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Measurement Of The Convective Heat Transfer Coefficient For Narrow Pore Size Distribution Polypropylene Flat Sheet Membrane Module By Vacuum Membrane Distillation

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Membrane distillation (MD) is one of a membrane separation processes which can be used in the field such as seawater and brine desalination, waste water purification, fruit juice condensed, removing volatile components from dilute aqueous solutions and so on. PP is a novel MD material due to its hydrophobicity, thermal and chemical stability, good mechanical properties and low cost. The membrane structures, with a gradation in pore size but narrow pore size distribution, are desirable for MD application. The aim of this work is to develop the convective heat transfer coefficient of the PP hydrophobic microporous membranes prepared via thermally induced phase separation (TIPS) method, which is important for developing the MD performance for this membrane. In this work, the convective heat transfer coefficient for narrow pore size distribution iPP flat sheet membrane module was measured using pure water experimental results. Both Poiseuille flow and Knudsen diffusion were considered to develop the heat transfer and mass transfer mathematical models of pure water VMD process, temperature polarization coefficient was used to measure the boundary layer resistances which is relative to the total heat transfer resistance of the system. The mass transfer model of pure water was developed basing on dusty-gas model (DGM). C++ Language programming was used to investigate the temperature of the liquid-vapor interface of the feed, and the parameters of Dittus-Boelter equation were regressed using the pure water experimental results. The turbulence heat transfer coefficient of the iPP flat sheet membrane module was: $Nu = 0.0236 Re^{0.8} Pr^{0.378}$.

1. Introduction

Membrane distillation (MD) is known as a process which is a membrane separation technology with low cost and energy saving process, and which refers to the thermally driven transport of vapor through microporous and hydrophobic membranes (Lawson and Lloyd, 1997). MD is carried out for pure water or aqueous solutions Generally. MD configurations include direct contact membrane distillation (DCMD), vacuum membrane distillation(VMD), sweeping gas membrane distillation (SGMD) and air gap

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membrane Distillation (AGMD) (El-Bourawi ,Ding, et.al, 2006).
Polypropylene (PP) is one of the most popular membrane materials for MD process (Kim and Lloyd, 1991) due to its hydrophobicity, thermal and chemical stability, good mechanical properties and low cost (Mahmud, Kumar, et.al, 2002).Thermally induced phase separation (TIPS) has been used extensively to make microporous membranes since 1980s (Castro, 1981) . PP hydrophobic microporous membranes can be prepared by stretching or TIPS methods.
The MD performances of the membranes are related to the membrane morphology and structure parameters, such as membrane thickness, pore size distribution, porosity and tortuosity(Schofield, Fane, et.al, 1987; Lawson and Lloyd, 1996). The morphology of PP hydrophobic microporous membrane was controlled mainly by polymer concentration, the diluent and its concentration, cooling bath temperature during TIPS preparation process(Lloyd,1990; Lloyd, Kim,et.al, 1991).
Narrow pore size distribution iPP flat sheet hydrophobic microporous membranes were prepared via TIPS method, the diluent was bean oil(Tang N. , Wang X.K., et.al, 2006), which showed a good VMD performance for NaCl aqueous solution and seawater desalination. To silmulate the MD performance of the resultant membranes, the convective heat transfer coefficient of this membrane was developed basing on pure water VMD experimental result, which is important for MD process enhancement.

2. Pure water VMD experiment

The P-28 flat sheet membrane module was produced by CM-Celfa AG Co., Switzerland. The effective area of the membrane is 28cm^2, the aqueous feed was introduced in a stainless steel vessel with a capacity of 15L. The temperature of the feed solution was controlled by an automatic heating and controlling system, and it was monitored at the inlet and outlet ports of the membrane unit using two Pt-100 thermo-resistances connected to a digital thermometer which provide an accuracy of ±0.1℃. A gear pump was used to recirculate the feed from the feed tank through the membrane unit, the feed flow rate was monitored using a rotameter and a pressure meter connected to the permeate side of the membrane module was used to measure the pressure in the range of 0.1～101.3kPa.
Pure water (Distilled water) was used as feed, the permeate was collected, weighted and analyzed at the end of each experimental run. The schematic diagram of VMD experimental setup is shown in Fig.1.

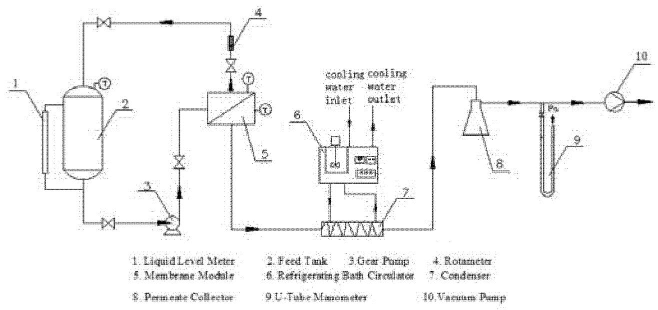


Fig.1 The schematic diagram of VMD experimental setup

3. Pure water VMD transfer models

Pure water kept turbulence flow in iPP flat sheet membrane module in this work. Pure water heat and mass transfer in VMD was presented in Fig.2.

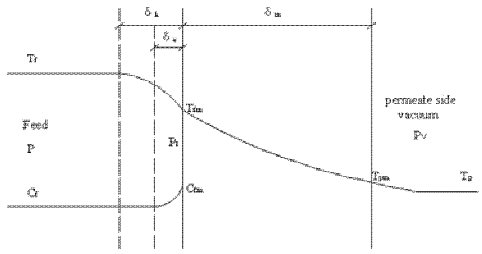


Fig.2 Diagram of pure water heat and mass transfer in VMD

3.1 Pure water VMD heat transfer model

Pure water heat transfer model in VMD was given by equation (1) to (4). Q_1, Q_2 and Q_3 were heat transferred from heat boundary layer to membrane surface, heat across the membrane and heat trasferred on cold side boundary layer, respectively.

$$Q_1 = h_f \Delta T_f = h_f (T_f - T_{fm}) \tag{1}$$

$$Q_2 = Q_V + Q_m = h_V \Delta T_m + h_m \Delta T_m = NH_V + h_m \Delta T_m \tag{2}$$

$$Q_3 = h_P \Delta T_P \tag{3}$$

Where h_f is the convective heat transfer coefficient, W/(m^2·K); h_m is the mixing heat transfer coefficent within membrane, W/(m^2·K), h_m is related to the porosity, thickness, air and heat conductivity coefficient of the membrane material, Lawson (1996) draw a conclusion from his work that h_m is 200~600 W/(m^2·K); h_p is the convective heat transfer coefficient on cold side boundary layer, W/(m^2·K); ΔT_f is temperature difference of feed side heat boundary layer, K; ΔT_p is temperature difference of permeated side heat boundary layer, K; ΔT_m is temperature difference across the membrane, K; T_f is the bulk temperature of pure water, K; T_{fm} is the temperature of pure water on vapor-liquid interface, K; H_v is molar latent heat of vaporization, J/mol; N is the molar flux of vaporization, mol/(m^2·s).

The absolte pressure on the vacuum side is lower than the vapour pressure at the same operational temperature, and there is less air within the membrane pore, so the heat conductivity lost was negligible during VMD process, i.e., Q_m=0. The temperature boundary layer is negligible in VMD, T_{pm}=T_p, so Q_3=0. The heat equilibrium on vapor-liquid interface of pure water VMD is given by equation (4).

$$Q = h_f \Delta T_f = h_f (T_f - T_{fm}) = NH_V \tag{4}$$

3.2 The temperature polarization of heat transfer boundary

The transfer resistances of pure water in VMD are consisted of two parts, one is the heat transfer resistance and mass transfer resistance on feed side boundary layer, the other is the resistance of the vapour across the membrane. A commonly used measure of the magnitudes of the boundary layer resistances relative to the total heat trasfer resistance of pure water in VMD is given by the temperature polarization coefficient (Bandini , Sarti, et.al, 1988; Bandini , Gostoli, et.al, 1992):

$$\Theta = \frac{T_f - T_{fm}}{T_f - T_{sat}} \tag{5}$$

Where Θ is temperature polarization coefficient, Θ approaches unity for well designed systems, i.e., there is no resistance across membrane, Θ approaches zero for poorly designed systerms that are limited by heat transfer through the boundary layers.T_{sat} is the equilibrium temperature of the feed that corresponds to the pressure on the permeate side, K. T_{sat} can be calculated from Antoine equation(Lawson and Lloyd, 1997).

Θ was regressed for iPP hydrophobic microporous membrane module using pure water VMD experimental result. The value of Θ was from 0.015to 0.050 according to feed volume flow rate 30L/h to 70L/h. The result showed that the transfer resistance was focused on the vapor acrossing the membrane.

3.3 The convective heat transfer coefficient model for iPP membrane module

McCabe (1985) gives the convective heat transfer coefficient for low viscosity liquid with turbulent flowing inside the tubes, Dittus-Boelter equation was simplied for pure water in VMD:

$$Nu = \frac{h_f d}{k^T} = uRe^s Pr^t \tag{6}$$

Where d is equivalent diameter of the tube, m; k^T is liquid conductivity coefficient, W/(m·K); Re and Pr are Reynolds number and Prandtl number, respectively; u,s and t are parameters which are related to the membrane module and transfer processes in VMD.

3.4 Pure water VMD mass transfer model

The gas diffusion mechanism for MD are: Knudsen diffusion, Poiseuille flow and Fick diffusion. There is no Fick diffusion in VMD, so the mechanism for pure water VMD is either Knudsen diffusion or both Knudsen diffusion and Poiseuille flow, which is depending on the mean free path of the vapour and the average pore size of the membrane (Cussler, 1996; Urtiaga, Ruiz,et.al, 2000).

Dusty-gas model (DGM) was the availble mathematical model which describes the gas diffusion mechanism whithin the membrane. Pure water mass trasfer model was developed basing on DGM shown in equation (7) to (9).

$$N = \frac{1}{RT_{avg}\delta}[K_0(\frac{8RT_{avg}}{\pi M_{H_2O}})^{1/2}\Delta P + B_0\frac{P_{avg}}{\mu_g}\Delta P] \tag{7}$$

$$B_0 = \frac{\varepsilon r^2}{8\tau} \tag{8}$$

$$K_0 = \frac{2\varepsilon r}{3\tau} \tag{9}$$

Where R is gas constant, R=8.314J/(mol·K); T_{avg} is the average temperature across the membrane, K; δ is the thickness of the membrane, m; M_{H2O} is molar weight of water, kg/mol; ΔP is the vaporization pressure difference across membrane, Pa; P_{avg} is the vaporization average pressure across the membrane, Pa; μ_g is vapour viscosity, Pa·s; ε is the porosity of the membrane, %; r is the avarage pore radius of the membrane,m; τ is the tortuosity of the membrane.

4. Results and Discussion

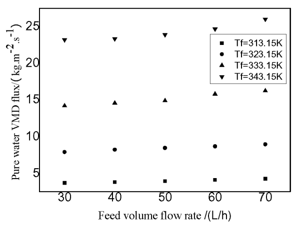
C++ Language programming was used to develop the temperature of the liquid-vapor interface of the feed, and the parameters of Dittus-Boelter equation were regressed using pure water experimental results.

4.1 Parameter "s" regression result

When the feed tempreture is constant, Prandtl number is constant too, equation (10) was developed from equation (6).

$$Nu = s \ln Re + constant \tag{10}$$

When pressure on vacuum side was 3kPa, Pure water experimental result was shown in Fig.3. Parameter "s" was regressed shown in Fig.4 when Pr=3.05, different feed tempreture were used for parameter "s" regression, "s" ≈0.8, that showed a turbulence flowing of pure water within the membrane module



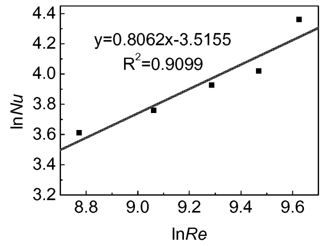


Fig.3 Effect of Feed volum flow rate on pure water VMD flux

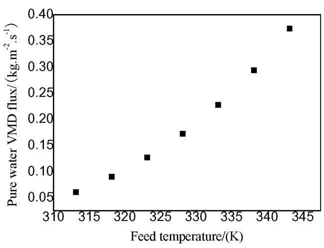
with Pr=3.05

4.2 Parameter "u"and "t" regression result

Parameter "s" in Dittus-Boelter equation was 0.8. The liquid flow and heat boundary layer condition were controlled by the feed bulk temperature when both the pressure on vacuum side and feed flow rate were constant. Equation (11) was developed from equation (6), from which parameters "u"and "t" were regressed.

$$\ln\frac{Nu}{Re^{0.8}} = t\ln Pr + \ln u \qquad (11)$$

Pure water VMD experimental result was shown in Fig.5, the pressure on vacuum side was 3kPa and feed volume flow rate was 70L/h. Parameters "u"and "t" were regressed shown in Fig.6, the regression was: t =0.378,u =0.0236.



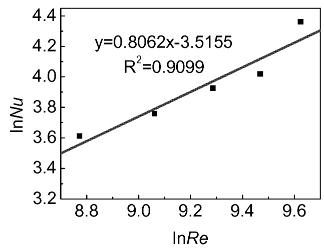


Fig.5 Effect of Feed temperature on water VMD flux

versus lnPr

5. Conclusion

The turbulence heat transfer coefficient of the iPP flat sheet membrane module was investigated, it was: $Nu = 0.0236Re^{0.8}Pr^{0.378}$. The convective heat transfer coefficient of iPP flat sheet membrane module can be used for relative heat process simulation, it is the key parameter to develop MD performance of the resultant iPP hydrophobic microporous membranes.

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References

Bandini S, Sarti G C, Gostoli C, 1988,Vacuum membrane distillation: pervaporation through porous hydrophobic membranes. proc. Third Int. Conf. Pervaporation processes in the Chemical Industry, Nancy, France, Bakish materials, 117-126.
Bandini S, Gostoli C, Sarti G C, 1992,Separation efficiency in vacuum membrane distillation. J. Membr. Sci., 73, 217-229.
Bourawi El- M.S., Ding Z., Ma R., Khayet M., 2006, A framework for better understanding membrane distillation separation process, J. Membr. Sci. 285, 4-29.
Cussler E L, 1996, Diffusion, Mass transfer in fluid systems. Ind edn. , Cambridge University Press, Cambridge.
Castro A.J., 1981, Methods for making microporousproducts,US Patent 4247498.
Kim S. S., Lloyd D.R., 1991, Microporous membrane formation via thermally-induced phase separation. III. Effect of thermodynamic interactions on the structure of isotactic po1ypropy1ene membranes. J. Membr. Sci., 64,13-29.
Lawson K.W., Lloyd D.R., 1997, Membrane distillation. J. Membr. Sci. 124, 1-25.
Lawson K W, Lloyd D R, 1996, Membrane distillation. I. Module design and performance evaluation using vacuum membrane distillation. J. Membr. Sci., 120, 111-121.
Lloyd D.R., 1990, Microporous membrane formation via thermal1y induced phase separation. I. Solid-liquid phase separation. J. Membr. Sci., 52, 239-261.
Lloyd D.R., Kim S.S., Kinzer K.E., 1991, Microporous membrane formation via thermal1y-induced phase separation. II. Liquid-liquid phase separation. J. Membr. Sci., 64, 1-11.
Lawson K W, Lloyd D R, 1996,Membrane distillation. II. Direct contact MD. J. Membr. Sci., 120: 123-133.
Mahmud H., Kumar A., Narbaitz R.M., Matsuura T., 2002, Mass transport in the membrane air-stripping process using microporous polypropylene hollow fibers: effect of toluene in aqueous feed, J. Membr. Sci. 209, 207-219.
McCabe W.L., Smith J.C. and Harriott P., 1985, Unit operations of chemical engineering, 4^{th} edn., McGraw-Hill, New York.
Schofield R W, Fane A G, Fell C J D, 1987, Heat and mass transfer in membrane distillation. J. Membr. Sci., 33, 299-313.
Tang N. , Wang X.K., Sha Z.L. ,et al., 2006, A Technology for Preparing Narrow Pore Size Distribution Membrane, CHISA , Praha, Czech Republic
Urtiaga A M, Ruiz G, Ortiz I, 2000, Kinetic analysis of the vacuum membrane distillation of chloroform from aqueous solutions. J. Membr. Sci., 165, 99-110.