EFFECT OF FEED SPACER SIZE AND MESH LENGTH ON PERMEATE FLUX ENHANCEMENT DRIVEN BY FORCED SLIP VELOCITY

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SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science.

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STUDENT'S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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ABSTRAK

Modul membran *spiral-wound* (SWM) memainkan peranan penting dalam proses penyahgaraman dan rawatan air industri. Polarisasi konsentrasi (CP) merupakan masalah kritikal dalam proses membran kerana pengumpulan larut yang berpanjangan berhampiran dengan permukaan membran mengurangkan prestasi membran dan menyebabkan pengotoran membran. Kajian terkini telah menunjukkan bahawa interaksi antara slip terpaksa yang tidak stabil dan pendorong pusaran (contohnya peruang) dalam modul membran *spiral-wound* menghasilkan peningkatan fluks dan pengurangan polarisasi konsentrasi yang ketara. Slip terpaksa merupakan pergerakan lapisan cecair nipis bersebelahan dengan permukaan membran yang dapat menyebabkan gangguan terhadap lapisan sempadan tumpuan di permukaan membran, serta meningkatkan pencampuran dalam sistem. Objektif tesis ini adalah untuk mengkaji kesan geometri peruang SWM modul terhadap optima frekuensi slip terpaksa dan prestasi peningkatan fluks dalam membran dengan kesan slip terpaksa. Kajian ini menggunakan Pengkomputeran Bendalir Dinamik (CFD) untuk menjalankan simulasi bagi mengkaji kesan geometri parameter peruang yang berbeza terhadap optima frekuensi slip terpaksa yang tidak mantap, serta kesannya terhadap prestasi membran bagi peruang zig-zag 2D. Analisis kajian telah menunjukkan bahawa optima frekuensi terjejas oleh interaksi lapisan ricih di peruang hiliran. Keberkesanan slip terpaksa mencapai nilai puncak (sehingga 15.6% peningkatan fluks) untuk saiz peruang dalam julat $0.5<d_f/h_{ch}<0.6$ disebabkan oleh keseimbangan antara slip terpaksa dengan modulus CP. Di samping itu, penumpahan pusaran ditahan untuk saiz peruang yang lebih kecil ($d_f/h_{ch}\leq0.4$) kerana daya kelikatan mendominasi daya perolakan disebabkan oleh nombor Reynolds filamen yang lebih kecil. Apabila jarak antara filamen meningkat, kenaikan fluks disebabkan oleh slip terpaksa adalah lebih tinggi (sehingga 31.5%), walaupun fluks sebenar menurun disebabkan oleh lapisan sempadan membran yang lebih maju. Hasil kerja ini juga menguatkan penemuan bahawa slip terpaksa adalah lebih efisien bagi reka bentuk peruang yang mempunyai pencampuran yang kurang dalam sistem membran (contohnya CP tinggi).

ABSTRACT

Spiral-wound membrane (SWM) modules have been an important role in industrial desalination and water treatment processes. Concentration polarisation (CP) is a critical problem for membrane processes because prolonged solute accumulation near the membrane surface reduces the membrane performance and promotes fouling. Recent studies have shown that the interactions between forced transient flow and eddy inducers (i.e. spacers) in the SWM modules result in significant permeate flux enhancement and reduction in concentration polarisation. Forced slip velocity is the movement of thin fluid layer adjacent to the membrane surface, which disrupts the concentration boundary layer and promotes mixing in membrane systems. The aim of this thesis is to study the effect of SWM feed spacer geometry on the resonant frequency of forced-slip and the resulting permeate flux enhancement generated by forced-slip perturbation. This thesis uses Computational Fluid Dynamics (CFD) code to simulate and investigate the effect of varying the spacer geometric parameters on the resonant frequency for an unsteady forced-slip, as well as the resulting membrane performance, for a 2D zig-zag spacer. The analysis shows that the resonant frequency is significantly affected by the interaction of the shear layer with successive downstream spacers. The effectiveness of forced-slip reaches a peak (up to 15.6% flux increase) for a spacer size in the range of $0.5<d_f/h_{ch}<0.6$ because of the trade-off between mixing-induced forced-slip and the CP modulus. In addition, vortex shedding is suppressed for smaller spacer sizes ($d_f/h_{ch}\leq 0.4$), because viscous forces dominate over convective forces due to a smaller filament Reynolds number. As the distance between filaments is increased, the increase in flux due to forced-slip is greater (up to 31.5%), albeit the actual flux decreases because the boundary layer is more developed. These results also reinforce the finding that forced-slip perturbation is more efficient for spacer designs with poor mixing (i.e. high CP).

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D	Solute diffusivity ($m^2\ s^{-1}$)
d_f	Filament diameter (m)
d_h	Hydraulic diameter (m)
$e = \dfrac{F_{coarse} - F_{fine}}{F_{fine}}$	Relative error in the calculation of an integral function
E_x	Electric field in the *x*-direction ($V\ m^{-1}$)
F	Integral function
f_{pl}	Peak frequency predicted by frequency response (Hz)
$f = \dfrac{d_h}{2\rho u_{eff}{}^2}\dfrac{\Delta p}{L}$	Friction factor
f_{cut}	Cut-off frequency (s^{-1})
f_s	Frequency of oscillation of slip velocity (s^{-1})
h_{ch}	Height of channel (m)
h_{gap}	Gap height measured between the membrane surface and the spacer (m)
J	Permeate flux ($kg\ m^{-2}\ s^{-1}$)
L_{in}	Entrance length (m)
L_m	Membrane length (m)
L_{out}	Exit length (m)
L_p	Membrane permeance ($m\ s^{-1}\ Pa^{-1}$)
l_m	Mesh length (m)
n	Distance in direction normal to a surface (m)
P_0	Dimensionless inlet transmembrane pressure
$Pn = Re^3 f_{TA}$	Power number
p	Pressure (Pa)
Δp_{tm}	Inlet transmembrane pressure (Pa)
$\mathbf{R} = \dfrac{N_{fine}}{N_{coarse}}$	Mesh refinement ratio
R	Membrane intrinsic rejection
Re_{CR}	Critical Reynolds number

$Re_f = \frac{\rho u_{avg} d_f}{\mu}$	Filament Reynolds number
$Re_h = \frac{\rho u_{eff} d_h}{\mu}$	Hydraulic Reynolds number
Re_s	Slip Reynolds number
$St = \frac{f_{pl} d_f}{\bar{u}_{gap}}$	Strouhal number
t	Time (s)
$U_{s,A}$	Dimensionless forced slip velocity amplitude
$U_{s,pulse}$	Dimensionless pulse slip velocity
$U_{s,t}$	Dimensionless forced slip velocity
u	Local velocity in the x-direction (m s^{-1})
u_{avg}	Average velocity (m s^{-1})
u_{b0}	Inlet velocity at any y-direction (m s^{-1})
$u_{eff} = u_{b0}/\varepsilon$	Effective velocity (m s^{-1})
$\bar{u}_{gap}$	Flow velocity between spacer and membrane wall (m s^{-1})
u_s	Slip velocity (m s^{-1})
$u_{s,A}$	Oscillation amplitude of slip velocity (m s^{-1})
$u_{s,pulse}$	A pulse in the slip velocity (m s^{-1})
v	Local velocity in the y-direction (m s^{-1})
V	Current linear speed of the flow at distance n from the wall.
w	Solute mass fraction
w_{ch}	Membrane channel width (m)
x	Distance in the bulk flow direction, parallel to membrane surface (m)
y	Distance from the bottom membrane surface, in direction normal to the surface (m)

Greek letters

$\gamma = w_w/w_{b0}$	Concentration polarisation modulus
$\dot{\epsilon}$	Shear strain rate (s^{-1})
ε	Porosity
ε_e	Permittivity (F m^{-1})

ζ	Zeta potential (V)
μ	Dynamic viscosity (kg m^{-1} s^{-1})
π	Osmotic pressure (Pa)
$\pi_0 = \varphi w_{b0}$	Inlet osmotic pressure (Pa)
Π_{L_p}	Dimensionless membrane permeance
ρ	Fluid density (kg m^{-3})
η	Dimensional number (number of dimensions in flow field)
σ	Reflection coefficient
τ	Wall shear stress (Pa)
φ	Osmotic pressure coefficient (Pa)

LIST OF ABBREVIATIONS

*b*0	Value at inlet bulk conditions
CFD	Computational Fluid Dynamics
CP	Concentration polarisation
EOF	Electro-osmotic flow
IW	Impermeable wall
max	Maximum value for variable
p	Value for the permeate
PW	Permeable wall
RO	Reverse osmosis
s	Value with forced slip
SWM	Spiral-wound membrane module
TA	Time-averaged value of variable
w	Value on the feed side membrane surface (wall)

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