Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 160 (2019) 223–230

Energy Procedia

www.elsevier.com/locate/procedia

2nd International Conference on Energy and Power, ICEP2018, 13–15 December 2018, Sydney, Australia

An experimental heat transfer investigation of using spacer in direct contact membrane distillation

Quoc Linh Ve[a]*, Kawtar Rahaoui[a], Mohammed Bawahab[a], Hosam Faqeha[a], Abhijit Date[a], Ahmadreza Faghih[b] and Aliakbar Akbarzadeh[a]

[a] *Energy Conservation and Renewable Energy Group, School of Engineering, RMIT University, Bundoora, Victoria 3083, Australia*
[b]*School of Mechanical Engineering, Yazd University, Yazd, Iran*

Abstract

Membrane distillation (MD) is a thermally-driven separation technology that can produce highly pure water. Direct contact membrane distillation (DCMD), where both hot and cold solution is directly in contact with the hydrophobic membrane is the most studied system due to its condensation method without an external condenser as well as its overall structural simplicity. In this paper, heat transfer analysis was carried out in DCMD experimentally to investigate how the presence of a spacer can effect on heat transfer coefficient. Results revealed that the heat transfer coefficient for spacer-filled channels (plastic and metallic material) is approximately from 3 to 3.5 times higher than that for empty channels. Additionally, from specific pumping power (SPP) for 1 cubic meter of freshwater production, it is predicted that DCMD with spacer-filled channels can consume far less electrical or mechanical energy than that with empty channels.

Keywords: Type your keywords here, separated by semicolons ;

* Corresponding author. Tel.: .:+61-420251709.
E-mail address: s3633369@student.rmit.edu.au

1876-6102 © 2019 The Authors. Published by Elsevier Ltd.
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)
Selection and peer-review under responsibility of the scientific committee of the 2nd International Conference on Energy and Power, ICEP2018.
10.1016/j.egypro.2019.02.140

1. Introduction

Membrane distillation (MD) is a thermally-driven membrane separation technology that can produce highly pure water. The principle of the separation is based on transmembrane temperature difference resulting in transmembrane vapor pressure gradient, as the driven force that allows only vapor molecules pass through porous hydrophobic membrane without the penetration of liquid [1-3].DCMD, a simplest MD configuration is the most studied system due to its condensation method without an external condenser[4]. Temperature polarization effect due to the difference between membrane surface and bulk fluid temperatures that result from the convective heat transfer resistances on feed and permeate sides is decided as the key factor that effect on pure water production. The balance convective heat fluxes in both sides which are controlled by hydrodynamic conditions and the heat flux through the membrane which is governed by the vapor mass flux determine the temperature polarization coefficient. Therefore, the reduction temperature polarization effect results in higher transmembrane vapor fluxes and this needs to be matched by higher convective heat transfer coefficient. The effect of temperature polarization can be reduced by improving the flow characteristic, i.e., increasing flow rates or turbulent flow conditions. Nevertheless, the higher flow rates the larger energy consumption by pumps seems not to be a useful method in economic viewpoint. Thus, utilizing net-like turbulence promoters (spacer) has been proposed as an effective way for changing flow characteristic as well as improving heat transfer coefficient in a favorable way [2, 3, 5, 6].

Yazan Taamneh and Kahled Bataineh [7] study the effect of the presence and spacer's filament orientation on the flow pattern and heat transfer enhancement in DCMD. They pointed out that with the presence of the spacer, the average Nusselt number, as well as the convection heat transfer, is higher in comparison with the empty channel. Moreover, the higher angle of orientation of top filament is (bottom filament is parallel with the direction of flow), higher convection heat transfer is acquired.

Young-Deu-Kim et al. [8] study the heat and mass transfer in DCMD by using different kinds of spacers on one or both sides of the module. From experimental results, the permeate flux is enhanced from 7% to 19% in case of only spacer-filled permeate channel and between 21% and 33% for only spacer-filled feed channel. This study also showed the maximum flux enhancement (43%) in comparison with empty channels when both sides of DCMD employed the thinnest and densest spacer with a hydrodynamic angle of 90^0.

From the above discussion, they only focus on how spacer configuration (porosity, hydrodynamic angel, thickness) effect on heat and mass transfer in direct contact membrane distillation. The effect of thermal conductivity spacer material was ignored in most works. Accordingly, the understanding of the heat transfer of DCMD is still incomplete. The object of this work is to investigate only heat transfer in direct contact membrane distillation under the effect of spacers with different thermal conductivity in case of laminar flow. Additionally, the specific pumping power analysis for one cubic meter of freshwater production will be discussed.

Nomenclature

A	Cross section area of copper, m^2	Sts	Stainless steel spacer
C_f	Specific heat coefficient, J kg^{-1} K^{-1}	g	Gravitational acceleration, m s^{-2}
D	Hydraulic diameter, m	h	Heat transfer coefficient, W m^{-2} K^{-1}
EE	Energy efficiency	h_{fg}	Heat of water vaporization, kJ kg^{-1}
H	The global heat transfer coefficient, W m^{-2} K^{-1}	h_L	Head loss, m
Nu	Nusselt number	k	Thermal conductivity, W m^{-1} K^{-1}
Q	The rate of heat transfer, W	l_m	Mesh size, m
Q_{diff}	Latent heat associated to the water vapor molecules, W	m	Mass flow rate, kg s^{-1}
Pr	Prandtl number	t	Thickness, m
Re	Reynolds number	*Greek letters*	
S_{vsp}	Specific surface of the spacer, m^{-1}	ε	Spacer porosity
SPP	Specific pumping power, kWhr m^{-3}	θ	Hydrodynamic angle, deg
T	Bulk temperature, K	*Subscripts*	
T_1	Temperature at the feed-copper, K	c	Copper
T_2	Temperature at the permeate-copper interface, K	f	Feed

TVC	Thermal vapour compression	d	Distillate
W_{pump}	Pumping power, W	p	Permeate
d_{fs}	Diameter of spacer filament, m	s	Spacer
Pls	Plastic spacer		

2. Theory

The theory related to a conventional DCMD system where a hydrophobic membrane is applied. To study only heat transfer in DCMD, hydrophobic membrane is replaced by a copper plate to eliminate the whole mass transfer. The schematic diagram of heat transfer in DCMD is shown in Fig.1.

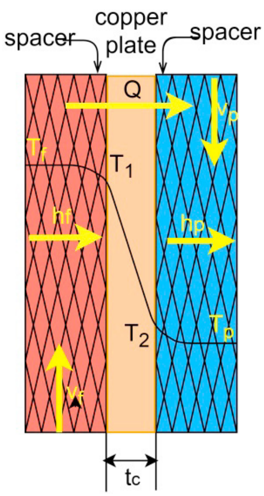

Figure 1. Sketch of temperature profile in experimental investigation

2.1. Heat transfer in DCMD

The heat transfer in DCMD can be described into three regions: (1) convective heat transfer in the feed side; (2) conductive heat transfer in the copper sheet; (3) convective heat transfer in permeate side. The heat transfer model can be illustrated through electrical analog as shown in Fig. 2.

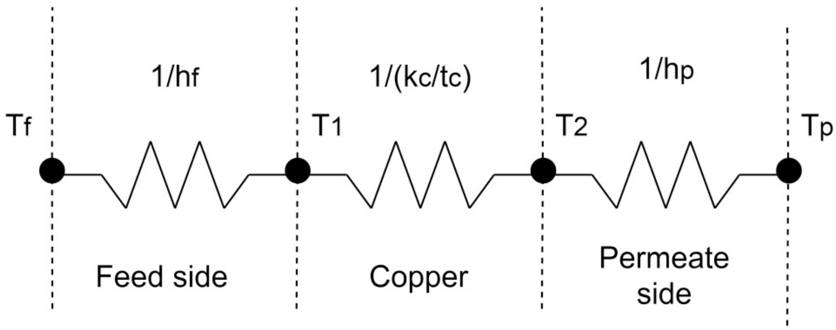

Figure 2. The electrical analogy of heat transfer resistance for DCMD

Convective heat transfer through thermal boundary layer at the feed side and permeate side:

$$Q_f = h_f \times A \times \left(T_f - T_1\right) \tag{1}$$

$$Q_p = h_p \times A \times \left(T_2 - T_p\right) \tag{2}$$

Conductive heat transfer through the copper plate

$$Q_C = -k_C \frac{dT}{dx} = \frac{k_C}{t_C} \times A \times \left(T_1 - T_2\right) \tag{3}$$

Where T_f and T_p are the average bulk feed and the average bulk permeate temperature which is estimated:

$$T_f = \frac{T_{f,in} + T_{f,out}}{2} \text{ and } T_p = \frac{T_{p,in} + T_{p,out}}{2} \tag{4}$$

At the steady state: $Q_f = Q_c = Q_p$

$$h_f \times A \times \left(T_f - T_1\right) = \frac{k_c}{t_c} \times A \times \left(T_1 - T_2\right) = h_p \times A \times \left(T_2 - T_p\right) = H \times A \times \left(T_f - T_p\right) \tag{5}$$

Where H is the total heat transfer coefficient of the DCMD process. The overall heat flux (Q) can be written:

$$Q = A \times \left[\frac{1}{h_f} + \frac{1}{k_c/t_c} + \frac{1}{h_p}\right]^{-1} \Delta T = H \times A \times \Delta T \tag{6}$$

The total heat transfer coefficient was also determined [9]:

$$H = \frac{Q}{A \times \Delta T_{\ln}} \tag{7}$$

$$\Delta T_{\ln} = \frac{\left(T_{f,in} - T_{p,out}\right) - \left(T_{f,out} - T_{p,in}\right)}{\ln\left[\left(T_{f,in} - T_{p,out}\right) / \left(T_{f,out} - T_{p,in}\right)\right]} \tag{8}$$

2.2. The spacers for DCMD

The net-type spacers are often placed in flow channels of the DCMD process to improve mass transfer. In the case of heat transfer without mass transfer, the heat transferred from the feed to distillate can be calculated from the equation [10]:

$$Q = m_f . C_f . \left(T_{f,in} - T_{f,out}\right) \tag{9}$$

The hydraulic diameter (D_s) specific surface of spacer (S_{vsp}), spacer voidage can be defined by [6, 11]

$$D_s = \frac{4\varepsilon_s}{(2/t_s) + (1-\varepsilon_s)S_{vsp}} \tag{10}$$

$$S_{vsp} = \frac{4}{d_{fs}} \tag{11}$$

$$\varepsilon_s = 1 - \frac{\pi d_{fs}^2}{2 l_m t_s \sin\theta} \tag{12}$$

2.3. Energy consumption

In DCMD, energy efficiency is commonly defined as "the ratio of the heat transfer due to flux (convection) to the total heat transported through the membrane (convection + conduction). However, in the case of only heat transfer is investigated without mass transfer, energy efficiency is given:

$$EE = \frac{Q_{diff}}{0.5(Q_f + Q_p)} \tag{13}$$

The rate of latent heat associated to the water vapor molecules and the required pumping power in feed side:

$$Q_{diff} = m_d \times h_{fg} \tag{14}$$

$$W_{pump} = m_f \times g \times h_L \tag{15}$$

The specific pumping power for 1 cubic meter of freshwater production:

$$SPP = \frac{W_{pump} \times 1000}{m_d} \tag{16}$$

3. Experimental procedures and apparatus

In the experiment, the DCMD module was placed in the vertical position to eliminate the free convection. The feed and permeate channel have the same dimensions (W x L x H = 180 x 180 x 1.84 mm).Tap water was used as the feed and permeate solutions. The copper plate was used instead of the membrane to eliminate the mass transfer with the thickness of 1mm and thermal conductivity of 400 $Wm^{-1}K^{-1}$. The feed solution was heated up to the required temperature in the urn and pumped in the feed channel by the submersible pump (Model No. LVM117). The tap water was supplied to the permeate channel by adjusting the valve in counter-current with the feed solution. The flow rates at both channels are measured by stopwatch and the digital scale. The solution temperatures were measured by thermocouples connected to the data logger. The pressure drop in feed channel was measured by manometers at inlet and outlet. The experimental test rig is illustrated in Fig. 3

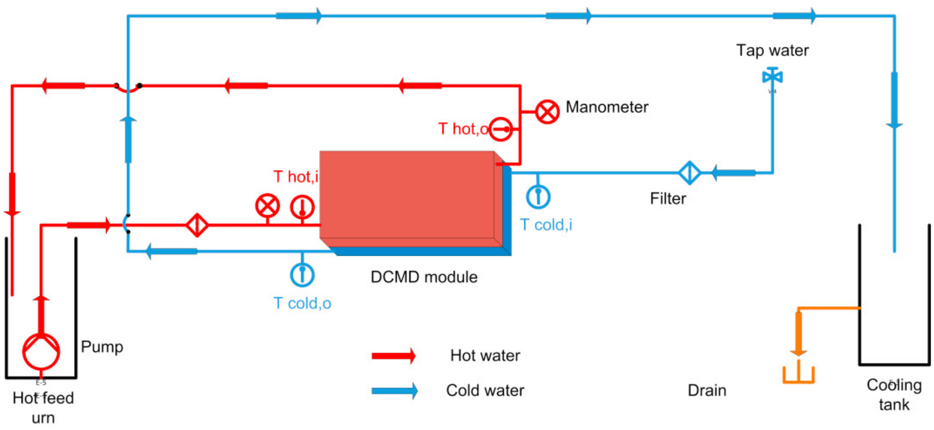

Figure 3. Test rig for heat transfer in DCMD module

4. Results and discussion

4.1. Effect of spacer on heat transfer coefficient

For the rough estimation of heat transfer for both sides of the DCMD module, heat transfer coefficient in both sides was assumed to equal. For this assumption, equation (6-9) was used to calculate the heat transfer and heat rate. The experiments were carried out with operation condition shown in Table 1 where velocities in both channels varied from 0.052(m/s) to 0.333 (m/s) corresponding to Reynold number from 300 to 1850 to ensure laminar flow. From Fig. 4a, it can be clearly seen that the heat transfer coefficient at the feed side increases when the velocity increases. Additionally, the heat transfer coefficient for spacer-filled channels was approximately from 3 to 3.5 times higher than that for empty channels. However, the heat transfer coefficient for the Pls is slightly higher than that for the Sts. This is due to the diameter of the filaments of the spacer (Table 2). The bigger the filaments are, the larger wake is created and this results in more convective heat transfer.

Table 1. Operation condition and heat transfer coefficients for DCMD modules with empty channels (Tf = 322K; Tp=295K) and spacer-filled channels (Tf = 317K; Tp=294K)

Fluid velocity (ms^{-1})		Heat transfer coefficient (h_f) ($Wm^{-2}K^{-1}$)			Heat rate (Q_f) (W)		
Feed	Permeate	Empty	Pls	Sts	Empty	Pls	Sts
0.052	0.052	1549	4929	4428	615.7	1289	1309
0.128	0.128	2445	8355	7439	1046.9	2610	2634
0.16	0.16	2891	9436	8798	1236.9	3025	3214
0.192	0.193	3317	10902	9941	1417.5	3558	3691
0.228	0.227	3733	12280	11193	1596.9	4037	4207
0.253	0.253	3935	13533	12020	1680.2	4573	4576
0.28	0.28	4303	14301	12693	1837.7	5341	4865
0.333	0.332	4964	15853	14684	2118.8	5978	5661

From Fig. 4b, the higher the flow rate is, the bigger the heat rate is. Furthermore, the heat rate for spacer-filled channels is nearly triple that for empty channels. In addition, although the temperature difference between feed and permeate side for spacer-filled channels experiments is smaller than that for empty channels one, the heat transfer coefficient and the heat rate are much larger for the former than for the latter (Table 1). Therefore, the predicted freshwater production with presence of spacers is higher than that without spacers..

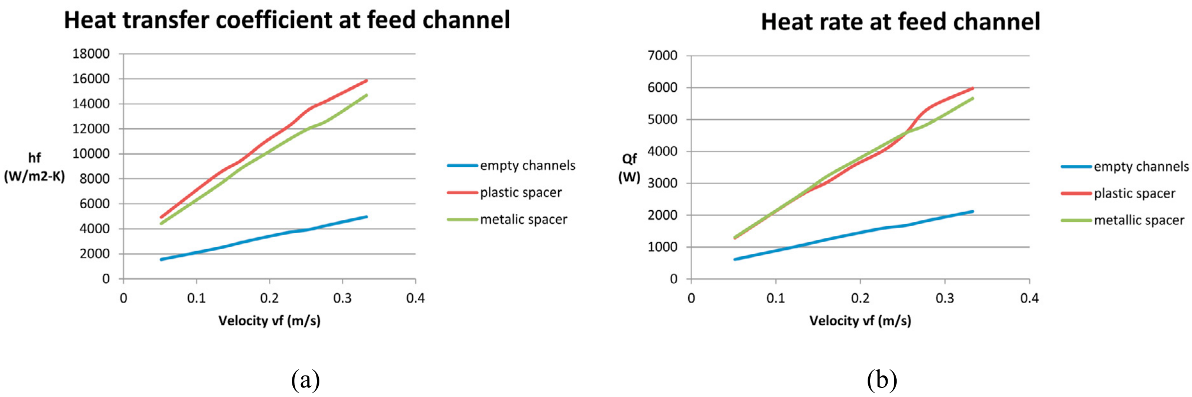

Figure 4. The effect of spacer on heat transfer coefficient (a) and heat rate (b) in DCMD

Table 2. Characteristics of spacers

Spacer	h_s (mm)	d_f (mm)	l_m (mm)	ε_s	S_{vsp} (m^{-1})	d_{hs} (mm)	Angle (θ) Deg.
Plastic	1.82	1.42	4.6	0.577	2816.9	1.008	90
Stainless steel	1.84	0.92	2.35	0.656	4347.8	1.016	90

4.2. Effect of spacer on specific pumping power for 1 cubic meter of freshwater production

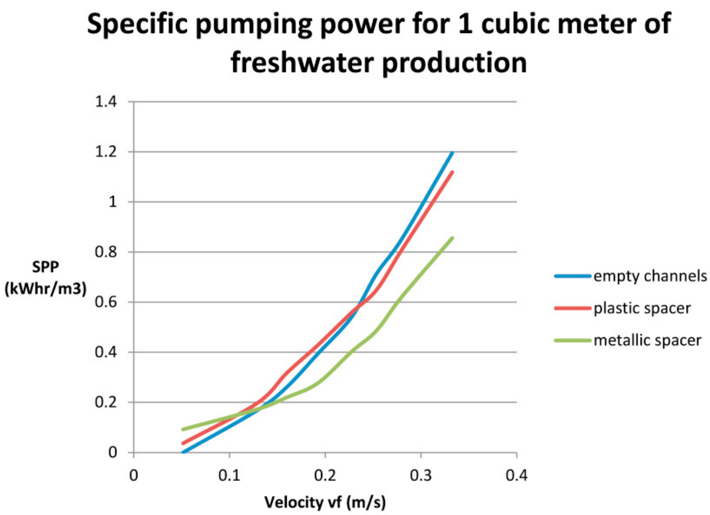

Figure 5. The specific pumping power for 1 cubic meter of freshwater production

According to [1-3], the energy efficiency of DCMD is from 31 to 90%. Therefore, we assumed that EE is only 50% for investigation of SPP by using Eq.(13-16). Additionally, in this experiment, only one pump was used at the feed side instead of 2 pumps for both sides and extra energy loss must be taken into account. Therefore, the estimated values of SPP must be three times larger than the calculated SPP.

From Fig. 5, the DCMD module with Sts has the lowest SPP than that with Pls-filled channels and empty channels. In case of 50% of EE assumption and reality situation, at the highest velocity, the amount of pumping energy per 1 cubic meter of freshwater production for Sts-filled channels was only 0.86 kWhr in comparison with 1.12 kWhr and 1.19 kWhr for empty channels and Pls-filled channels, respectively. Therefore, using the spacer in both channels of the DCMD module will acquire larger amount of freshwater production with lower energy consumption compared to DCMD with empty channels.

5. Conclusion

Heat transfer matter in DCMD module without hydrophobic membrane was carried out in two cases: empty channels and spacer-filled channels. The results showed that the heat transfer coefficient and the heat rate were enhanced 3 times and more for spacer-filled channels case in comparison with empty channels. Furthermore, the results also pointed out that spacer-filled channels in DCMD will have smaller SPP for one cubic meter of freshwater production than that without the spacer.

References

[1] Khayet M, Matsuura T. Membrane Distillation: Principles and Applications, *in Membrane Distillation*. 2011, Elsevier: Amsterdam. p. 1-16.

[2] Phattaranawik J, Jiraratananon R, Fane AG. Effects of net-type spacers on heat and mass transfer in direct contact membrane distillation and comparison with ultrafiltration studies. *Journal of Membrane Science*, 2003. **217**(1): p. 193-206.

[3] Phattaranawik J, Jiraratananon R, Fane AG, Halim C. Mass flux enhancement using spacer filled channels in direct contact membrane distillation. *Journal of Membrane Science*, 2001. **187**(1): p. 193-201.

[4] Ashoor BB, Mansour S, Giwa A, Dufour V, Hasan SW. Principles and applications of direct contact membrane distillation: A comprehensive review. *Desalination*, 2016. **398**(Supplement C): p. 222-246.

[5] Da Costa AR, Fane AG, Fell CJD, Franken ACM. Optimal channel spacer design for ultrafiltration. *Journal of Membrane Science*, 1991. **62**(3): p. 275-291.

[6] Schock G, Miquel A. Mass transfer and pressure loss in spiral wound modules. *Desalination*, 1987. **64**(C): p. 339-352.

[7] Taamneh Y, Bataineh K. Improving the performance of direct contact membrane distillation utilizing spacer-filled channel. *Desalination*, 2017. **408**: p. 25-35.

[8] Kim YD, Francis L, Lee JG, Ham MG, Ghaffour N. Effect of non-woven net spacer on a direct contact membrane distillation performance: Experimental and theoretical studies. *Journal of Membrane Science*, 2018. **564**: p. 193-203.

[9] Geankoplis CJ. Transport processes and unit operations. 1993, Englewood Cliffs, New Jersey 07632, USA: Prentice-Hall International, Inc. 937.

[10] Gryta M, Tomaszewska M. Heat transport in the membrane distillation process. *Journal of Membrane Science*, 1998. **144**(1): p. 211-222.

[11] Da Costa AR. Fluid flow and mass transfer in spacer-filled channels for ultrafiltration. A.C.E. Da Costa and F.o.A.S.U. Industrial Chemistry, Editors. 1993.