Desalination and Water Treatment
www.deswater.com

34 (2011) 63–69
October

1944-3994/1944-3986 © 2011 Desalination Publications. All rights reserved
doi: 10/5004/dwt.2011.2870

Effects of channel spacers on direct contact membrane distillation

Yanbin Yun[a],*, Jianxin Wang[a], Runyu Ma[b], Anthony Gordon Fane[c]

[a] *College of Environmental Science & Engineering, Beijing Forestry University, Beijing 100083, P.R. China*
Tel. +86-13241730890; email: y.yanbin@unsw.edu.au
[b] *College of Chemical Engineering, Beijing University of Chemical Technology, Beijing 100029, P.R. China*
[c] *School of Chemical Engineering, University of New South Wales, Sydney NSW, 2052, Australia*

Received 3 September 2010; Accepted 3 January 2011

ABSTRACT

The effects of spacers on flux enhancement of direct contact membrane distillation (DCMD) had been studied for high concentration NaCl aqueous solution. For DCMD experiments, spacers were filled in different channels of the module. The effects of spacers on temperature polarization and concentration polarization were demonstrated. By contrasting different modes of spacers filling channels, it was found that: (1) the coarse spacer enhanced fluxes up to 30% and heat transfer coefficients by approximately two times over the empty channels; (2) the effect of spacer filled in the hot-side channel on the flux was much bigger than that in the cool-side; (3) The sequence of the spacers effects on flux was: coarse spacer > fine spacer > without spacer.

Keywords: Direct contact membrane distillation; Spacer; Heat transfer; High concentration; NaCl solution; Mass transfer

1. Introduction

Membrane distillation (MD), a relatively new process, is an evaporation process of feeding volatile components through porous hydrophobic membrane. Compared with conventional desalination processes, e.g., reverse osmosis, distillation and flash evaporation, the main advantages of MD are: (1) production of a high purity distillate; (2) no limitations caused by osmotic pressure effects; (3) lower operation temperatures; (4) lower operation pressures; (5) lower membrane mechanical intensity demand; (6) lower energy expenditure; (7) no corrosion problems by using plastic equipments.

As a member of MD, the direct contact membrane distillation (DCMD) has liquid phases in direct contact with both sides of the hydrophobic membrane, which shows simple configuration and high permeate and is best suited for applications in which the major permeate component is water, such as desalination or concentration of aqueous solutions [1,2]. The heat and mass transfer mechanisms have been studied widely for low concentration solutions [3]. For high concentration (or close to equilibrium saturation), the complexity may be caused by changes in many operating parameters, such as: decrease of feed vapor pressure, increase of feed viscosity and so on, which lead to evaporation efficiency decrease. Moreover, temperature polarization and concentration polarization may become more severe. Attempts to reduce these effects have been made by improving the flow characteristics, i.e., enhancing flow rates or turbulent flow conditions. However, larger energy consumption by pumps is not appealing in economic viewpoint. An alternative method to use spacers has been proposed [4], which reduces concentration polarization and temperature polarization without increasing flow rates. For spiral ultrafiltration (UF) module and spiral reverse osmosis (RO) module, spacers or turbulence promoters are put into flow channels to promote wakes and eddy in laminar flow. Hence, mass transfer is enhanced. On average, feed channel spacers

---

*Corresponding author.

Presented at the AMS6/IMSTEC10, The 6th conference of the Aseanian Membrane Society in conjunction with the 7th International Membrane Science and Technology Conference, Sydney Australia, November 22–26, 2010

reduce the extent of concentration polarization because of the enhanced wall shear rates. However, the stagnant regions (in front and behind some spacer filaments) lead to enhanced concentration polarization, which suggests certain spacer designs could promote local scale and cake formation in spiral wound elements [5]. For DCMD, L. Martinez [6] had studied two basic separator configurations: open flow separators and screen separators. The use of screen separators increased the flux and thus heat transfer was significantly improved in the module with screen separators compared with the module with open flow separators. J. Phattaranawik [7] investigated 20 spacers with different voidages and hydrodynamic angles to determine the spacer performance in heat and mass transfer enhancement. The results showed that spacers enhanced mass fluxes up to 30–60% and increased heat transfer coefficients by approximately two times over the empty channels. The optimum spacer geometry was found at the voidage of 0.6 and the hydrodynamic angle of 90°, respectively. However, the values of heat transfer coefficients, NaCl diffusion coefficient, temperature polarization coefficients and concentration polarization coefficients for spacer-filled channels in DCMD had not been evaluated for higher concentration NaCl solution.

The object of this work was to provide the basic data for DCMD module. The effects of spacers different in voidages, and hydrodynamic angles on mass transfer of DCMD were investigated for high concentration NaCl solutions. In addition, the effect of flow rates on flux was investigated when fine spacer was put in both channels of the module. The theory of the heat and mass transfer enhancement by net-type spacers in DCMD to propose the heat transfer correlation for spacer-filled channel was studied.

2. Theory

In the process of the DCMD, water vapor transfer in membrane is the rate-limiting step for mass transfer, which can be considered as gas molecule transfer in the porous medium. The pore size of the porous medium is so small that gas diffusion mechanism is confirmed by the relation between pore size and molecular mean free path. In the range of 0°C~100°C, the mean free molecular path of the gaseous water molecules is about 0.2 μm, as the same as the pore diameter of experiments membrane; and vapor diffusion coefficient D_{WA} of molecular diffusion model and D_{KW} of Knudsen diffusion model are in the same order of magnitude. So in the apertures, collisions between molecule-molecule and molecule-aperture wall must be considered. That is to say, DCMD mass transfer process is a blend transition diffusion which includes Knudsen diffusion and molecular diffusion.

By conservation of momentum theory, a transition model can be written as

$$N = \frac{D_{WA} Pe}{t\delta RT_m} \ln\left(\frac{1 - P_{pm}/P + D_{WA}/D_{KA}}{1 - P_{fm}/P + D_{WA}/D_{KA}}\right) \tag{1}$$

When $D_{KW}/D_{WA} << 1$, Eq. (1) can be simplified as Knudsen diffusion model. When $D_{KW}/D_{WA} >> 1$, Eq. (1) can be changed as molecular diffusion model.

Vapor pressure of pure water is given by Antoine equation

$$P^o = \exp\left(23.238 - \frac{3841}{T - 45}\right) \tag{2}$$

When solute concentration of the feed is low, the vapor pressure of feed is expressed by Raoult law

$$P = P^o(1 - x) \tag{3}$$

When solute concentration of the feed is high, the vapor pressure of feed is calculated by

$$P = P^o(1 - x)(1 - 0.5x - 10x^2) \tag{4}$$

For high concentration feed, special attention must be given to concentration polarization not only because the boundary layers increase the overall resistance to mass transfer but also because the solutes are accumulated on the membrane surface and can become sufficient to cause spontaneous wetting of the membrane. It is possible to characterize concentration polarization by a solute transfer analysis.

$$\ln\frac{c_{fm} - c_p}{c_f - c_p} = \frac{N\delta_c}{D\rho} \tag{5}$$

When solute rejection is assumed to be 100%, Eq. (5) can be changed as

$$N = K\rho \ln\frac{c_{fm}}{c_f} \tag{6}$$

The mass transfer coefficient ($K = D/\delta_c$) can be evaluated using the mass transfer analogy of the heat transfer experiential correlation. Two conditions are as follows:

(1) For spacers inducing directional flow change

$$Sh^s = 0.664 k_{dc} \left(\mathrm{Re}^s\right)^{0.5} Sc^{0.33} \left(\frac{2d_h^s}{l_m}\right)^{0.5} \tag{7}$$

where

$$k_{dc} = 1.654\left(\frac{d_f}{h}\right)^{-0.039} \varepsilon^{0.75}(\sin(\theta/2))^{0.086} \tag{8}$$

(2) For empty

$$Sh = 4.36 + \frac{0.036\,\mathrm{Re}\,\mathrm{Pr}(d_h/L)}{1 + 0.0011(\mathrm{Re}\,\mathrm{Pr}(d_h/L))^{0.8}} \tag{9}$$

For DCMD, the driving force of heat is a temperature difference caused by having a hot feed and a cold permeate. The heat transfer process from the feed to the permeate can be split into three steps: (1) Heat (Q_f) is first transferred from the hot feed across the heat boundary layer to the hot-side membrane surface; (2) Heat (Q_m) is passed through the membrane not only by vaporization latent heat (Q_v) but also by heat conduction (Q_c); (3) Heat (Q_p) is removed from the cool-side membrane surface through the heat boundary to the cool permeate. According to conservation of energy:

$$Q_f = Q_m = Q_p \tag{10}$$

$$\begin{aligned} h_f\left(T_f - T_{fm}\right) &= N\Delta H + \frac{k_m}{\delta}\left(T_{fm} - T_{pm}\right) \\ &= h_p\left(T_{pm} - T_p\right) \end{aligned} \tag{11}$$

From Eq. (11) and assuming $h_f = h_p$, the interfacial temperatures of the membrane can be obtained as:

$$T_{fm} = \frac{(T_f + T_p)\,k_m/\delta + h_f T_f - N\Delta H}{2\,k_m/\delta + h_f} \tag{12}$$

$$T_{pm} = \frac{(T_f + T_p)\,k_m/\delta + h_p T_p + N\Delta H}{2\,k_m/\delta + h_p} \tag{13}$$

ΔH is vapor enthalpy evaluated at average membrane temperature $(T_f + T_p)/2$.

The temperatures in the layers adjacent to the membrane differ from the temperature measured in the bulk liquid at both sides of the membrane. This phenomenon is called the temperature polarization. It causes the decrease of vapor pressure difference across the membrane and thus leads to the reduction of mass flux. Investigations often use temperature polarization coefficient (TPC) defined as:

$$TPC = \frac{T_{fm} - T_{pm}}{T_f - T_p} \tag{14}$$

TPC can evaluate the fraction of the total thermal driving force that contributes to the mass transfer driving force. However, the real driving force of mass transfer in MD is the vapor pressure difference across the membrane. So when a high concentration NaCl solution is considered, TPC is not suitable to be used as a measure of the driving force imposed because the existing vapor pressure decreases. For this reason, pressure polarization coefficient (PPC) is introduced as

$$PPC = \frac{p_{fm} - p_{pm}}{p_f - p_p} \tag{15}$$

It evaluates the fraction of the total thermal driving force imposed that contributes to the mass transfer driving force.

3. Experimental

The main element of DCMD was the membrane module consisting of the two symmetric compartments, hot and cold, separated by the hydrophobic membranes prepared by PVDF. The flow chart was shown in our previous work [8]. Spacers were fabricated from cylindrical polypropylene rods. Some important characteristics of the spacer were listed in Table 1. The poly (vinylidene fluoride) (PVDF) hydrophobic microfiltration membrane were provided by Millipore, whose properties were: pore diameter 0.2 μm porosity 80%, membrane thick 125 μm, heat conduction coefficient 0.14 w/m/K. The membrane module was made from Perspex (polymerized methlmethacrylate) with a flow channel of 40 mm wide, 100 mm long, and 2.5 mm high (Fig. 1.). Spacers used were simply inserted into the channel and not fixed to the membrane surface.

Table 1
Characteristics of spacers

Spacer name	Material	h_{sp} (mm)	d_f (mm)	l_m (mm)	ε_s	S_{vsp} (m^{-1})	d_h (mm)	Angle (θ)
Fine	PP	1.15	0.55	2.8	0.852	7273	1.21	90
Coarse	PP	2.10	1.15	4.85	0.793	3478	1.90	80

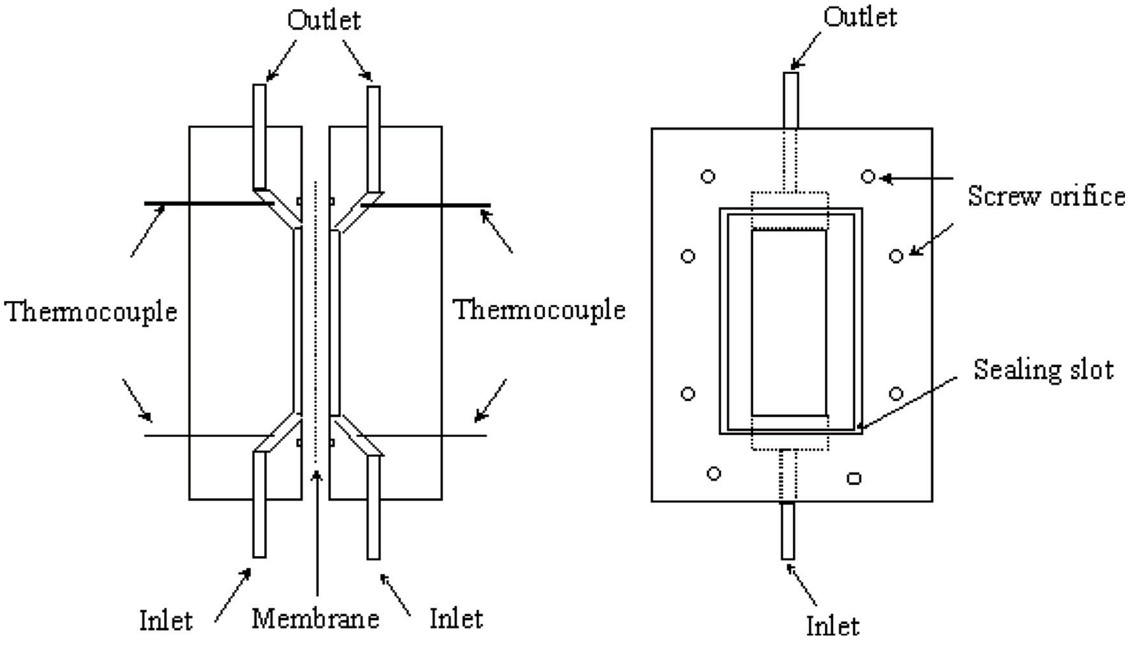

Fig. 1. Membrane module (left: cutaway view; right: surface of interior).

NaCl solution was used as the feed. The cold system was initially supplied by pure water. The control systems maintained the required values of temperature and the flow rates of streams at the module entrance. The double-barreled creeping motion pump (MUSTERFLEX) produced the same flow rates for both the feed and the permeate flows. In experiments, the hot feed and the cold permeate flowed in the module in a parallel-current mode.

4. Results and discussions

In experiments, the same flow rates for both the feed and the permeate flows were 0.145 m/s. The feed temperature and the permeate temperature were 70.0°C and 20.5°C, respectively. Pure water used to permeate and NaCl solution used to feed had not been degassed. The experiments conditions were summarized in Table 2.

Fig. 2 showed that the flux increased observably with spacer placed in the module. For the same flow rate, the same T_f and T_p, the fluxes were higher obviously for the coarse spacer than for the fine spacer and both of them higher than for empty. These results suggested that the use of spacers enhanced the appearance of turbulences due to the formation of eddies and wakes when the fluid passes spacer strands. For the coarse spacer the thick filaments and high voidage generated bigger wakes and thus a higher degree of turbulence when compared to

Table 2
Experiments conditions

	Experiments						
	1	2	3	4	5	6	7
Cool channel	Empty	Coarse spacer	Empty	Coarse spacer	Fine spacer	Fine spacer	Coarse spacer
Hot channel	Empty	Empty	Coarse spacer	Coarse spacer	Fine spacer	Coarse spacer	Fine spacer
The initail concentration of NaCl solution in hot side (wt/wt)	17.79%	21.0%	20.79%	16.13%	21.83%	20.0%	20.20%
In cool side	Pure water						

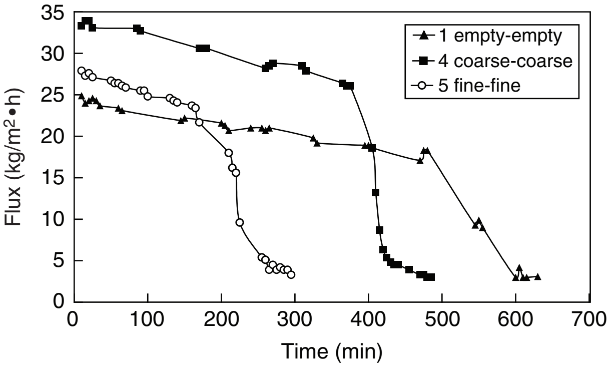

Fig. 2. Effects of different spacers on flux.

the fine spacer [4]. The smaller wakes around the thinner strands of the fine spacer generated lower flow disturbulence and so h_f was lower for this spacer configuration than for the coarse spacer configuration. For the same NaCl concentration of the feed (22%), Table 3 showed that the effect of spacer on h_f, TPC and PPC was: coarse spacer > fine spacer > empty.

In order to investigate the effect of coarse spacer on flux, a couple of experiments were implemented. Firstly, coarse spacer was made in the feed channel of the module and different spacer (coarse spacer/fine spacer/empty) was filled in permeate channel (Fig. 3.). It was found that the fluxes were slightly higher for the fine spacer than for empty in permeate channel of the module, and both of them were lower than for the coarse spacer in permeate channel of the module. From Table 3, The effect of spacer on TPC, PPC and h_f were same on fluxes: coarse spacer > fine spacer > empty. Secondly, coarse spacer was put in permeate channel of the module and different spaces were set in feed channel (Fig. 4). The result was same with the Fig. 3. Comparing Fig. 3 with Fig. 4, the same result could be observed. The effects of spacers on flux, TPC, PPC and h_f were in following ascending order: empty < fine spacer < coarse spacer.

By comparing the empty channels and coarse spacer filled in hot/cool channels (Fig. 5), it was found that: (1) the experimental results of coarse spacer filled

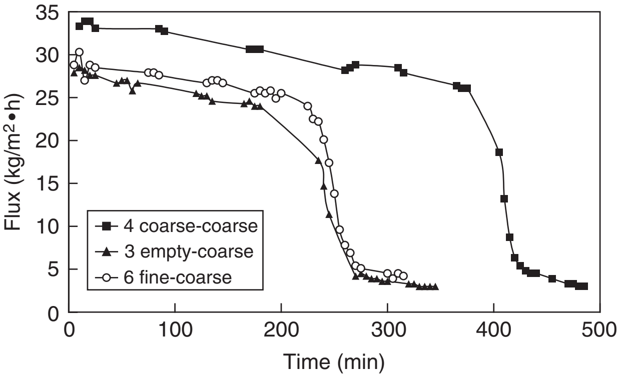

Fig. 3. Different spacers in cool of the module.

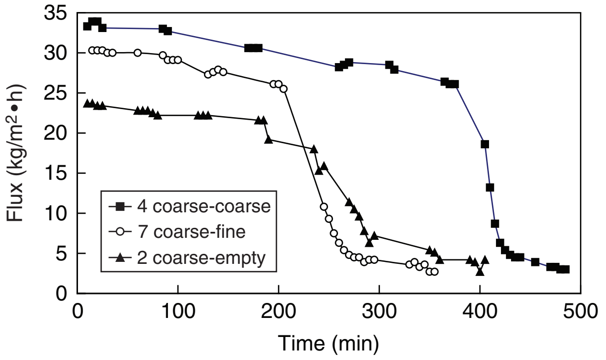

Fig. 4. Different spacers in hot-cell of the module.

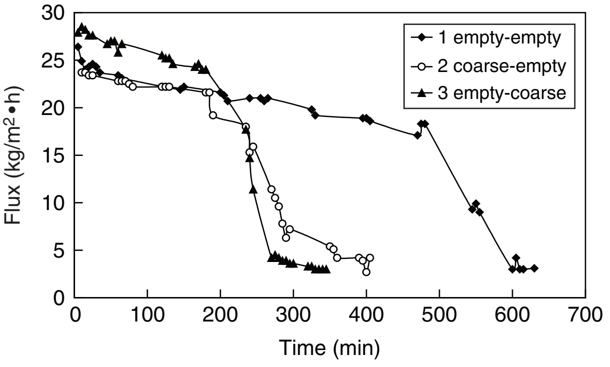

Fig. 5. Effects of no spacer on flux.

Table 3
Simulation result (flow rates: 0.145 m/s, the feed temperature 70.0°C; the permeate temperature: 20.5°C; NaCl concentration: 22%)

Experiments	1	2	3	4	5	6	7
TPC	0.7256	0.7141	0.8144	0.8828	0.8031	0.8433	0.8428
PPC	0.5302	0.5149	0.6171	0.6840	0.6042	0.6451	0.6418
H_f	4500	4500	8000	13600	7700	9800	10200

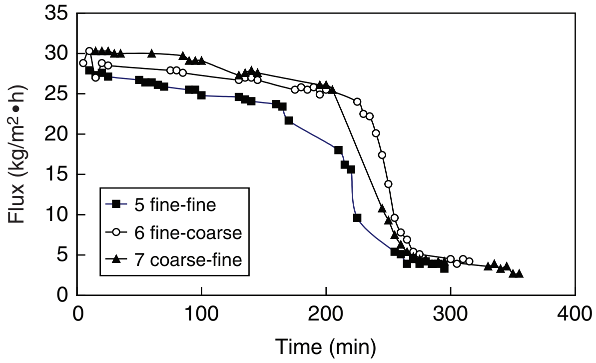

Fig. 6. Effects of fine spacer on flux.

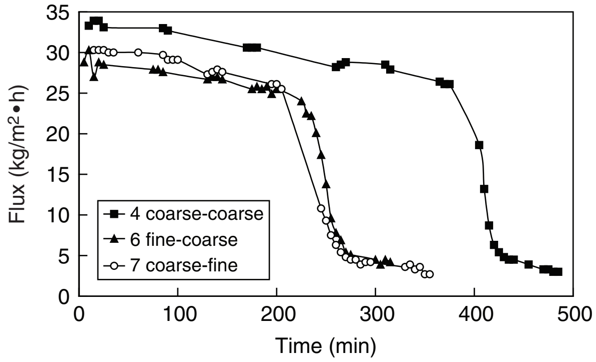

Fig. 7. Effects of coarse spacer on flux.

in cool channel was same to that of the empty channels; (2) when cool channel was empty, the flux was higher for coarse spacer in hot channel than for empty channel; (3) the effect of coarse spacer was higher for hot channel than for cool channel. Table 3 showed that TPC, PPC and h_f were same when coarse spacer and no spacer were in permeate channel of the module, and both of them were lower than for the coarse spacer in feed channel of the module. Thus, the effect of flow regime on flux for hot channel was bigger than that for cool channel.

In the same manner, the experiments were conducted for comparing the fine spacer filled in both channel of the module and the coarse spacer filled in hot (or cool) channel. Fig. 6 showed that coarse spacer could slightly improve flux whether in hot channel or in cool channel. However, the flux of fine spacer filled in channel of the module was lower than that of coarse spacer filled in both channel of the module (Fig. 7). Table 3 showed that the effect of spacer on TPC, PPC and h_f was: coarse spacer filled in both channel of the module > coarse spacer filled in feed channel and fine spacer in permeate channel > fine spacer filled in feed channel and coarse spacer in permeate channel > fine spacer filled in both channel of the module.

While concentration of NaCl solution was close to saturation, concentration polarization increased sharply. Crystal was formed on the membrane surface. Thus membrane fouling increased sharply and fluxes went down simultaneously (Figs. 2–7). For detailed analyses, see reference [8].

The flux ascended slightly when the recirculation rate rose (Table 4). The intention of using the higher recirculation rate was to increase the heat transfer coefficient, K, Re_f, and to reduce temperature polarization and concentration polarization. This meant that the temperatures at the membrane surface approximated more closely that of the bulk streams, and thus the transmembrane temperature difference became larger. That is to say, TPC and PPC enhanced gradually as velocity of flow increased. Therefore, driving force became large and the flux consequently rose.

Table 4
Effect of flow rate on the permeate (the feed temperature 68.0°C; the permeate temperature: 20.5°C; NaCl concentration: 17.76%, fine spacer in both channel of the module)

Velocity of flow (m/s)	Permeate (kg/m^2/h)		Re_f	TPC	PPC	h_f/h_p	K
	Experimental result	Simulation result					
0.082	26.12	26.41	210	0.7825	0.6262	6800	2.04×10^{-4}
0.145	27.35	27.74	372	0.8077	0.6522	8000	2.71×10^{-4}
0.187	28.09	28.26	480	0.8248	0.6699	9000	3.08×10^{-4}
0.235	28.50	28.69	603	0.8337	0.6792	9600	3.46×10^{-4}
0.282	29.11	29.01	724	0.8465	0.6925	10600	3.79×10^{-4}
0.329	29.70	29.27	845	0.8596	0.7061	11800	4.09×10^{-4}

5. Conclusions

For DCMD, using spacers to improve flow regime was better than increasing flow rates. The effects of spacer-filled in channel of hot side on flux was much bigger than in channel of cool side and the sequence of the effect of spacers on flux was: coarse spacer > fine spacer > without spacer. Higher heat transfer coefficient was a key to improve heat efficiency and flux of DCMD, which was decided by flow regime and physics of the fluid.

Acknowledgements

The authors would like to thank "State Forestry Bureau 948 Project (2009–4–62)" and "the Fundamental Research Funds for the Central Universities" for financial support.

Symbols

c — molar concentration of NaCl solution (mol/l)
d_h — hydraulic radius (m)
h — convective heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
ΔH — latent heat of water ($J \cdot kg^{-1}$)
k — heat conduction coefficient ($W \cdot m^{-1} \cdot K^{-1}$)
k_c — mass transfer coefficient ($m\ s^{-1}$)
M — molecular weight ($g\ mol^{-1}$)
N — mass flux across membrane ($kg \cdot m^{-2} \cdot s^{-1}$)
p^o — vapor pressure (Pa)
Q — heat flux ($W \cdot m^{-2}$)
T — temperature (K)
x — molar fraction of NaCl
δ — the thickness of the membrane (m)
ε — porosity (-)
τ — membrane tortuosity (-)
μ — viscosity ($Pa \cdot s$)
ρ — solution density ($kg\ m^{-3}$)
r — radius of the membrane pore size (m)
Re — Reynolds (-)
Pr — Prandtl (-)
Nu — Nusselt (-)
Sc — Schmidt (-)
Sh — Sherwood (-)

subscripts

f — the bulk of the feed
fm — membrane surface of the feed
p — the bulk of the permeate
pm — membrane surface of the permeate
m — membrane
W — water
A — air
av — average

References

[1] K.W. Lawson and D.R. Lloyd, Membrane distillation, J. Membr. Sci., 124 (1997) 1–25.

[2] F.A. Banat and J. Simandl, Desalination by membrane distillation: A parametric study, Separ. Sci. Technol., 33 (1998) 201–226.

[3] R.W. Schofield, A.G. Fane and C.J.D. Fell, Heat and mass transfer in membrane distillation, J. Membr. Sci., 33 (1987) 299–313.

[4] J. Phattaranawik, R. Jiraratananon and A.G. Fane, Mass flux enhancement using spacer filled channels in direct contact membrane distillation, J. Membr. Sci., 187 (2001) 193–201.

[5] A. Subramani, S. Kim and E.M.V. Hoek, Pressure, flow, and concentration profiles in open and spacer-filled membrane channels, J. Membr. Sci., 277 (2006) 7–17.

[6] L. Martınez-Diez, M.I. Vazquez-Gonzalea and F.J. Florido-Diaz, Study of membrane distillation using channel spacers, J. Membr. Sci., 144 (1998) 45–56.

[7] J. Phattaranawik, R. Jiraratananon and A.G. Fane, Effects of net-type spacers on heat and mass transfer in direct contact membrane distillation and comparison with ultrafiltration studies, J. Membr. Sci., 217 (2003) 193–206.

[8] Y.B. Yun, R.Y. Ma, W.Z. Zhang, A.G. Fane and J.D. Li, Direct contact membrane distillation mechanism for high concentration NaCl solutions, Desalination, 188 (2006) 251–262.