Asian Journal of Chemistry; Vol. 25, No. 12 (2013), 6873-6876

ASIAN JOURNAL OF CHEMISTRY

http://dx.doi.org/10.14233/ajchem.2013.15020

Modeling and Experimental Study on Air-Gap Membrane Distillation

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(*Received*: 26 December 2012; *Accepted*: 5 June 2013) AJC-13591

Membrane distillation (MD) is an attractive separation process compared to the traditional separation processes such as distillation or reverse osmosis. Requiring lower operation temperature and being able to use low-grade thermal energy are the major features of membrane distillation. Membrane distillation can be classified into four configurations. Air gap membrane distillation (AGMD) is one of the most versatile membrane distillation configurations which can be applied to almost any applications. The model of air gap membrane distillation module is established in this paper based on the mechanism of heat and mass transfer. The outlet temperature of hot feed stream and cold stream can be predicted by this model. Thereafter the design of air gap membrane distillation system can be achieved based on the presented module model. Many experiments have been done to validate the rationality of the model.

Key Words: Membrane distillation, Air gap membrane distillation, Module model, Desalination, Heat transfer mechanism.

INTRODUCTION

Membrane distillation (MD) is an innovative membrane separation process. Membrane distillation has many significant advantages, such as high system compactness, low operating temperature, less energy consumption. Therefore it can use the low temperature heat sources, including waste or solar heat. With low cost capital and utility costs relative to conventional separation processes, such as distillation and reverse osmosis, membrane distillation has been applied to water desalination, food processing, wastewater treatment and concentration of solution. Air gap membrane distillation (AGMD) is the most versatile membrane distillation configuration which can be applied to almost any applications[1-5]. In this paper, modeling and experimental study on air gap membrane distillation would be performed and the model of air gap membrane distillation module would be developed.

Many studies on the heat and mass transfer mechanism of membrane distillation processes have been done. Gryta and Tomaszewska[6] investigated the membrane distillation process with a laminar flow of the streams. The applicability of the model to describing the heat transfer in membrane distillation processes was presented and verified experimentally. Guijt *et al.*[7,8] presented a predictive model for air gap membrane distillation in a counter current flow configuration using fiber membranes. The water vapour transport across the membrane was described by the dusty-gas model that described simultaneous Knudsen diffusion, molecular diffusion and viscous flow. Alklaibi *et al.*[9] considered the air gap membrane distillation process as a two-dimensional conjugate problem, in which a simultaneous numerical solution of the momentum, energy and diffusion equations of the feed and cold solutions have been carried out. The results were validated in comparison with experimental results. Subsequently, Alklaibi *et al.*[10] investigated the sensitivity of the permeate flux to the main parameters, including the temperature, concentration, velocity, *etc.*, for air gap membrane distillation. Although these simulation studies provide comprehensive explanation on the nature of the process, these rigorous models are unable to be adapted for the design of the large scale membrane distillation system. In this paper, the model of air gap membrane distillation module would be developed by simplifying the models of heat and mass transfer mentioned above. The outlet temperature of hot feed stream and cold stream can be predicted by this model. Thereafter the design of air gap membrane distillation system can be achieved based on the presented module model.

Air gap membrane distillation module model: A simple mass transfer model for air gap membrane distillation processes, in which the heat and mass transfer with temperature polarization are taken into consideration, is used here[4].

$$J = \frac{\Delta T}{R_{MD}} \quad (1)$$

$$R_{MD} = \partial T_{MD}^{-2.1} + \beta \quad (2)$$

$$\Delta T = T_h - T_c \quad (3)$$

$$T_{MD} = \frac{T_h + T_c}{2} \quad (4)$$

where J (kg/s m^2) is the mass flux and ΔT (ºC) is the trans-membrane temperature difference. T_h and T_c (ºC) are the temperatures of the hot side and the cold side of membrane distillation, respectively. R_{MD} denotes the membrane distillation resistance, which can be calculated by the simplified relationship, eqn. 1. T_{MD} is a parameter defined by eqn. 4. ∂ and β are the coefficients. They mainly depend on the geometric characteristics of the air gap membrane distillation module and the property of the feed solution. They can be determined by regressing with experimental data for different aqueous solutions.

For the air gap membrane distillation module shown in Fig. 1, the temperature difference of the hot feed stream between the inlet temperature (T_{bi}) and the outlet temperature (T_{bo}) is not very big because of the existence of the air gap and thereby (T_h) can be regarded as the average temperature of T_{bi} and T_{bo}. Similarly, the cold side temperature (T_c), also can be regarded as the average value of the entering and the leaving temperature.

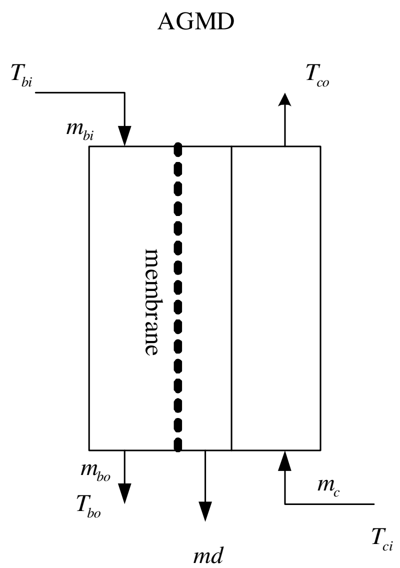


Fig. 1. Diagram of the air gap membrane distillation module structure

$$T_h = \frac{T_{bi} + T_{bo}}{2} \quad (5)$$

$$T_c = \frac{T_{ci} + T_{co}}{2} \quad (6)$$

where T_{ci} and T_{co} are the inlet temperature and the outlet temperature of the coolant stream, respectively. In this situation, the permeate flux of the module can be represented by the average value.

In this paper, it is assumed that the outlet temperature of permeate water is equal to the outlet temperature of the hot feed stream. Thus, the air gap membrane distillation module can be considered as a heat exchanger. The heat balance for hot and cold stream is:

$$Q = C_w m_{bi}(T_{bi} - T_{bo}) = C_w m_c (T_{co} - T_{ci}) \quad (7)$$

The heat released from the hot feed stream is carried away by the coolant stream. C_w is the specific heat of water. m_{bi} denotes the flowrate of the hot feed stream entering the module. m_c is the flowrate of the coolant stream.

In the air gap membrane distillation module, the air gap is very minute in comparison with the membrane area and the cold plate area; then the maximum possible amount of heat transfer is available. In such a case, the outlet temperature of the hot feed stream is equal to the inlet temperature of the coolant stream when the flowrate of the coolant stream is larger than that of the hot feed stream. Then the air gap membrane distillation effectiveness, ε, which is defined as the ratio of the actual heat transfer in a given air gap membrane distillation module to the maximum possible amount of heat transfer, is represented by:

$$\varepsilon = \frac{C_w m_c (T_{co} - T_{ci})}{C_w m_{bi}(T_{bi} - T_{ci})} \quad (8)$$

with the combination of eqns. 7 and 8, the outlet temperature T_{bo} can be solved by,

$$T_{bo} = T_{bi} - \varepsilon(T_{bi} - T_{ci}) \quad (9)$$

In eqn. 9, it is necessary to firstly determine the air gap membrane distillation effectiveness ε. The relationship similar to the heat exchanger effectiveness is employed here.

$$\varepsilon = \frac{1 - \exp\left[-NTU\left(1 - \frac{m_{bi}}{m_c}\right)\right]}{1 - \frac{m_{bi}}{m_c}\exp\left[-NTU\left(1 - \frac{m_{bi}}{m_c}\right)\right]} \quad (10)$$

$$NTU = \frac{UA}{C_w m_{bi}} \quad (11)$$

where NTU is defined as the number of transfer units. U denotes the overall heat transfer coefficient. A denotes the area and it is approximately equal to the membrane area for the flat sheet membrane module or the tubular membrane module. In air gap membrane distillation processes, the total heat flux Q_T (kJ/m^2) consists of two parts, the latent heat by water evaporation Q_V and the sensible heat by heat conduction Q_C, which is expressed by

$$Q_T = Q_V + Q_C = k_v \Delta T + k_s \Delta T = U\Delta T \quad (12)$$

where k_v denotes the heat transfer coefficient of the vapour heat and k_s denotes the heat transfer coefficient of the conductive heat. Both k_v and k_s make up the overall heat transfer coefficient U. The vapour heat is also expressed by

$$Q_V = J\lambda \quad (13)$$

where λ is the latent heat of evaporation. With the combination of eqns. 1, 2, 12 and 13, k_v can be determined by

$$k_v = \frac{\lambda}{\partial T_{MD}^{-2.1} + \beta} \quad (14)$$

For the heat conduction, the heat transfer resistance between the hot feed stream and the coolant stream includes the hot solution, the membrane, the air gap, the condensate film, the cooling plate and the cold solution. Thereby the overall heat transfer coefficient of the conductive heat k_s is represented by

$$k_s = \left(\frac{1}{h_1} + \frac{\delta_m}{k_m} + \frac{\delta_a}{k_a} + \frac{\delta_{cp}}{k_{cp}} + \frac{1}{h_f} + \frac{1}{h_2} \right)^{-1} \quad (15)$$

where h_1 and h_2 are the heat transfer coefficients of the hot solution and the cold solution, respectively. h_f is the heat transfer coefficient of the condensate film. k_m, k_a and k_{cp} represent the thermal conductivity of the membrane, air and the cooling plate, respectively. Here the effect of the temperature on the thermal conductivity is neglected. δ_m, δ_a and δ_{cp} are the thickness of the membrane, the air gap and the cooling plate, respectively. Among these heat transfer resistances, the air gap is the most effective, hence the overall heat transfer coefficient of the conductive heat mainly depend on the separation distance of the air gap and the thermal conductivity of air.

For a unit of the module, the mass balance of the hot feed stream is represented by:

$$m_{bi} = m_{bo} + JS_m \quad (16)$$

where m_{bo} denotes the flow rate of the hot feed stream leaving the module. S_m is the membrane module area.

All the above mathematic models can be used to calculate the outlet temperature and the permeated flux of an air gap membrane distillation module. In order to validate the rationality of the model, a desalination experiment using the air gap membrane distillation module has been done in the experimental section.

EXPERIMENTAL

The experimental equipment of air gap membrane distillation system was set up as shown in Fig. 2. The system consists of three major components, the air gap membrane distillation modules, the solar energy collector and the feed water heater which energy come from the extra heat source. In the air gap membrane distillation modules, the hot feed stream (the brackish water) and cold stream (fresh water) are pumped from the feed tank and cold stream tank and enter into the membrane

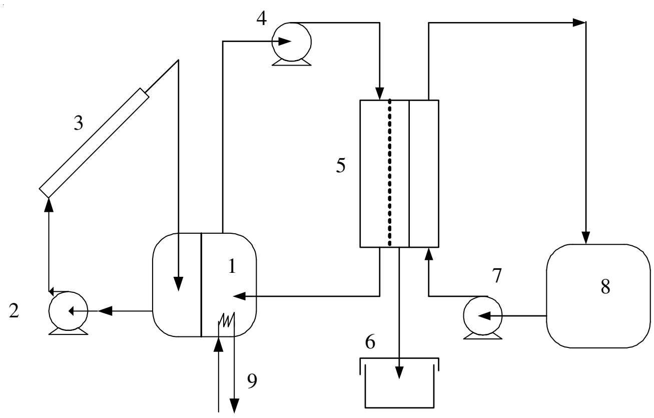


Fig. 2. Air gap membrane distillation system flow chart. 1. The feed tank with heater; 2. The recycle pump for hot medium; 3. The solar energy collector; 4. The pump for hot feed stream; 5. Membrane module; 6. The pure water storage; 7. The pump for coolant stream; 8. The tank of coolant stream; 9. The extra heat source

modules in a counter current mode. The heat is transferred from hot feed stream to cold stream, at the same time the permeated (pure water) is condensed on the cold surface and flow into the permeate tank. The feed stream leaving the modules will return the feed tank and is heated by the solar energy collector. Then the hot feed stream enters again in membrane modules and so on.

The experimental parameters and module features[3,8] are listed in Table-1. The model parameters α and β in eqn. 4 are firstly regressed with the experimental data. The model predicted results are validated by our membrane module experimental ones. Fig. 3 shows the model predicted values and experiments are in good agreement.

Based on the established air gap membrane distillation module model, the sensitivity of the process thermal efficiency to the operating temperature is analyzed. The experimental results are shown in Fig. 4. In Fig. 4(a), the value of thermal efficiency (η_m) increases as the temperatures of the hot feed stream T_{bi} increases because the permeate flux increases with the enlarging *trans*-membrane temperature difference. In Fig. 4(b), lowering the temperatures of the coolant stream T_{ci} increases the permeate flux but decreases η_m because of the

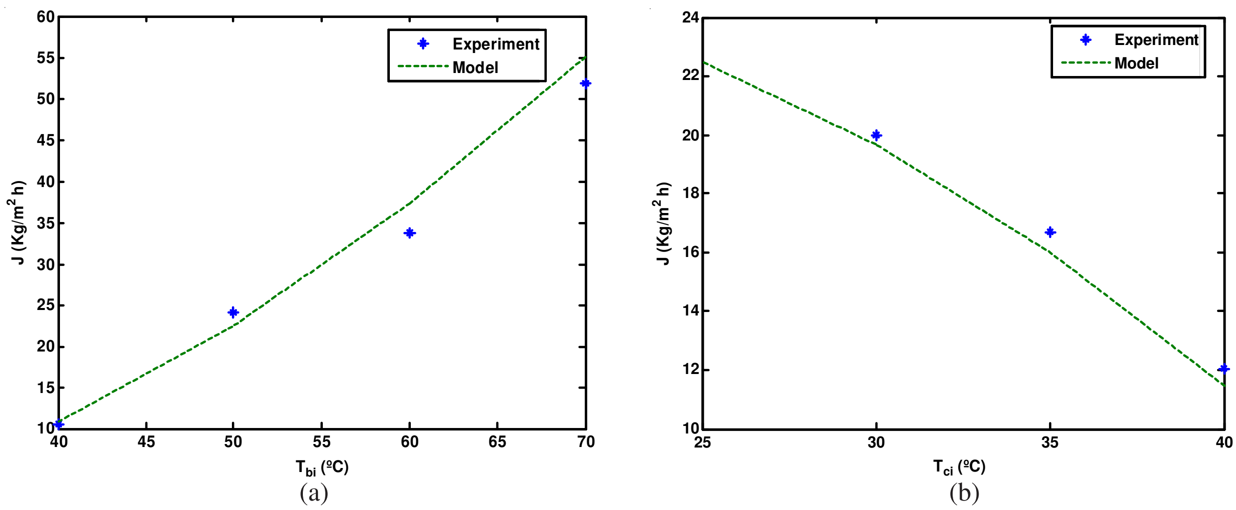
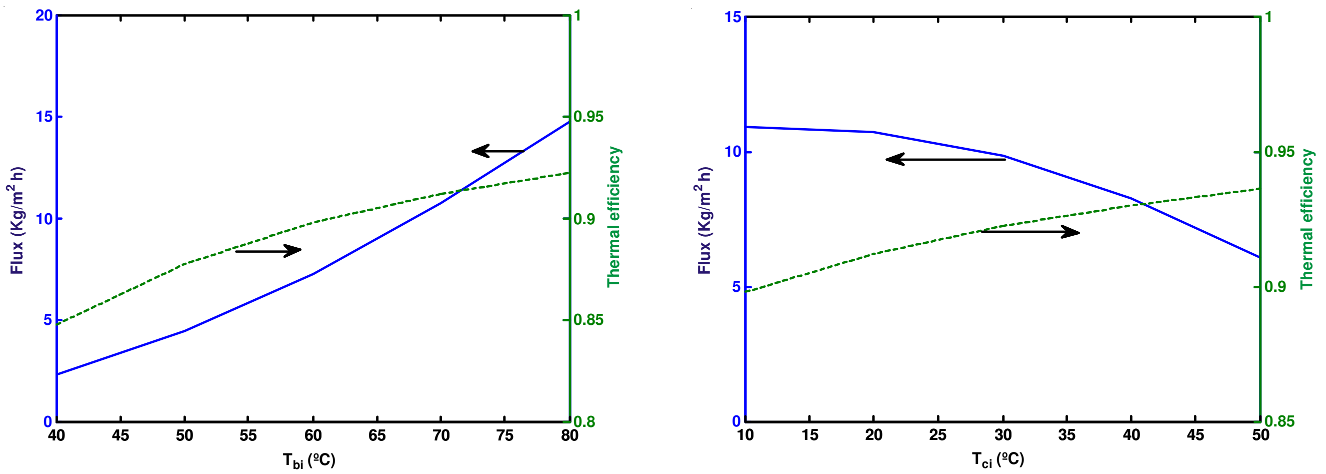


Fig. 3. (a) Effect of the inlet temperature of the hot feed stream on the permeate flux in comparison with experiments when T_{ci} = 25ºC; (b) Effect of the inlet temperature of the cold feed stream on the permeate flux in comparison with experiments when T_{bi} = 50 ºC



(a) (b)

Fig. 4. (a) Effect of the hot feed stream (T_{bi}) on the permeate flux (J) and the thermal efficiency (η_m) when T_{ci} = 20 ºC; (b) effect of the cold feed stream (T_{ci}) on the permeate flux (J) and the thermal efficiency (η_m) when T_{hi} = 70 ºC

TABLE-1
EXPERIMENTAL PARAMETERS AND MODULE FEATURES

∂, β the coefficients in eqn. 2	3.2×10^7, 6×10^3
The area of the membrane module (m^2), S_m	1.6
The range of the flowrate for each membrane module (kg/s),	0.24-0.3
The heat transfer coefficient of the hot solution and the cold solution (w/m^2 k), h_1, h_2	500, 800
The heat transfer coefficient of the condensate film (w/m^2 k), h_f	192
The thickness of the membrane, the air gap and the cooling plate (mm), δ_m, δ_a and δ_{cp}	0.4, 2, 1.5
The thermal conductivity of the membrane, air and the cooling plate (w/m·k), k_m, k_a and k_{cp}	0.2, 0.03, 60
The latent heat of evaporation (kJ/kg), λ	2257.2
The specific heat of water (kJ/kg ºC), C_w	4.2
The range of the operating temperature of the hot feed stream (ºC), T_{bi}	40-80
The range of the operating temperature of the coolant stream (ºC), T_{ci}	20-50

decrease of the contribution of the mass transfer resistance of the cold stream to the total mass transfer resistance. In this figure, the value of η_m can range from 0.85-0.95 when T_{bi} and T_{ci} vary within the operating scope.

Conclusion

Air gap membrane distillation is a kind of membrane distillation configuration; it can be applied to seawater and brackish desalination. The module model is indispensable to design and operate an air gap membrane distillation system. In this paper, the air gap membrane distillation module model have been established and the rationality of the model have been validated by doing many desalination experiments. The results show that the model predicted values and experiments are in very good agreement.

ACKNOWLEDGEMENTS

Financial support from the Natural Science Foundation of Guangxi (No. 2012GXNSFAA053025) and Guangxi Higher Education Institutes Talent Highland Innovation Team Scheme (GJR201147-12) are gratefully acknowledged.

REFERENCES

1. A.M. Alklaibi and N. Lior, *Desalination*, **171**, 111 (2004).
2. M.S. El-Bourawi, Z. Ding, R. Ma and M. Khayet, *J. Membr. Sci.*, **285**, 4 (2006).
3. R. Chouikh, S. Bouguecha and M. Dhahbi, *Desalination*, **181**, 257 (2005).
4. G.L. Liu, C. Zhu, C.S. Cheung and C.W. Leung, *Heat Mass Transf.*, **34**, 329 (1998).
5. C. Charcosset, *Desalination*, **245**, 214 (2009).
6. M. Gryta and M. Tomaszewska, *J. Membr. Sci.*, **144**, 211 (1998).
7. C.M. Guijt, G. W. Meindersma, T. Reith and A.B. de Haan, *Sep. Purif. Technol.*, **43**, 233 (2005).
8. C.M. Guijt, G.W. Meindersma, T. Reith and A.B. de Haan, *Sep. Purif. Technol.*, **43**, 245 (2005).
9. A.M. Alklaibi and N. Lior, *J. Membr. Sci.*, **255**, 239 (2005).
10. A.M. Alklaibi and N. Lior, *J. Membr. Sci.*, **282**, 362 (2006).