivity measurements were performed with membrane equilibrated with 0.5 M NaCl solutions in all studies except [5], in which 1 M NaCl was used.

Membrane	Apparent Permselectivity	Ionic Conductivity (S/m)	$\alpha_{g/c}$	$C_g^m D_g^m$ $(\times 10^{-9}\ mol/(cm \cdot s))$	Reference
CMX	0.99	0.564	199	1.49	3
CMH-PES	0.947	0.618	36.7	1.60	3
FKS	0.942	0.267	33.5	0.689	3
Qianqiu	0.82	1.04	10.1	2.52	3
CMV	0.988	0.441	166	1.17	3

FKD	0.895	0.528	18.0	1.33	3
SPEEK 65	0.891	0.590	17.3	1.49	3
SPEEK 40	0.953	0.259	41.6	0.672	3
sCNT 0 wt %	0.862	0.613	17.3	1.54	5
sCNT 2 wt %	0.858	0.621	16.8	1.56	5
sCNT 10 wt %	0.862	0.800	17.3	2.01	5
sCNT 20 wt %	0.845	0.820	15.3	2.05	5
GCM-0-29	0.958	1.05	46.6	2.74	6
GCM-0-34	0.937	1.16	30.7	2.99	6
GCM-0-42	0.935	1.72	29.8	4.43	6
GCM-0-58	0.889	2.53	17.0	6.36	6
GCM-0-60	0.87	2.59	14.4	6.44	6
GCM-0-63	0.87	2.72	14.4	6.77	6
GCM-0-71	0.871	2.51	14.5	6.25	6
GCM-0.5-33	0.964	1.25	54.6	3.27	6
GCM-0.5-45	0.882	1.96	15.9	4.91	6
GCM-1.5-50	0.938	1.67	31.3	4.31	6
GCM-2.5-30	0.983	0.51	117	1.35	6
GCM-2.5-70	0.943	2.03	34.1	5.25	6
GCM-2.5-120	0.915	2.42	22.5	6.17	6
GCM-3-51	0.971	1.39	68.0	3.65	6

GCM-5-85	0.99	1.27	199	3.36	6
sPPO	0.877	1.29	15.3	3.22	6
MSC-0-23	0.76	1.69	7.3	3.96	6
MSC-0-31	0.721	2.72	6.2	6.23	6
MSC-1.5-27	0.956	0.97	44.5	2.52	6
MSC-3.5-29	0.967	0.97	59.6	2.54	6
MSC-3.5-32	0.967	1.13	59.6	2.96	6
Nafion 117	0.902	2.8	19.4	7.09	6
Nafion 120	0.96	1.6	49.0	4.17	6

S2. Properties of IEMs for vanadium redox flow batteries

Table 3. Properties of cation-exchange membranes for vanadium redox flow batteries.

Membrane	Proton Conductivity (S/m)	Vanadium Permeability (cm²/min)	Permeability Measurement Conditions	$\alpha_{H/V}$	$C_H^m D_H^m$ ($\times 10^{-8}\ mol/(cm \cdot s)$)	Ref.
BPSH60	12.1	2.17×10^{-5}	1 M salts in 2 M H_2SO_4	22.3	3.22	7
P-BPSH60 (R5)	10.4	9.90×10^{-6}	1 M salts in 2 M H_2SO_4	41.9	2.77	7
P-BPSH60 (R7)	10.4	9.40×10^{-6}	1 M salts in 2 M H_2SO_4	44.2	2.77	7
P-BPSH60 (R10)	10.8	1.17×10^{-5}	1 M salts in 2 M H_2SO_4	36.8	2.87	7
Nafion 212	7.4	4.10×10^{-6}	1 M salts in 2 M H_2SO_4	72.1	1.97	7
Nafion 117	5.9	3.20×10^{-6}	1 M salts in 2 M H_2SO_4	73.6	1.57	7
N-PWA-10%	6.6	9.85×10^{-7}	1.5 M salts in 3 M H_2SO_4	178.3	1.76	8
N-PWA-20%	6.4	6.74×10^{-7}	1.5 M salts in 3 M H_2SO_4	252.8	1.70	8
N-PWA-30%	6.1	2.46×10^{-7}	1.5 M salts in 3 M H_2SO_4	660.0	1.62	8
N-PWA-40%	5.3	1.13×10^{-6}	1.5 M salts in 3 M H_2SO_4	125.1	1.41	8

PSf-MI-PS 126%	5.2	1.08×10^{-7}	1.5 M salts in 3 M H_2SO_4	1281.4	1.38	9
PSf-MI-PS 150%	7	1.44×10^{-7}	1.5 M salts in 3 M H_2SO_4	1293.7	1.86	9
PSf-MI-PS 190%	10.9	4.74×10^{-7}	1.5 M salts in 3 M H_2SO_4	612.0	2.90	9
sPEEK	3.9	2.26×10^{-7}	1.5 M salts in 3 M H_2SO_4	459.3	1.04	10
sPEEK/PVdF (95/5)	3.2	6.00×10^{-8}	1.5 M salts in 3 M H_2SO_4	1419.4	0.85	10
PEEK/PVdF/UAN (95/5/1)	3.8	6.00×10^{-8}	1.5 M salts in 3 M H_2SO_4	1685.5	1.01	10
PEEK/PVdF/UAN (95/5/2)	3.7	6.00×10^{-8}	1.5 M salts in 3 M H_2SO_4	1641.2	0.98	10
PEEK/PVdF/UAN (95/5/5)	3.8	6.50×10^{-8}	1.5 M salts in 3 M H_2SO_4	1555.9	1.01	10
SPTES-45	2.3	1.23×10^{-7}	1.2 M salts in 3 M H_2SO_4	627.6	0.62	11
SPTES-50	4.4	2.60×10^{-7}	1.2 M salts in 3 M H_2SO_4	563.9	1.17	11
SPTES-55	9.2	2.96×10^{-7}	1.2 M salts in 3 M H_2SO_4	1036.2	2.45	11
SPES-45	3.7	2.03×10^{-8}	1.2 M salts in 3 M H_2SO_4	6064.2	0.98	11
SPES-50	4.9	2.30×10^{-8}	1.2 M salts in 3 M H_2SO_4	7053.4	1.30	11

SPES-55	10	6.14×10^{-8}	1.2 M salts in 3 M H_2SO_4	5418.1	2.66	11
SPFEK-[PDDA/PSS] (0)	2.5	2.26×10^{-7}	1 M salts in 2 M H_2SO_4	432.8	0.65	12
SPFEK-[PDDA/PSS] (2)	2.4	1.16×10^{-7}	1 M salts in 2 M H_2SO_4	819.1	0.63	12
SPFEK-[PDDA/PSS] (4)	2.3	1.09×10^{-7}	1 M salts in 2 M H_2SO_4	842.4	0.61	12
SPFEK-[PDDA/PSS] (6)	2.1	1.00×10^{-7}	1 M salts in 2 M H_2SO_4	854.3	0.57	12
SPFEK-[PDDA/PSS] (8)	1.9	8.90×10^{-8}	1 M salts in 2 M H_2SO_4	870.2	0.52	12
SPFEK-[PDDA/PSS] (10)	1.8	8.50×10^{-8}	1 M salts in 2 M H_2SO_4	850.1	0.48	12
SPEEK	3.0	2.30×10^{-8}	1.5 M salts in 3 M H_2SO_4	3477.1	0.80	13
SPEEK/L10	2.9	1.80×10^{-8}	1.5 M salts in 3 M H_2SO_4	4259.3	0.77	13
SPEEK/L15	3.0	1.70×10^{-8}	1.5 M salts in 3 M H_2SO_4	4627.1	0.79	13
SPEEK/L20	2.6	2.02×10^{-8}	1.5 M salts in 3 M H_2SO_4	3449.7	0.70	13
SPEEK/L25	2.5	4.20×10^{-8}	1.5 M salts in 3 M H_2SO_4	1570.2	0.66	13
OPBI	0.60	9.87×10^{-9}	1.5 M salts in 3 M H_2SO_4	1612.5	0.16	14

OPBI/BF4-5	0.59	9.24×10^{-9}	1.5 M salts in 3 M H_2SO_4	1702.2	0.16	14
OPBI/BF4-10	0.67	8.33×10^{-9}	1.5 M salts in 3 M H_2SO_4	2127.8	0.18	14
OPBI/BF4-15	0.68	6.22×10^{-9}	1.5 M salts in 3 M H_2SO_4	2909.5	0.18	14
OPBI/BF4-20	0.74	5.25×10^{-9}	1.5 M salts in 3 M H_2SO_4	3746.2	0.20	14
BPSH25	2.3	6.60×10^{-8}	1 M salts in 3 M H_2SO_4	1391.2	0.61	15
BPSH35	7.5	9.60×10^{-8}	1 M salts in 3 M H_2SO_4	3118.8	2.00	15
BPSH45	14	9.60×10^{-8}	1 M salts in 3 M H_2SO_4	58.2	3.73	15
SPI	3.3	1.89×10^{-7}	1 M salts in 2 M H_2SO_4	694.9	0.88	16
SPI/AIOOH-5 %	3.1	1.77×10^{-7}	1 M salts in 2 M H_2SO_4	703.7	0.83	16
SPI/AIOOH-10 %	3.1	1.14×10^{-7}	1 M salts in 2 M H_2SO_4	1068.1	0.81	16
SPI/AIOOH-15 %	2.8	1.42×10^{-7}	1 M salts in 2 M H_2SO_4	790.0	0.75	16
SPI/AIOOH-20 %	1.7	2.95×10^{-7}	1 M salts in 2 M H_2SO_4	231.4	0.46	16
SD3-7-100	1.4	7.33×10^{-8}	1.5 M salts in 3 M H_2SO_4	515.3	0.38	17

SD4-6-100	1.8	3.83×10^{-8}	1.5 M salts in 3 M H_2SO_4	1263.6	0.48	17
SD5-5-100	4.0	1.32×10^{-6}	1.5 M salts in 3 M H_2SO_4	80.6	1.06	17

S3. References

1. Geise, G. M., Hickner, M. A., Logan, B. E. *ACS Appl. Mater. Interfaces*, 2013, **5**, 10294–10301.
2. Guler, E., Zhang, Y., Saakes, M., Nijmeijer, K. *ChemSusChem*, 2012, **5**, 2262–2270.
3. Güler, E., Elizen, R., Vermaas, D. A., Saakes, M., Nijmeijer, K. *J. Memb. Sci.*, 2013, **446**, 266–276.
4. Golubenko, D. V., Van der Bruggen, B., Yaroslavtsev, A. B. *J. Appl. Polym. Sci.*, 2020, **137**, 48656.
5. Fan, H., Huang, Y., Yip, N. Y. *J. Memb. Sci.*, 2020, **610**, 118259.
6. Golubenko, D. V., Pourcelly, G., Yaroslavtsev, A. B. *Sep. Purif. Technol.*, 2018, **207**, 329–335.
7. Wang, T., Moon, S. J., Hwang, D. S., Park, H., Lee, J., Kim, S., Lee, Y. M., Kim, S. *J. Memb. Sci.*, 2019, **583**, 16–22.
8. Yang, X. B., Zhao, L., Sui, X. L., Meng, L. H., Wang, Z. B. *J. Colloid Interface Sci.*, 2019, **542**, 177–186.
9. Yan, X., Zhang, C., Dong, Z., Jiang, B., Dai, Y., Wu, X., He, G. *ACS Appl. Mater. Interfaces*, 2018, **10**, 32247–32255.
10. Jung, H. Y., Cho, M. S., Sadhasivam, T., Kim, J. Y., Roh, S. H., Kwon, Y. *Solid State Ionics*, 2018, **324**, 69–76.
11. Choi, S. W., Kim, T. H., Jo, S. W., Lee, J. Y., Cha, S. H., Hong, Y. T. *Electrochim. Acta*, 2018, **259**, 427–439.
12. Wang, Y., Wang, S., Xiao, M., Han, D., Hickner, M. A., Meng, Y. *RSC Adv.*, 2013, **3**, 15467–15474.
13. Ye, J., Cheng, Y., Sun, L., Ding, M., Wu, C., Yuan, D., Zhao, X., Xiang, C., Jia, C. *J. Memb. Sci.*, 2019, **572**, 110–118.
14. Song, X., Ding, L., Wang, L., He, M., Han, X. *Electrochim. Acta*, 2019, **295**, 1034–1043.
15. Semiz, L., Demirci Sankir, N., Sankir, M. *J. Memb. Sci.*, 2014, **468**, 209–215.
16. Zhang, Y., Li, J., Wang, L., Zhang, S. *J. Solid State Electrochem.*, 2014, **18**, 3479–3490.
17. Zhang, H., Zhang, H., Li, X., Mai, Z., Wei, W., Li, Y. *J. Power Sources*, 2012, **217**, 309–315.