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Energetic consideration and flux characteristics of roughed-surface membrane in presence of reversing shear

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ABSTRACT

Flux characteristics and energy dissipation for oscillatory flat surface membranes roughed with turbulence promoters (TP) have been investigated both theoretically and experimentally. The combined effect of oscillations and TP has proven effective in enhancing the microfiltration flux by an almost order of magnitude over that for a non-oscillatory flat surface membranes, and close to four times higher than that achieved in the absence of TP under the same oscillation conditions. The power dissipation was determined using the drag and inertia forces acting on individual promoters, as well from the solution of the boundary layer equations with time-invariant eddy viscosity for large and small roughness conditions. Using higher oscillation frequency and lower amplitudes was found to be more effective for flux enhancement and energy utilization where near *self cleaning* conditions were achieved at specific energy consumption of less than ~0.5 kW h/m^3 filtrate. Both grooved and flat TP gave similar results in terms of flux enhancement and energy consumption per unit filtrate, with the former slightly better. Membrane fouling was found to follow the intermediate blocking fouling mechanism for oscillatory membranes as compared to cake filtration for non-oscillating systems. The quasi-steady state flux was satisfactorily predicted using an analytical model based on oscillatory rough surfaces with $R^2 = 0.95$.

Keywords: Oscillatory motion; Turbulence promoters; Power dissipation; Flux enhancement; Membrane; Micro filtration

1. Introduction

Although membrane processes are currently recognized as an effective separation techniques, in many industrial applications, decline in permeate flux due to membrane fouling and concentration polarization still present a challenge that could lead to lower productivities. The most adapted approach to mitigate such effects is cross flow filtration (CFF) which increases the shear rate at the membrane surface by increasing the tangential feed flow (Bauser et al., 1982; Belfort et al., 1994; Jonsson, 1993; Kennedy et al., 1974; Zydney and Colton, 1986). The major drawback of CFF is the frequent need to re-circulate the feed, which could potentially damage the material to be filtered leading to finer and more difficult material to filter and more likely to flux decline. CFF could be augmented using turbulence promoters or roughness elements, as for example the case of stamped ceramic membranes (Stopka et al., 2001). The main challenge to such approach however is the potential development of high axial pressure drop, which increases pumping energy and decreases the transmembrane pressure (TMP) along the axial membrane surface.

An alternate approach to CFF is dynamic filtration (DF) in which a relative motion is created between the membrane and its housing such that high shear is generated at the membrane surface that is decoupled from feed flow rate. Several DF

Abbreviations: CF, cake filtration mechanisms; CFF, cross flow filtration; DF, dynamic filtration; FTP, flat turbulence promoters; GTP, grooved turbulence promoters; IB, intermediate pore blocking; NTP, no-turbulent promoters; QSS, quasi-steady state; TMP, transmembrane pressure; TP, turbulence promotors.

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Nomenclature

a	oscillation amplitude (m)
b	fouling rate constant
A	active surface area (m^2)
A_f	total frontal area of promoter element (m^2)
A_s	windward wetted area of promoter element (m^2)
c	concentration (mol/m^3)
C_d	drag coefficient
C_m	inertia coefficient
D_e	effective diffusion coefficient (m^2/s)
E	flux enhancement factor
f	oscillation frequency (Hz)
g	acceleration of gravity (m/s)
f_s	friction factor
F	force to oscillate the filtration unit (N)
F_f	fluid force (N)
h	promoter height (m)
h_s	Nikuradse equivalent sand roughness (m)
J	filtration flux (m^3/m^2/s or LMH)
J_{qs}	quasi-steady state filtration flux (m^3/m^2/s)
k_i	blocking model parameter Eq. (19) (variable)
k_{ib}	intermediate blocking model parameter (m^{-1})
k_{cf}	cake filtration model parameter (s/m^2)
KC	Keulegan–Carpenter number ($KC = 2\pi u_0/\omega h$)
L	length of the membrane surface (m)
m_s	mass of the filtration unit (kg)
n	blocking model index
N	number of promoters
Δp	transmembrane pressure drop (Pa)
P	power (W)
R	filtration resistance (m/kg)
Re_L	length Reynolds number ($Re_L = awL/\nu$)
S	area of smooth surface without promoters (m^2)
S_f	total frontal area (m^2)
Sc	Schmidt number ($Sc = \nu/D_e$)
Sh_J	Sherwood number ($Sh_J = J_{qs}L/D_e$)
t	time (s)
T	oscillatory period (s)
$\bar{u}$	mean velocity component (m/s)
u	oscillation velocity (m/s)
u_0	maximum velocity oscillation amplitude (m/s)
u_f	frictional velocity (m/s)
V	permeate volume (m^3)
y	distance from surface (m)
W	promoter width (m)

Greek symbols

α	wall factor (=0.0812)
β	fouling factor
δ	boundary layer thickness (m)
δ_l	laminar boundary layer thickness (m)
γ_{max}	maximum shear rate (s^{-1})
η	dimensionless distance, Eq. (2)
λ	promoters density
ε_t	eddy viscosity (m^2/s)
κ	Karman constant (0.41)
ν	fluid kinematic viscosity (m^2/s)
μ	fluid dynamic viscosity (Pa s)
ρ	fluid density (kg/m^3)
ρ_s	filtration unit material density (kg/m^3)
σ	amplitude ratio factor
τ_l	laminar shear stress (Pa)
τ	shear stress (Pa)
τ_0	maximum shear stress (Pa)
ζ	Euler number (0.5772)
ψ	defined in Eq. (10)
φ	specific energy (kW h/m^3)
ω	circular frequency of oscillation, $2\pi f$ (s^{-1})

Subscripts

b	bulk
f	friction
0	initial condition ($t = 0$)
qs	quasi-steady state
p	pumping
w	wall

modules have been developed including use of pulsating flows (Bellhouse et al., 1973; Finnigan and Howell, 1989; Gupta et al., 1992), vibrating membranes (Akoum et al., 2004; Beier et al., 2006; Beier and Jonsson, 2007; Gomaa et al., 2011a), rotating membranes (Serra et al., 1999), and the motion of a mechanical device close to the membrane surface (Fillaudeau et al., 2007; Jaffrin et al., 2004). Furthermore, and similar to CFF, use of turbulence promoters and roughness elements has been reported to improve shear rate and enhance filtration performance as for example the case of rotating disc equipped with vanes (Brou et al., 2002). Commercial DF devices have been reported and an excellent review of the different classes and their main characteristics has been given by Jaffrin (2008).

The advantage of DF in microfiltration using oscillatory membranes can be attributed to the fact that, the energy dissipation in this case is mainly focused on the boundary layer at solid/liquid interface rather than the bulk of the fluid as in case of oscillatory flow systems (Gomaa et al., 2004). Use of transverse turbulence promoters in presence of oscillations was also found very effective in generating the shear as well as secondary flows contributing to fouling limitation and enhancing membrane microfiltration flux by an almost order of magnitude higher than that in non-oscillatory flat surface membranes, and close to three times the values achieved in absence of TP under similar conditions (Gomaa et al., 2011b). The authors however did not address the effect of surface roughness on power dissipation and specific energy consumption per unit volume of filtrate. In a recent study, and using a similar approach, flux enhancement of submerged hollow fibre membrane system was achieved by imposing transverse oscillating membrane motion (Kola et al., 2012). In this case the hollow fibres acted as turbulence promoters and created the necessary shear and secondary flows at the surface, resulting in enhanced filtration flux. The authors provided estimates of power requirement based on fluid inertial and drag force for single oscillating cylinder and showed the potential benefit of lowering energy inputs for fouling mitigations in submerged systems using these types of transverse vibrating systems.

The objective of this contribution is to investigate both theoretically and experimentally the effect of turbulence promoters design on microfiltration characteristics of oscillatory membranes. The investigation includes the effect of operating and design parameters on fouling mechanism, effective surface roughness, flux enhancement, as well as