Electronic Supplementary Materials

For https://doi.org/10.1631/jzus.A1900181

Mass transfer enhancement of hollow fiber membrane deoxygenation by Dean vortices

Qing-ran KONG, Yi-zhen ZHANG, Hua TIAN, Li-feng FANG,
Ming-yong ZHOU, Li-ping ZHU, Bao-ku ZHU[†‡]

Key Laboratory of Macromolecule Synthesis and Functionalization (Ministry of Education), Key Laboratory of Adsorption and Separation Materials & Technologies of Zhejiang Province, ERC of Membrane and Water Treatment (Ministry of Education), Department of Polymer Science and Engineering, Zhejiang University, Hangzhou, 310027, China

[†]E-mail: zhubk@zju.edu.cn

[‡] Corresponding author

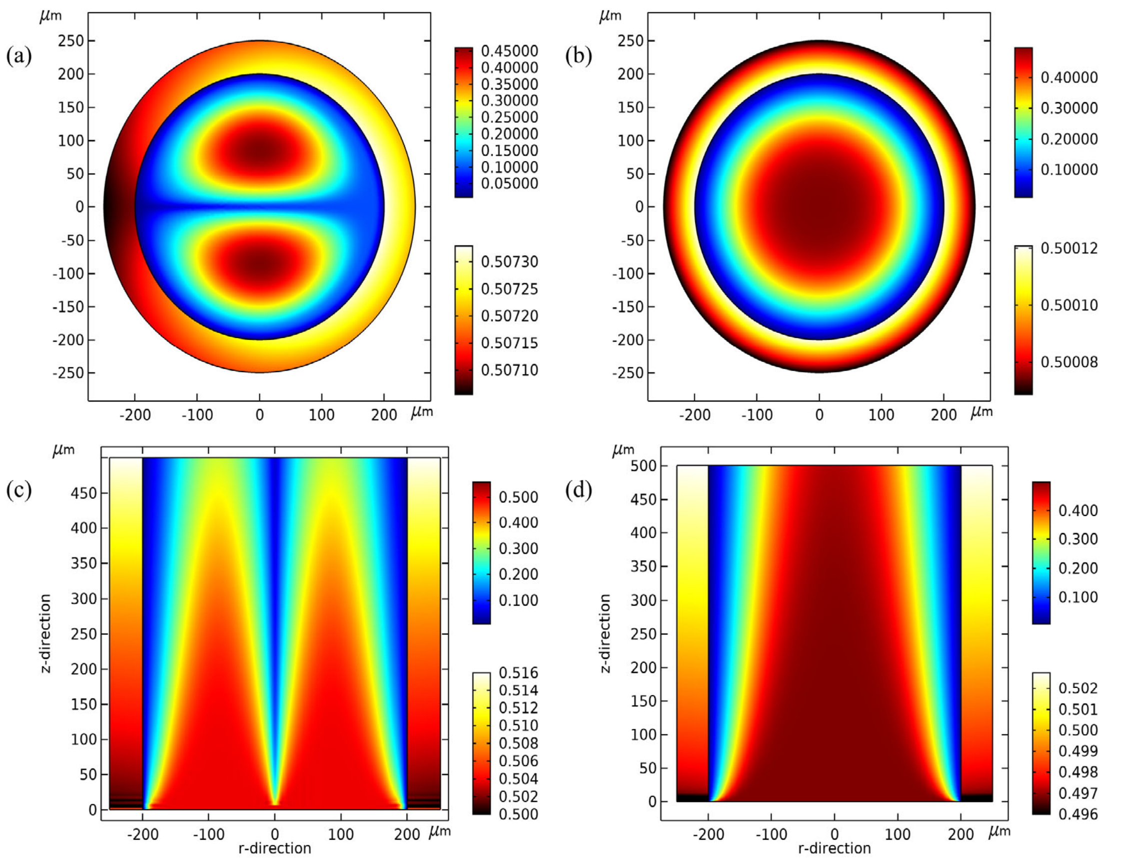

Fig. S1 Concentration profiles of N_2 of (a) HHFM deoxygenation (κ =162.9 m^{-1}, z=0.5 m), (b) SHFM deoxygenation (κ =0, z=0.5 m) on the cross-section and (c) HHFM deoxygenation (κ =162.9 m^{-1}), (d) SHFM deoxygenation (κ =0) along the axis direction. Re=217, T=298.2 K, $\overline{v}$ =0.5 m s^{-1}, p/p_0=0.50, l=1.0 m

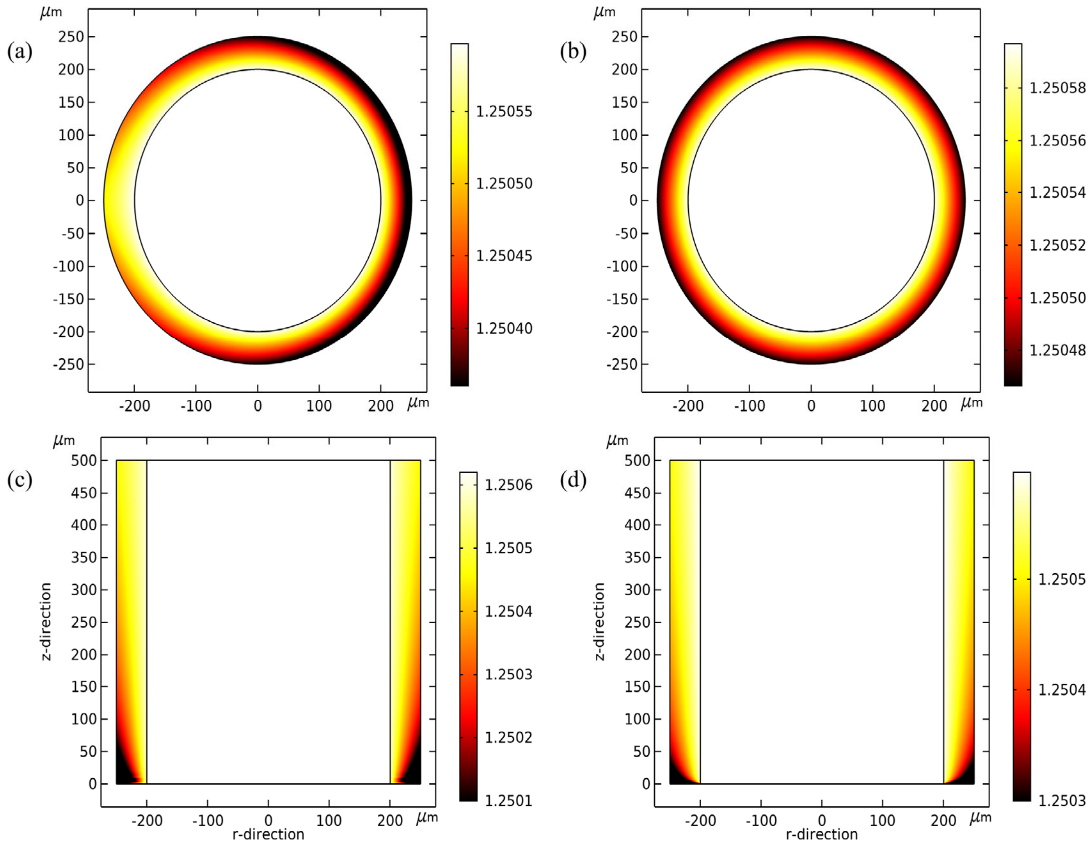

Fig. S2 Porous membrane concentration profiles of H_2O vapor of (a) HHFM deoxygenation (κ =162.9 m^{-1}, z=0.5 m), (b) SHFM deoxygenation (κ =0, z=0.5 m) on the cross-section and (c) HHFM deoxygenation (κ =162.9 m^{-1}), (d) SHFM deoxygenation (κ =0) along the axis direction. Re=217, T=298.2 K, $\overline{v}$ =0.5 m s^{-1}, p/p_0=0.50, l=1.0 m

Table S1 Parameters used for simulation

T (K)	$D_{O2,l}$ ($\times10^{-9}$ m^2 s^{-1})	$D_{N2,l}$ ($\times10^{-9}$ m^2 s^{-1})	$D_{O2,k}$ ($\times10^{-5}$ m^2 s^{-1})	$D_{N2,k}$ ($\times10^{-5}$ m^2 s^{-1})	$D_{H2O,k}$ ($\times10^{-5}$ m^2 s^{-1})	μ_w ($\times10^{-6}$ m^2 s^{-1})
278.2	2.011	1.254	2.859	3.057	3.812	1.377
288.2	2.084	1.495	2.910	3.111	3.880	1.129
298.2	2.156	1.803	2.960	3.165	3.946	0.919
308.2	2.228	2.176	3.010	3.217	4.012	0.748

Table S1 (continued) Parameters used for simulation

T (K)	$\mu_{O2,g}$ ($\times10^{-5}$ Pa s)	$\mu_{N2,g}$ ($\times10^{-5}$ Pa s)	$\mu_{H2O,g}$ ($\times10^{-6}$ Pa s)	H_{O2} (GPa)	H_{N2} (GPa)	p_w (kPa)
278.2	1.945	1.682	8.214	2.893	6.001	0.847
288.2	1.998	1.726	8.614	3.692	7.446	1.685
298.2	2.050	1.769	9.014	4.423	8.752	3.098
308.2	2.103	1.813	9.414	5.086	9.918	5.555

Table S2 Experimental data of HHFM and SHFM deoxygenation

No.	v (m s^{-1})	κ (m^{-1})	p/p_0	T (K)	c_f (mol m^{-3})	c_{out} (mol m^{-3})	σ (x10^{-2})*
1	0.10	162.9	0.90	298.2	0.256	0.246	1.81
2	0.25	162.9	0.90	298.2	0.256	0.249	1.33
3	0.50	162.9	0.90	298.2	0.256	0.252	2.43
4	0.75	162.9	0.90	298.2	0.256	0.253	1.11
5	1.00	162.9	0.90	298.2	0.256	0.253	1.93
6	1.25	162.9	0.90	298.2	0.256	0.254	2.69
7	0.10	162.9	0.70	298.2	0.256	0.224	0.59
8	0.25	162.9	0.70	298.2	0.256	0.236	2.18
9	0.50	162.9	0.70	298.2	0.256	0.244	2.52
10	0.75	162.9	0.70	298.2	0.256	0.247	1.98
11	1.00	162.9	0.70	298.2	0.256	0.249	2.07
12	1.25	162.9	0.70	298.2	0.256	0.251	1.53
13	0.10	162.9	0.50	298.2	0.256	0.188	0.55
14	0.25	162.9	0.50	298.2	0.256	0.212	2.74
15	0.50	162.9	0.50	298.2	0.256	0.227	2.35
16	0.75	162.9	0.50	298.2	0.256	0.233	1.36
17	1.00	162.9	0.50	298.2	0.256	0.236	1.28
18	1.25	162.9	0.50	298.2	0.256	0.239	1.95
19	0.10	162.9	0.30	298.2	0.256	0.139	1.37
20	0.25	162.9	0.30	298.2	0.256	0.178	1.51
21	0.50	162.9	0.30	298.2	0.256	0.203	1.61
22	0.75	162.9	0.30	298.2	0.256	0.213	2.08
23	1.00	162.9	0.30	298.2	0.256	0.219	2.57
24	1.25	162.9	0.30	298.2	0.256	0.222	1.83
25	0.10	162.9	0.050	298.2	0.256	0.0550	0.36
26	0.25	162.9	0.050	298.2	0.256	0.118	1.46

27	0.50	162.9	0.050	298.2	0.256	0.159	1.44
28	0.75	162.9	0.050	298.2	0.256	0.176	0.74
29	1.00	162.9	0.050	298.2	0.256	0.185	2.49
30	1.25	162.9	0.050	298.2	0.256	0.192	2.18
31	0.10	0	0.90	298.2	0.256	0.248	2.80
32	0.25	0	0.90	298.2	0.256	0.252	1.43
33	0.50	0	0.90	298.2	0.256	0.254	1.58
34	0.75	0	0.90	298.2	0.256	0.255	2.03
35	1.00	0	0.90	298.2	0.256	0.255	0.88
36	1.25	0	0.90	298.2	0.256	0.255	1.91
37	0.10	0	0.70	298.2	0.256	0.232	2.39
38	0.25	0	0.70	298.2	0.256	0.243	1.83
39	0.50	0	0.70	298.2	0.256	0.250	1.98
40	0.75	0	0.70	298.2	0.256	0.252	1.36
41	1.00	0	0.70	298.2	0.256	0.253	2.53
42	1.25	0	0.70	298.2	0.256	0.254	1.47
43	0.10	0	0.50	298.2	0.256	0.205	1.46
44	0.25	0	0.50	298.2	0.256	0.227	1.78
45	0.50	0	0.50	298.2	0.256	0.240	1.74
46	0.75	0	0.50	298.2	0.256	0.245	2.18
47	1.00	0	0.50	298.2	0.256	0.248	2.15
48	1.25	0	0.50	298.2	0.256	0.249	2.53
49	0.10	0	0.30	298.2	0.256	0.169	1.61
50	0.25	0	0.30	298.2	0.256	0.205	1.57
51	0.50	0	0.30	298.2	0.256	0.226	2.31
52	0.75	0	0.30	298.2	0.256	0.235	1.90
53	1.00	0	0.30	298.2	0.256	0.240	1.06
54	1.25	0	0.30	298.2	0.256	0.243	2.40

55	0.10	0	0.050	298.2	0.256	0.104	0.10
56	0.25	0	0.050	298.2	0.256	0.166	0.47
57	0.50	0	0.050	298.2	0.256	0.201	2.11
58	0.75	0	0.050	298.2	0.256	0.217	1.83
59	1.00	0	0.050	298.2	0.256	0.225	1.94
60	1.25	0	0.050	298.2	0.256	0.230	2.46
61	0.10	162.9	0.050	278.2	0.391	0.111	0.83
62	0.25	162.9	0.050	278.2	0.391	0.203	1.32
63	0.50	162.9	0.050	278.2	0.391	0.259	1.62
64	0.75	162.9	0.050	278.2	0.391	0.282	1.22
65	1.00	162.9	0.050	278.2	0.391	0.297	0.49
66	1.25	162.9	0.050	278.2	0.391	0.309	0.59
67	0.10	162.9	0.050	288.2	0.314	0.0791	0.43
68	0.25	162.9	0.050	288.2	0.314	0.154	0.92
69	0.50	162.9	0.050	288.2	0.314	0.200	1.47
70	0.75	162.9	0.050	288.2	0.314	0.220	0.67
71	1.00	162.9	0.050	288.2	0.314	0.233	2.07
72	1.25	162.9	0.050	288.2	0.314	0.243	2.24
73	0.10	162.9	0.050	308.2	0.218	0.0352	0.24
74	0.25	162.9	0.050	308.2	0.218	0.0898	0.87
75	0.50	162.9	0.050	308.2	0.218	0.124	0.89
76	0.75	162.9	0.050	308.2	0.218	0.140	1.22
77	1.00	162.9	0.050	308.2	0.218	0.151	1.24
78	1.25	162.9	0.050	308.2	0.218	0.159	1.55
79	0.10	0	0.050	278.2	0.391	0.178	0.65
80	0.25	0	0.050	278.2	0.391	0.270	0.71
81	0.50	0	0.050	278.2	0.391	0.318	1.89
82	0.75	0	0.050	278.2	0.391	0.338	2.00

83	1.00	0	0.050	278.2	0.391	0.349	2.92
84	1.25	0	0.050	278.2	0.391	0.357	2.06
85	0.10	0	0.050	288.2	0.314	0.137	0.96
86	0.25	0	0.050	288.2	0.314	0.212	1.16
87	0.50	0	0.050	288.2	0.314	0.252	1.56
88	0.75	0	0.050	288.2	0.314	0.269	2.07
89	1.00	0	0.050	288.2	0.314	0.278	1.58
90	1.25	0	0.050	288.2	0.314	0.285	1.31
91	0.10	0	0.050	308.2	0.218	0.0842	0.52
92	0.25	0	0.050	308.2	0.218	0.139	0.92
93	0.50	0	0.050	308.2	0.218	0.169	2.03
94	0.75	0	0.050	308.2	0.218	0.182	0.68
95	1.00	0	0.050	308.2	0.218	0.189	1.97
96	1.25	0	0.050	308.2	0.218	0.194	1.51

* σ is the standard deviation of C_{out} obtained from three parallel experimental data.

Table S3 Experimental results of long-time run for 100 h at *Re*=43.5, *T*=298.2 K, *k*=162.9 m^{-1}, $\overline{v}$ =0.1 ms^{-1}, p/p_0=0.50

t (h)	c_{out} (mol m^{-3})
0.20	0.0550
0.50	0.0553
1.0	0.0550
5.0	0.0548
10	0.0550
25	0.0553
50	0.0553
75	0.0550
100	0.0548

Table S4 Boundary conditions used to model Liu's (Liu *et al.*, 2005) and Kaufhold's (Kaufhold *et al.*, 2012) works.

Mathematical expressions	
Boundary conditions of Liu's work	
Lumen side aqueous phase (i=O_2, N_2)	
$z=0: c_{O_2}=c_{O_2,f} \qquad c_{N_2}=0,$	(S1)
$z=l: \partial c_i/\partial z=0,$	(S2)
$r=0: \partial c_i/\partial r=0.$	(S3)
Lumen side-membrane pores interface (i=O_2, N_2)	
$r=r_1: \left(\mathrm{D}_i\,\partial c_i/\partial r\right)\big\vert_{\text{lumen}}=\boldsymbol{N}_i\big\vert_{\text{membrane}}=\left(-\bar{D}_i\nabla c_i+c_i\bar{\boldsymbol{v}}\right)\big\vert_{\text{membrane}},$	(S4)
$r=r_1: \left(H_i c_i/\left(c_i+\rho_{\text{w}}/M_w\right)/RT\right)\big\vert_{\text{lumen}}=c_i\big\vert_{\text{membrane}},$	(S5)
$r=r_1: c_{H_2O}\big\vert_{\text{membrane}}=p_{\text{w}}.$	(S6)
Membrane pores-shell side interface (i=O_2, N_2, H_2O)	
$r=r_2: c_{N_2}=c\vert_{\text{shell}} \qquad c_{O_2}=c_{H_2O}=0.$	(S7)
Boundary conditions of Kaufhold's work	
Lumen side aqueous phase (i=O_2, N_2)	
$z=0: c_{N_2}=c_{N_2,f} \qquad c_{O_2}=0,$	(S8)
$z=l: \partial c_i/\partial z=0,$	(S9)
$r=0: \partial c_i/\partial r=0.$	(S10)
Lumen side-membrane pores interface (i=O_2, N_2)	
$r=r_1: \left(\mathrm{D}_i\,\partial c_i/\partial r\right)\big\vert_{\text{lumen}}=\boldsymbol{N}_i\big\vert_{\text{membrane}}=\left(-\bar{D}_i\nabla c_i+c_i\bar{\boldsymbol{v}}\right)\big\vert_{\text{membrane}},$	(S11)
$r=r_1: \left(H_i c_i/\left(c_i+\rho_{\text{w}}/M_w\right)/RT\right)\big\vert_{\text{lumen}}=c_i\big\vert_{\text{membrane}},$	(S12)
$r=r_1: c_{H_2O}\big\vert_{\text{membrane}}=p_{\text{w}}.$	(S13)
Membrane pores-shell side interface (i=O_2, N_2, H_2O)	
$r=r_2: \left(RT\sum c_i\right)\big\vert_{\text{membrane}}=p\vert_{\text{shell}},$	(S14)

$$r = r_2 : c_i / \sum c_i = N_i / \sum N_i . \tag{S15}$$

References

Kaufhold, D., Kopf, F., Wolff, C., Beutel, S., Hilterhaus, L., Hoffmann, M., Scheper, T., Schlüter, M., Liese, A., 2012. Generation of dean vortices and enhancement of oxygen transfer rates in membrane contactors for different hollow fiber geometries, *Journal of Membrane Science*. **423-424**(12):342-347.

Liu, L., Li, L., Ding, Z., Ma, R., Yang, Z., 2005. Mass transfer enhancement in coiled hollow fiber membrane modules, *Journal of Membrane Science*. **264**(1):113-121.