CHARACTERISATION OF HEAT AND MASS TRANSFER IN THE RECTANGULAR FLAT-SHEET POLYVINYLIDENE FLUORIDE MEMBRANE FOR VACUUM MEMBRANE DISTILLATION

CHIAM CHEL KEN

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Chiam Chel Ken
(TANDATANGAN PENULIS)

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PROF. IR. DR. ROSALAM HJ. SARBATLY

Tarikh: 23 Jun 2014

DECLARATION

I hereby declare that the data of the research written in this thesis are original and the experimental data are found by me. This thesis has not been submitted previously for a higher degree in any university.

In addition, I also declare that the material in this thesis is my own except for quotations, excerpts, equations, summaries and references, which have been duly acknowledged.

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Chiam Chel Ken

PK2009 9075

CERTIFICATION

NAME : **CHIAM CHEL KEN**

MATRIC NO. : **PK2009 9075**

TITLE : **CHARACTERISATION OF HEAT AND MASS TRANSFER IN THE RECTANGULAR FLAT-SHEET POLYVINYLIDENE FLUORIDE MEMBRANE FOR VACUUM MEMBRANE DISTILLATION**

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DECLARED BY

1. SUPERVISOR

Prof. Ir. Dr. Rosalam Hj. Sarbatly Signature

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ABSTRACT

This thesis presents a study of the heat and mass transfer performance in a laboratory-scale vacuum membrane distillation (VMD) process by using a rectangular cross-flow flat-sheet membrane module. One type of commercial polyvinylidene fluoride membrane with a nominal pore size of 0.2 μm and an effective area of 71.4 cm^2 is tested. Results show that the traditional Nusselt and Sherwood correlations, which are frequently employed in the membrane distillation literature, are not suitably used to estimate the heat and mass transfer coefficients in the VMD system for Reynolds numbers ranging from 150 to 1400. By using distilled water as the feed solution, a new semi-empirical heat transfer correlation by suggesting Knudsen-viscous mechanism governs the water vapour transport across the membrane is developed. Compared to the feed flow rate, the feed temperature is the limit to the heat transfer. The heat transfer coefficients are strongly dependent on the physical properties of the feed solution, but less relied on the design of the membrane module. A semi-empirical mass transfer correlation is derived based on the analogy between heat and mass transfer. In a desalination experiment, it was observed that approximately 30% of the experimental data fit well with the semi-empirical Nusselt and Sherwood correlations. The heat transfer process is limited by the resistances in the feed boundary layer and the membrane. The heat transfer resistance in the membrane increases when that in the feed boundary layer decreases and vice versa. More than 50% of the heat transfer resistances occur in the liquid feed phase at feed flow rates below 1200 mL/min, whereas the remaining occur in the membrane itself. At feed flow rates that exceed 1200 mL/min, the heat transfer resistance in the membrane becomes dominant. The Knudsen-viscous resistance controls the mass transfer through the membrane while the mass transfer resistance in the liquid feed phase is absent. The membrane deformed during the VMD operation as the result of the external pressure that originated from the hydraulic pressure of the feed solution and the vacuum pressure acts on the membrane downwardly. It was noticed that the dimples stamped on the membrane surface by the perforation of the support do not significantly affect the heat and mass transfer performance during VMD. The deformed membrane with the dimpled surface is compacted. The permeability of the deformed membrane is enhanced from 3 to 20% by the compaction as a result of the membrane thickness reduction. Nusselt and Sherwood correlations that consider membrane deformation are developed to predict the flux through the deformed membrane. The differences between the fluxes calculated using the correlations with membrane deformation effects and the correlations without membrane deformation effects are generally less than 9%, suggesting that membrane deformation due to the membrane permeability enhancement may exert no significant influence on the performance of VMD.

ABSTRAK

Pencirian Pemindahan Haba dan Jisim Dalam Membran Berlembaran-rata Berbentuk Segiempat untuk Penyulingan Membran Vakum

Tesis ini mengkaji pemindahan haba dan jisim bagi sebuah sistem penyulingan membran vakum (PMV) berskala makmal. Sistem PMV tersebut dikaji dengan menggunakan satu modul membran berlembaran-rata yang berbentuk segiempat. Sejenis membran komersial yang diperbuat daripada fluorida polivinilidene telah diuji. Membran tersebut mempunyai saiz liang nominal berukuran 0.2 µm. Keluasan membran yang digunakan adalah 71.4 cm^2. Keputusan kajian menunjukkan bahawa korelasi-kolerasi Nusselt dan Sherwood tradisional, yang mana sering digunakan dalam kajian-kajian penyulingan membran, adalah tidak sesuai digunakan untuk menganggarkan pekali pemindahan haba dan jisim bagi sistem PMV dalam kajian ini yang beroperasi dalam lingkungan nombor Reynolds dari 150 hingga 1400. Satu kolerasi separa-empirik untuk pemindahan haba telah dibangunkan dengan menggunakan air suling sebagai suapan. Mekanisme Knudsen-likat menguasai pemindahan wap menerusi membran. Suhu suapan lebih mempengaruhi proses pemindahan haba jika dibandingkan dengan kadar aliran suapan. Pekali pemindahan haba adalah sangat bergantung kepada ciri-ciri fizikal larutan suapan tetapi ia kurang dipengaruhi oleh rekabentuk modul membran. Satu kolerasi separa-empirik untuk pemindahan jisim diperolehi berdasarkan analogi antara pemindahan haba dan jisim. Satu kajian penyahgaraman mendapati bahawa kira-kira 30% daripada data eksperimen menepati nilai-nilai yang dianggarkan dengan menggunakan korelasi-kolerasi separa-empirik Nusselt dan Sherwood tersebut. Rintangan dalam fasa suapan dan fasa membran mengehadkan pemindahan haba. Pengaruh rintangan dalam fasa membran bertambah apabila rintangan dalam fasa suapan berkurang dan sebaliknya. Rintangan dalam fasa suapan mengawal lebih 50% daripada jumlah rintangan pemindahan haba apabila sistem PMV beroperasi kadar aliran suapan kurang dari 1200 mL/min. Rintangan dalam fasa membran menguasai process pemindahan haba apabila kadar aliran suapan melebihi 1200 mL/min. Rintangan bermekanisme Knudesn-likat dalam fasa membran mengawal proses pemindahan jisim dalam PMV manakala rintangan pemindahan jisim dari fasa suapan boleh diabaikan. Permukaan dan struktur membran terubah bentuk kerana tekanan dari suapan dan tarikan vakum dikenakan pada membran semasa PMV beroperasi. Lekuk yang terbentuk pada permukaan membran tidak mempengaruhi proses pemindahan haba dan jisim, manakala ketelapan membran tersebut bertambah dari 3 hingga 20% yang disebabkan pemadatan di mana ketebalan membran berkurangan. Kolerasi-kolerasi Nusselt dan Sherwood telah dibangunkan dengan mempertimbangkan kesan membran terubah bentuk. Perbezaan antara fluks yang dianggarkan berdasarkan korelasi-kolerasi iaitu dengan mengambil kira kesan membran terubah bentuk dan tanpa kesan membran terubah bentuk adalah kurang daripada 9%, di mana kesan membran terubah bentuk boleh diabaikan.

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LIST OF ABBREVIATIONS

AGMD	-	Air gap membrane distillation
CPC	-	Concentration polarisation coefficient
DCMD	-	Direct contact membrane distillation
DW	-	Distilled water
LEP_w	-	Liquid entry pressure of water
V-L	-	Vapour-liquid
MD	-	Membrane distillation
MDE	-	Membrane deformation effect
MTBE	-	methyl tert-butyl ether
NaCl	-	Natrium chloride
PE	-	Polyethylene
PP	-	Polypropylene
PTFE	-	Polytetrafluoroethylene
PV	-	Pervaporation
PVDF	-	Polyvinylidene fluoride
PVP	-	Polyvinylpyrrolidone
RO	-	Reverse osmosis
SEM	-	Scanning electron microscopy
SGMD	-	Sweeping gas membrane distillation
SMS	-	Smooth membrane surface
TCA	-	1,1,1-trichloroethane
TCE	-	trichloroethylene
TPC	-	Temperature polarisation coefficient
VLE	-	Vapour-liquid equilibrium
VMD	-	Vacuum membrane distillation
VOC	-	Volatile organic compound

LIST OF SYMBOLS

a	-	Empirical constant for Equation (3.29)
A	-	Area (m^2)
c	-	Concentration (mol/m^3)
C	-	Membrane distillation coefficient, mass transfer coefficient (kg/m^2 s Pa)
C_p	-	Heat capacity (J/kg K)
d	-	Diameter (m)
D	-	Diffusion coefficient (m^2/s)
F_c	-	Tube-row correction factor (-)
g	-	Gravitation acceleration (9.81 m/s^2)
Gr	-	Grashof number (-)
Gz	-	Graetz number (-)
h	-	Individual heat transfer coefficient (W/m^2 K)
H	-	Overall heat transfer coefficient (W/m^2 K); Henry's constant (Pa)
ΔH_v	-	Heat of vaporisation (J/kg)
J	-	Mass flux (kg/m^2 s or kg/m^2 h)
k	-	Individual mass transfer coefficient (kg m/mol s or m/s); thermal conductivity (W/m K)
k_B	-	Boltzmann constant (1.38×10^{-23} J/K)
kn	-	Knudsen number (-)
K_m	-	Membrane permeability coefficient (s $mole^{1/2}$ m^{-1} $kg^{-1/2}$)
K	-	Overall mass transfer coefficient (W/m K)
L	-	Length (m)
m	-	Mass (kg)
M	-	Molecular weight (kg/mol)
n_s	-	Mole fraction of solute (-)
n_+, n_-	-	Valence (-)
Nu	-	Nusselt number (-)
p	-	Partial pressure (Pa)

P	-	Vapour pressure, absolute pressure (Pa)
$\bar{P}$	-	Mean partial pressure (Pa)
P°	-	Saturation vapour pressure (Pa)
Pr	-	Prandtl number (-)
Q	-	Heat flux (J/m^2 s)
r	-	Radius (m)
R	-	Resistance (m^2 s K/J or m^2 s Pa/kg); rejection (%); universal gas constant (8.31 J/mol K)
R_v	-	Removaval efficiency (%)
Re	-	Reynolds number (-)
s	-	Standard deviation (kg/m^2 s)
s_w	-	Minimum weighed standard deviation (-)
Sc	-	Schimidt number (-)
Sh	-	Sherwood number (-)
t	-	Time (s)
T	-	Temperature (K)
v	-	Diffusion valume (m^3); velocity (m/s)
V	-	Volume (m^3)
w	-	Weight (kg)
$\dot{w}$	-	Rate of water vapour lost (kg/s)
x	-	Mass fraction (-)
y	-	Mole fraction in vapour phase (-)

Subscript

0	-	Initial
1	-	Final, upstream
2	-	Downstream
A	-	Component A
b	-	Bulk
B	-	Component B
c	-	Cold
cal	-	Calculated

d - One drop

dis - Discharging

e - Exposed

exp - Experimental

f - Feed

G - Gas

h - Hot; hydraulic

i, j - Component i, j

I - Interface

Kn - Knudsen-type

L - Liquid

m - Membrane

op - Operation

p - Permeate; pore

percen. - Percentage (%)

r - Retentate

s - Solid; smooth

T - Total

U-D - Upstream to downstream

v - Vaporisation; vapour

vis - Viscous-type

w - Water

Superscript

b, c - Empirical constants for Equation (3.29)

HT - Heat transfer

MT - Mass transfer

* - Equilibrium

Greek letter

α - Separation factor (-)

β - Concentration factor (-); thermal expansion coefficient (K^{-1})

γ	-	Surface tension (N/m); activity coefficient (-)
δ	-	Thickness (m)
ε	-	Porosity (-)
η_v	-	Viscosity of vapour (Pa s)
θ	-	Angle (°)
λ	-	Mean free path (m)
λ_+, λ_-	-	Limiting ionic conductance (-)
μ	-	Viscosity of liquid (Pa s)
ρ	-	Density (kg/m^3)
σ	-	Collisions diameter (m)
τ	-	Tortuosity (-)