Shear enhancing hydrodynamics for low pressure membrane processes

Farhad Zamani

2014

Farhad Zamani. (2014). Shear enhancing hydrodynamics for low pressure membrane processes. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/61789>

<https://doi.org/10.32657/10356/61789>

NANYANG
TECHNOLOGICAL
UNIVERSITY

SHEAR ENHANCING HYDRODYNAMICS
FOR LOW PRESSURE MEMBRANE PROCESSES

Farhad Zamani

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

2014

**SHEAR ENHANCING HYDRODYNAMICS
FOR LOW PRESSURE MEMBRANE PROCESSES**

Farhad Zamani

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

A thesis submitted to the Nanyang Technological University in
partial fulfillment of the requirement for the degree of

Doctor of Philosophy

2014

Acknowledgment

Firstly, I would like to express my deep respect and gratitude to my supervisor Associate Professor Adrian Wing-Keung Law for his encouragement, guidance, support and patience. He taught me the skills of research methodology and guided me with his solid knowledge, and made me believe in myself.

Also, I would like to show my sincere gratitude to my co-supervisor, Professor Anthony Gordon Fane for his guidance and support as well as for the opportunity to be part of Singapore Membrane Technology Centre (SMTTC) to fulfill my PhD. It would not have been possible without his help.

I would like to reserve special thanks to Prof. William Bill Krantz for his valuable advice and critical comments.

Many thanks go to Associate Professor Wang Rong as the SMTTC director.

I would like to acknowledge the Environment and Water Industry Programme Office (EWI) of Singapore for the support of this work (Project MEWR C651/06/175).

Many thanks to my friends and people in SMTTC, Ebrahim Akhondi, Amir Hooshang Taheri, Dr. Filicia Wicaksana, Dr. Miles Edward Rzechowicz, Li Tian, Lin Long, Xia Lijun, Jiang Yishuai, Agnes Kurniawati Harijanto, Dr. Saeid Rajabzadeh and Dr. Chong Tzyy, for their sharing of knowledge and making my

PhD life more enjoyable. I am also thankful to Ms. Zan Ong Chin Chin as the SMTC Assistant Manager for her kind help.

Last but not least, I would like to thank my beloved wife, parents and sisters for their love, support and never-ending encouragements during my study.

Table of Contents

Acknowledgment.....	i
Table of Contents	iii
Abstract.....	ix
List of Tables	xi
List of Figures.....	xii
List of Symbols	xx
List of Abbreviations	xxii
1 Introduction	1
1.1 Background and Motivation.....	1
1.2 Objectives.....	4
1.3 Thesis Outline	5
2 Literature Review	7
2.1 Membrane: A Broad Concept	7
2.2 Different Membrane Operational Modes	8
2.2.1 Dead End and Crossflow Filtrations	9
2.2.2 Constant Pressure and Constant Flux Operations.....	10
2.2.3 Concept of Critical Flux.....	11
2.3 Mass Transfer in Pressure Driven Membrane Filtration	15

2.4	Hydrodynamics in Membrane Processes	16
2.4.1	Concentration Polarization (CP) Concept	17
2.4.2	Particles Back Transport Mechanisms	19
2.4.3	Numerical Approaches	24
2.4.4	Particle Image Velocimetry (PIV).....	27
2.5	MBR Systems	29
2.5.1	Different Types of Submerged MBRS	31
2.6	Anti-Fouling Techniques for Submerged MBR Systems	32
2.6.1	Aeration	34
2.6.2	Vibrating Systems	38
2.7	Conclusion Remarks	54
3	Materials and Methods	57
3.1	Experimental Setup.....	57
3.2	Model Fouling Agents	60
3.2.1	Bentonite.....	60
3.2.2	Humic Acid	60
3.3	Membranes.....	61
3.4	PIV Setup.....	62
3.5	Pore Size Distribution Analysis Methods	63
3.5.1	Liquid Displacement Porometry (LDP)	63
3.5.2	Evaporimetry (EP)	66

3.5.3	Field-Emission Scanning Electron Microscope (FESEM)	70
4	Prediction of Supermicron Particle Deposition in Crossflow	
	Microfiltration	71
4.1	Abstract	71
4.2	Introduction	72
4.3	Model Development and Numerical Solution.....	75
4.3.1	Velocity Profile in a Channel with Flux through the Membrane.....	75
4.3.2	Mass Transfer of Supermicron Particles near the Membrane Surface	78
4.4	Material and Methods.....	85
4.4.1	Experimental Protocol	86
4.5	Results and Discussion.....	89
4.5.1	Determination of critical fluxes	92
4.5.2	Comparison between Predictions of the Different Models.....	93
4.5.3	Critical Modified Peclet Number.....	94
4.6	Conclusions	97
5	Hydrodynamic Analysis of Vibrating Hollow Fibre Membranes	100
5.1	Abstract	100
5.2	Introduction	101
5.3	Hydrodynamic Analysis	103
5.3.1	Analytical Solution for the Hydrodynamics of a Sinusoidal Vibrating Single Fibre.....	103

5.3.2	Analytical Solution for Optimizing the Distance between Two Vibrating Surfaces.....	108
5.4	CFD Modeling	110
5.4.1	Computational Domain	110
5.4.2	Solution Description	112
5.5	Results and Discussion	113
5.5.1	Wall Shear Rate of a Vibrating Fibre	113
5.5.2	Optimum Distance between Two Vibrating Surfaces	117
5.5.3	CFD Simulations of Vibrating Bundles of Fibres	119
5.6	Conclusions.....	121
6	Introducing Effective Hydrodynamic Parameters on Depolarization for Transverse Vibrating Hollow Fibre Membranes	123
6.1	Abstract.....	123
6.2	Introduction.....	124
6.3	Theory and Prior Studies	128
6.4	Materials and Methods.....	135
6.4.1	PIV Experimental Apparatus.....	135
6.4.2	Vibrating Hollow Fibre Experiments	136
6.4.3	CFD Simulation.....	138
6.5	Results and Discussion	141
6.5.1	Validation of CFD Simulations by PIV Results.....	143

6.5.2	Gauge Pressure Variation for an Oscillating Fibre Membrane.....	144
6.5.3	Hydrodynamic Comparison of Oscillating Fibre Membranes with Different Layouts.....	147
6.5.4	Comparison of Longitudinal and Transverse Oscillating Membranes 149	
6.6	Conclusions	151
7	Comparison of Different Anti Fouling Techniques in terms of the Membrane Selectivity and Fouling Mode.....	153
7.1	Abstract	153
7.2	Introduction	153
7.3	Materials and Methods	156
7.3.1	Experimental Apparatus and Protocol	156
7.3.2	Model Foulant	156
7.3.3	Pore Size Distribution Analysis Methods	157
7.4	Results and Discussion.....	157
7.4.1	TMP Rise Monitoring	157
7.4.2	TOC-Level Analysis	158
7.4.3	Pore Size Distribution Analysis	159
7.5	Conclusions	162
8	Preliminary Observation of Supermicron Particles Polarization near a Vibrating Surface.....	164

8.1	Abstract.....	164
8.2	Introduction.....	164
8.3	Materials and Methods.....	167
8.4	Results and Discussion	168
8.5	Conclusions.....	171
9	Conclusions and Recommendations	173
9.1	Conclusions.....	173
9.1.1	Introducing a Generalized Criterion for Particle Deposition in CFMF Using DOTM Results.....	173
9.1.2	Hydrodynamic Analysis of Longitudinal Vibrating Hollow Fibre Membranes	174
9.1.3	Hydrodynamic Analysis of Transverse Oscillating Hollow Fibre Membranes	175
9.1.4	Effects of Different Anti-Fouling Techniques on the Fouling Mechanism	176
9.1.5	Supermicron Particles Polarization near a Vibrating Surface	176
9.2	Recommendations.....	176
	References.....	178

Abstract

Low pressure membrane applications, such as microfiltration (MF) and ultrafiltration (UF), have been widely employed in wastewater treatment systems including membrane bioreactors (MBRs). The main problem of these applications is that the operating life period of the membrane is greatly reduced due to the rapid fouling rate, resulting in frequent cleaning of the membrane and consequently increasing the plant maintenance and operating cost. Dynamic shear-enhancing approaches, including vibrating hollow fibres membrane modules, have been proven to be effective to reduce concentration polarization and membrane fouling. However, to date, the effects of the parameters of vibrating system on the fouling have not been well studied comprehensively.

In order to obtain a better understanding of the behavior of supermicron particles in the shear flows, the particle deposition in a simple crossflow microfiltration (CFMF) channel was first investigated theoretically and experimentally. Direct observation through the membrane (DOTM) was employed to determine the local critical flux in the channel. The mass transfer of the particles in the channel was simulated using the finite difference method. The results showed that a critical modified Peclet number (Pe_{crit}) can be introduced as a generalized (not depending on the hydrodynamics) criterion for the onset of particle deposition rather than the critical flux.

The effects of vibration parameters, namely frequency and amplitude, and geometrical parameters (such as fibre radius and bundle packing density) on the

wall shear rate at the membrane surface were studied both analytically and numerically for longitudinal vibrating fibres. The CFD results showed a good agreement with the analytical solution results.

For transverse oscillating fibres, in addition to the shear flow around the membrane fibres, some secondary flows also exist. CFD simulations were performed to analyse the secondary flows induced by transverse oscillating membrane fibres. In addition, the hydrodynamics of different fibre layouts, such as bundle and curtain of membrane fibres, were studied and compared. For validation purpose, the CFD simulation results were compared with experimental data acquired using the technique of Particle Image Velocimetry (PIV) in the laboratory with different Reynolds numbers. The computational results generally showed a good agreement with the experimental observations.

The effect of different anti-fouling techniques (such as aeration and vibration) on the internal fouling of the membranes was assessed using different methods, including liquid displacement porometry (LDP), evapoporometry (EP) and field-emission scanning electron microscopy (FESEM). The results suggested that using vibration might have adverse effects on the performance of the membrane with internal fouling.

Finally, the behavior of accumulated particles near vibrating surfaces was also evaluated using PIV. The results showed that in order to prevent the cake formation on the membrane surface, shear rate (induced by vibration) and washing flows (generated by aeration) are both needed.

List of Tables

Table 2.1	The flux and pressure range in different pressure driven membrane processes (adopted from Wicaksana (2006)).....	8
Table 4.1	Particle diameter (d_p), concentration (c_b) and crossflow velocity (CFV) values for the five cases in this study.	88
Table 5.1	Maximum wall shear rate obtained from the cylindrical solution $\gamma_{w,max}^*$ and C.S. $\alpha^{0.5}$ and the phase delay of wall shear rate (ϕ).....	116
Table 5.2	Resulting wall shear rates for two vibrating fibres with different radii for different frequencies.	117
Table 5.3	Resulting wall shear rates for a vibrating fibre with different kinematic viscosities for different frequencies.....	118
Table 6.1	Mesh properties of grid independence test for studied case.	141
Table 6.2	Hydrodynamic comparison of oscillating fibre membranes with different layouts.	148
Table 6.3	Comparison of transverse and longitudinal oscillation modes in terms of the TMP rise, surface maximum shear rate and power consumption.	150

List of Figures

Figure 1.1	Schematic of a hollow fibres module with different modes of vibration: (a) longitudinal vibration; (b) transverse vibration; and (c) torsional vibration.	4
Figure 2.1	Different pressure driven membrane processes and their application range (adopted from Cui and Muralidhara (2010)).	9
Figure 2.2	Schematic of differences between the modes of operation for pressure driven membrane filtration: (a) dead end and (b) crossflow.	11
Figure 2.3	Schematic diagram of the operational conditions over time: (a) constant pressure filtration and (b) constant flux filtration.	11
Figure 2.4	Determination of critical flux using flux stepping method.	13
Figure 2.5	Estimating critical flux by monitoring the particle deposition using DOTM performed by Li, et al. (1998).	14
Figure 2.6	Determination of critical flux using mass balance method.	15
Figure 2.7	Schematic diagram of CP in a steady state membrane filtration process.	18
Figure 2.8	Forces acting on a particle near the surface of membrane in a filtration system (Ripperger and Altmann 2002).	23
Figure 2.9	CT scan of fibres arrangement at different heights in the bubbling column (Buetehorn, et al. 2011).	25
Figure 2.10	Different types of velocity profile in a vibrating membrane channel (Ahmad, et al. 2010).	26
Figure 2.11	The principles of the PIV operation (DantecDynamics 2012).	28
Figure 2.12	Schematic of a conventional activated sludge process.	29
Figure 2.13	Different configurations of a MBR: (a) cross flow configuration, and (b) submerged configuration.	31

Figure 2.14	Schematic of a submerged MBR configuration using flat plate membranes.....	32
Figure 2.15	A submerged hollow fibre membrane MBR module manufactured by Zenon (Cui, et al. 2003).....	33
Figure 2.16	Classification of anti fouling methods used in MBR applications (Shahnawaz 2009).	34
Figure 2.17	Classification of different bubble shapes and associated vortices: (a) Small bubble with Stokes streamline (b) Ellipsoidal bubble with helical vortices (c) Spherical cap bubble with ring type vortices (adopted from Miyahara, et al. 1988).	36
Figure 2.18	Fouling rate in different superficial air velocities and the phenomenon of optimal air velocity for the filtration of 0.65 g/l Bentonite solution (Xia, et al. 2013).	37
Figure 2.19	Percentages of energy consumption in a typical MBR plant by different components of the plant (adopted from Fenu, et al. 2010). 38	
Figure 2.20	Schematic of a VSEP unit series i15 and different parts the vibrating system (NewLogic 1987).....	39
Figure 2.21	Flow diagram of a typical VSEP unit and flow circulation in a filter pack (NewLogic 1987).	40
Figure 2.22	Schematic view of a vibrating membrane used in a VSEP system. ...	41
Figure 2.23	Variation of permeate flux vs. mean shear rate in log-log coordinate for the MF of a yeast solution (Akoum, et al. 2002).	42
Figure 2.24	Variation of permeate flux vs. mean shear rate in log-log coordinate for UF of albumin for two different temperatures of 10 and 35°C (Akoum, et al. 2002).	43
Figure 2.25	Variation of vibration amplitude and filtration flux (Test 1) with frequency in a VSEP system. In Test 2, the frequency was decreased to 58Hz and raised back to its maximum (Akoum, et al. 2002).	44
Figure 2.26	Schematic flow diagram of the VSEP used by Low, et al. (2004).	44

Figure 2.27	A Submerged MBR (SMBR) hollow fibres module with axial vibration (Low, et al. 2005).....	46
Figure 2.28	A Submerged MBR (SMBR) hollow fibres module with axial vibration (Low, et al. 2005).....	47
Figure 2.29	A SMBR hollow fibres module with torsional vibration (Low, et al. 2005).....	47
Figure 2.30	(a) The use of chess pattern horizontal vane to induce transverse vibration combined with axial vibration in a submerged hollow fibre system (Genkin, et al. 2006); (b) Side view of the chess pattern for the submerged hollow fibres.	48
Figure 2.31	Comparison of permeate flux of hollow fibre bundle with no motion, lengthwise and torsional vibration (Low, et al. 2005).....	49
Figure 2.32	Comparison of permeate flux in VSEP and hollow fibre bundle with axial oscillation (Low, et al. 2005).....	49
Figure 2.33	Cartesian coordinate system used by Beier, et al. (2006) to calculate the wall shear rate on the hollow fibre membrane surface.....	50
Figure 2.34	Correlation between critical flux and mean shear rate in the filtration of baker's yeast suspension. Results are plotted in a Log-Log diagram (Beier, et al. 2006).....	52
Figure 2.35	Critical flux vs. coagulant concentration at frequency of 1.7 Hz (Beier, et al. 2006).....	53
Figure 2.36	Comparison of critical flux vs. frequency in coagulant free and coagulant added suspensions (Genkin, et al. 2006).	53
Figure 2.37	(a) Shear rate and critical flux vs. frequency in the axial vibrating hollow fibre system and (b) Log-Log diagram of J_{crit} vs. frequency. Slopes show the power of f in the correlation between J_{crit} and f (Genkin, et al. 2006).....	55
Figure 3.1	Vibrating flat sheet membrane experimental setup: (a) schematic diagram and (b) photograph.	58

Figure 3.2	The flat sheet membrane holder: (a) schematic representation of the cross-section, (b) exploded view and (c) photograph.....	59
Figure 3.3	Air bubble sheet generated near the membrane surface: (a) front view and (b) side view.....	60
Figure 3.4	Particle size distribution for Bentonite particles by volume percentage.	61
Figure 3.5	Particle size distribution for humic acid particles by number percentage.	61
Figure 3.6	Principle of the LDP technique: (a) schematic representation of a draining cylindrical pore and (b) comparison of pores with different diameters.....	65
Figure 3.7	Gas flow rate versus the differential pressure in LDP (adopted from Jena and Gupta 2010).	66
Figure 3.8	Schematic representations of (a) the EP apparatus and (b) the test cell.	68
Figure 3.9	Three phases of the liquid evaporation in an EP experiment: (a) weight of the test cell versus the time and (b) evaporation rate versus the time.	69
Figure 4.1	Schematic of CFMF showing the parallel plate channel geometry, the axial and transverse velocity profiles. concentration profile, concentration polarization boundary layer, and cake formation layer; particle deposition begins downstream from the channel inlet owing to the local dependence of the critical permeation flux.	77
Figure 4.2	Algorithm (Newton's method) used for solving the nonlinear convective diffusion equation.....	83
Figure 4.3	The effect of the transverse (panel a) and transverse (panel b) grid numbers on the concentration at the middle of the channel wall constituting the membrane.....	84
Figure 4.4	Schematic of the DOTM setup.	86

Figure 4.5	Placement of the transparent Anopore membrane in the channel; (b) the total membrane surface area viewed under the microscope.	87
Figure 4.6	Permeation flux (v_w) and transmembrane pressure (TMP) as a function of time for the flux-stepping protocol; the two micrographs show the particle deposition at 79 and 85 seconds from which the particle deposition rate can be determined as illustrated.....	89
Figure 4.7	The membrane surface coverage at the same time at different distances from the channel inlet: (a) left edge or inlet; (b) Point 1; (c) middle of the channel; (d) Point 2; (e) right edge or exit.	90
Figure 4.8	(a) Particle deposition rate as a function of permeate flux at Point 2 from which the critical flux is determined for the different cases; (b) Comparison between the critical fluxes determined at Points 1 and 2 for the different cases.	93
Figure 4.9	Shear-induced diffusion coefficient D_s (panel a) and the dimensionless concentration polarization boundary layer thickness δ_c^* ($= \delta_c/h$) (panel b) as a function of the dimensionless distance from the channel inlet for the model developed in this study (dashed line), the SID model (dash-dot line) and the SID-MOD (solid line) for Case 1.....	94
Figure 4.10	Critical modified Peclet numbers predicted by the SID model at Points 1 and 2 for the five cases corresponding to different operating conditions.	96
Figure 4.11	Critical modified Peclet numbers predicted by the SID-MOD model at Points 1 and 2 for the five cases corresponding to different operating conditions.	96
Figure 4.12	Critical modified Peclet numbers predicted by the model developed in this study at Points 1 and 2 for the five cases corresponding to different operating conditions.	97
Figure 5.1	Schematic diagram of geometry, boundary conditions and coordinate system for an axial vibrating fibre.....	103

Figure 5.2	Schematic diagram of geometry, boundary conditions and coordinate system for two parallel vibrating surfaces.	108
Figure 5.3	Cross section of (a) in-line and (b) staggered layout of hollow fibres. Hatched areas are the computational domains for CFD modeling. ...	111
Figure 5.4	Meshing and boundary conditions.	112
Figure 5.5	$\gamma_{w,max}^*$ vs. α obtained from the cylindrical solution and Cartesian solution in Log-Log scale.	115
Figure 5.6	Effect of the distance between two vibrating plates on the resulting wall shear rate.	118
Figure 5.7	The wall shear rate for fibre bundles with staggered and in line configuration vs. the distance between the fibres.	120
Figure 5.8	Membrane wall shear stress distribution for frequency of 5 Hz and fibre's radius of 0.4 mm for the following distances between the fibres and configuration: (a) staggered-0.12 mm (b) Inline-0.12 mm (c) staggered-0.4 mm (d) Inline-0.4 mm (e) staggered-1 mm (f) Inline-1 mm.	121
Figure 6.1	Schematic diagram of mechanisms involved in the fouling control in a crossflow filtration process.	125
Figure 6.2	Schematic representation of the vibration membrane surface and the region of influence of vibration, growing concentration polarization layer and associated boundary conditions.	127
Figure 6.3	Oscillating cylinder in a stationary fluid: the geometry, oscillating non-inertial coordinate system chosen in this study and two-dimensional streaming flow and vortices and simplified secondary flows around the cylinder in quarter 4.	130
Figure 6.4	Schematic representation of calculating the time-mean circulation around a square located in Quarter 1 as a measure of the intensity of the vortices around the oscillating fibre.	135

Figure 6.5	(a) Schematic diagram of the PIV experiment; (b) photograph of the oscillating mechanism, the rod holder, rod and glass tank; (c) the rod from the CCD camera point of view.	137
Figure 6.6	The geometry, meshing and boundary conditions for a simulation case: (a) the whole domain; (b) close to the oscillating fibre.....	139
Figure 6.7	Grid independence test for surface-averaged shear rate on the oscillating fibre surface within the 4 th oscillation period.	141
Figure 6.8	The streaming flows away from the vibrating surface and the induced vortices at two different times: (a) PIV experiments; (b) CFD simulations.	142
Figure 6.9	CFD and PIV results of time-mean velocity $\bar{u}$ (averaged for $4T < t < 5T$) along the vibrating axis (x -axis) for an oscillating rod with diameter of 1 cm, amplitude (A) of 1cm and frequencies of: (a) 15; (b) 30; (c) 60; (d) 90 and (e) 120 rpm.	145
Figure 6.10	CFD and PIV results and relative errors for time-mean circulation Γ (averaged for $4T < t < 5T$) in Quarter 1 and over an square with dimension of $5d$ for an oscillating rod with diameter of 1 cm and amplitude (A) of 1cm in different frequencies.	146
Figure 6.11	Gauge pressure distribution around the oscillating fibre for different times within the 4 th oscillation period.	146
Figure 7.1	TMP rise versus time for different anti-fouling techniques at permeate flux of 40 l/m ² h.	158
Figure 7.2	TOC level in the permeate of the filtration tests with different anti-fouling techniques.	159
Figure 7.3	Largest and average pore diameters (measured by LDP) of clean and fouled membranes; effect of different anti-fouling techniques.....	160
Figure 7.4	Average pore diameter (measured by EP) of clean and fouled membranes; effect of different anti-fouling techniques.	161

Figure 7.5	FESEM images of the cross-section of the membranes: (a) clean membrane and membranes used in filtration tests in different modes: (b) aeration; (c) vibration; (d) relaxation; (e) aeration plus vibration; (f) dead-end.....	163
Figure 8.1	The schematic representation of the vibration membrane surface and the region of influence of vibration, coordinate system and time-averaged velocity components.....	166
Figure 8.2	(a) 3D schematic diagram of the vibrating membranes and the PIV setup; (b) PIV camera point of view.....	168
Figure 8.3	$\bar{u}$ and $\bar{v}$ contours near vibrating membrane with different frequencies: (a) 15; (b) 30; (c) 60; (d) 90; (e) 120 rpm.....	170
Figure 8.4	Accumulation of seeding particles on the membrane surface in different filtration modes: (a) dead-end; (b) vibration; (c) aeration; (e) vibration plus aeration.	171
Figure 8.5	$\bar{u}$ and $\bar{v}$ contours for filtration tests with different modes: (a) aeration; (b) vibration; (c) aeration plus vibration.....	172

List of Symbols

English symbol

a	Particle radius	m
A	Amplitude of vibration	m
d	Membrane displacement	m
D	Diffusion coefficient	m ² /s
f	frequency	Hz(1/s)
F_{Ad}	Adhesion force	N
F_{bt}	Back transport force	N
F_d	Deposition force	N
F_D	Drag force	N
J_{crit}	Critical flux	L /m ² day
J_0	0 th order Bessel's function of first kind	-
r	Radial coordinate	m
r_o	Radius of hollow fibre	m
t	Time	s
u	Velocity of fluid in the x -direction	m/s
v	Velocity of fluid in the y -direction	m/s
v_f	Permeate velocity at the membrane surface	m/s
x	Longitudinal coordinate	m
y	Lateral coordinate	m
Y_0	0 th order Bessel's function of second kind	-
z	Directional coordinate	m

Greek symbols

α	Dimensionless parameter of cylindrical - solution ($r_o^2 \omega / \nu$)	
γ	Mean shear flow rate	1/s
θ	Angular coordinate	rad
μ	Viscosity	kg/m s
ν	Kinematic viscosity	m ² /s
ρ	Density	Kg/m ³
τ	Shear stress	Pa
Φ	Volumetric concentration of particles	mol/m ³
ω	Angular frequency	rad/s

Superscript

o	Denotes attenuating term of velocity profile
$*$	Denotes dimensionless parameters

Subscripts

bt	Denotes the back transport
D	Denotes the drag effects
max	Denotes the maximum of a quantity
r	Denotes the radial component of a vector in cylindrical coordinates
x	Denotes the longitudinal component of a vector in Cartesian coordinates
y	Denotes the lateral component of a vector in Cartesian

	coordinates
z	Denotes the directional component of a vector in Cartesian and cylindrical coordinates
w	Denotes the wall of the membrane
θ	Denotes the angular component of a vector

List of Abbreviations

CCF	Cross-flow filtration
CP	Concentration polarization
CS	Cartesian solution
MBR	Membrane bioreactor
MF	Microfiltration
OPM	Oscillation per minute
SMBR	Submerged membrane bioreactor
TMP	Trans membrane pressure
UF	Ultrafiltration
VSEP	Vibratory shear enhanced processing
PIV	Particle image velocimetry

Chapter 1

Introduction

1.1 Background and Motivation

At present, the main challenge in low pressure membrane applications is the rapid fouling rate of the membranes due to heavily loaded suspensions and the high fluxes used commonly in these applications. Several techniques have been developed in the industry to prevent or reduce fouling during the membrane filtration process. These techniques could be categorized into two major methods:

- Air Bubbling
- Dynamic Shear-Enhanced Membrane Filtration

With air bubbling, bubbles are used to induce turbulences and scrub the surface of the membrane (Brindle, et al. 2000) From hydrodynamic point of view, air bubbling generates higher shear stresses on the membrane surface, and induces additional flows in different directions that scatter particles from the surface. Besides, the movement of fibres, which is induced by bubbles, can also be considered as a possible reason of fouling reduction for loose submerged hollow fibre modules (Cui, et al. 2003). However, one of the main disadvantages of this technique is its high power consumption. It is reported that a significant portion of power consumption of a submerged system is due to aeration (Gander, et al. 2000). This problem arises because the bubble distribution is hardly controllable, and hence a

huge portion of aeration energy is wasted. Another problem of aeration is that with increasing aeration rate, the system performance in terms of flux improvement reaches a limit and no further improvement can be achieved. Finally, the shear rate induced by bubbling is relatively weak and consequently only modest fluxes in filtering operation with bubbling can be employed (Cui, et al. 2003; Genkin, et al. 2006).

It is well known that high shear rates on the surface of membrane can reduce the Concentration Polarization (CP), cake build-up and consequently fouling in membrane systems. In conventional Cross-Flow Filtration (CFF), these high shear rates are achieved by increasing the tangential flow velocity along the membrane surface and decreasing the channel width. This combination of factors results in high pressure drop along the membrane. In order to provide a high flow velocity and concomitant high pressure gradient, a huge amount of pumping energy is therefore required. Also, due to the pressure gradient in the direction of the permeate flow, the Trans Membrane Pressure (TMP) of the process varies in at different parts of membrane and thus causes a non-optimal utilization of whole membrane (Jaffrin 2008).

In dynamic or shear-enhanced filtration, a moving part is used to induce shear rate on the surface of the membrane instead. Some common methods of shear enhanced systems are rotating cylindrical membrane, rotating disk systems and vibrational membranes.

A rotating cylindrical membrane consists of cylindrical membranes rotating in a fixed cylindrical housing. Rotating disk systems use rotating disks near fixed

circular membranes. These two systems have several drawbacks such as complexity and limited membrane area that lead to higher equipment cost. Thus, the commercial success of the industrial scales of these applications has been limited (Akoum, et al. 2002; Jaffrin 2008).

Different modes of vibration can be used in different membrane systems. For instance, a hollow fibres system can be vibrated longitudinally, transversely and torsionally (Figure 1.1). A flat membranes system can vibrate torsionally as well, around a vertical axis. Therefore, it seems that the method of vibrating membranes could be more effective and applicable in comparison with alternate methods. In addition, anaerobic systems are gaining momentum in the wastewater industry due to their potential of energy production. The vibration approach would be ideal for anaerobic MBR systems.

Many experimental studies have been carried out on vibrational membranes. These studies and their results will be discussed in Chapter 2. At the same time, theoretical analysis and numerical modeling of these systems are rare. The modeling needs for the study of a vibrational membrane system can be divided into two parts:

1. Modeling of the hydrodynamic of the system that can predict the shear rate on the membrane surface and flow characterization near the membrane.
2. Modeling of the reverse transport mechanism of the supermicron particles away from the membrane surface in a shear flow, which enables the prediction of the back transport induced on the particles caused by shear and consequently the critical flux of the membrane.

Figure 1.1 Schematic of a hollow fibres module with different modes of vibration: (a) longitudinal vibration; (b) transverse vibration; and (c) torsional vibration.

Therefore, comprehensive hydrodynamic models are required to help understand the effects of hydrodynamics on the performance of the low pressure membrane systems.

1.2 Objectives

The research objectives of this study are summarized as follows:

- Develop a model to predict the onset of deposition of supermicron particles in shear flows on the membrane surface. This model will be verified with accurate experimental results.
- Develop a model to determine the velocity profile and wall shear rate around lengthwise vibrating hollow fibre systems using analytical formulations and numerical simulations.

- Study the hydrodynamics around a transverse oscillating hollow fibre membrane. The hydrodynamics of different configurations of oscillating fibres will be modeled and compared. The modeling will be verified with PIV results.
- Determine the effects of vibration on the internal fouling of the membrane. The vibration approach will also be compared with other anti-fouling techniques such as aeration.
- Investigate the behavior of accumulated particles on the surface of a vibrating membrane.

1.3 Thesis Outline

This thesis is organized in nine chapters as follows:

- Chapter 1 ***Introduction:*** This chapter presents the introduction of this study and describes the contents of this report.
- Chapter 2 ***Literature review:*** This chapter reviews the prior studies on the low pressure membrane systems and anti-fouling techniques in these systems.
- Chapter 3 ***Materials and methods:*** The materials, experimental protocols, characterization methods and experimental apparatus are described in this chapter.
- Chapter 4 ***Prediction of supermicron particle deposition in the shear flow in crossflow microfiltration:*** The onset of particle deposition in a crossflow channel was investigated via DOTM. A new numerical modeling of supermicron particles in the shear flows was presented

in this chapter. The critical Peclet number was introduced as a generalized criterion for the onset of particle deposition in the shear flows.

Chapter 5 ***Hydrodynamic analysis of vibrating hollow fibre membranes:***

This chapter introduces a new analytical solution for the flow field around a longitudinal vibrating hollow fibre. CFD simulations were performed to calculate the induced shear rate on the membrane surface in vibrating fibre bundles with different layouts.

Chapter 6 ***Hydrodynamic Analysis of Transverse Oscillating Hollow Fibre***

Membranes: A comprehensive study of the hydrodynamics in transverse oscillating fibre membrane systems is presented in this chapter.

Chapter 7 ***A Comparison of Different Anti-Fouling Techniques, in Terms of***

Membrane Rejection and Fouling Mode: The effects of membrane vibration on the internal fouling of the membrane are investigated in this chapter.

Chapter 8 ***Preliminary Observation of Supermicron Particles Polarization***

near a Vibrating Surface: The behaviour and motion of accumulated particles on the surface of vibrating membranes are studied.

Chapter 9 ***Conclusions and Recommendations:***

This chapter summarizes the important findings of the current study and provides recommendations for further research work.

Chapter 2

Literature Review

This chapter briefly reviews some basic definitions and concepts of membrane processes, as well as the literature on shear enhancing methods in membrane processes.

2.1 Membrane: A Broad Concept

A membrane can be considered as a semi-selective barrier which can block the transmission of particular particles while allowing other particles to permeate through. Nowadays, numerous kinds of membranes exist. The membranes are made with different properties, materials, thickness, structures, etc. For instance, a membrane can be as thin as 100 nm and as thick as a centimetre, and it can be made of organic or inorganic materials. The structure of a membrane may be symmetric or asymmetric, and homogeneous or heterogeneous. Different driving forces can cause the mass transfer through a membrane such as an electrical field or a difference in temperature, concentration or pressure between two sides of the membrane (Mulder 1996).

Pressure driven membrane processes, which this study deals with, can be classified into microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) based on the particle size and range of the applied pressure for the

processes. In these processes, a pressure difference between two sides of the membrane, called transmembrane pressure (TMP), causes the flux through the membrane. The typical pressure and flux range used in different pressure driven membrane processes are shown in Table 2.1. In this study, low pressure membrane processes refer to microfiltration and ultrafiltration. Figure 2.1 summarizes the application range of these processes from the particles size point of view.

Table 2.1 The flux and pressure range in different pressure driven membrane processes (adopted from Wicaksana (2006)).

Membrane Process Type	Pressure Range (bar)	Flux Range (L/m ² h bar)
Microfiltration	0.1-2.0	>50
Ultrafiltration	1.0-5.0	10-50
Nanofiltration	5.0-20	1.4-12
Reverse Osmosis	10-100	0.05-1.4

2.2 Different Membrane Operational Modes

The operational conditions of membrane systems can be categorized from different viewpoints. The feed stream can be fully filtered or only a percentage can pass through the membrane to the permeate side. Also, in a filtration process, either the TMP or the flux can be fixed.

Figure 2.1 Different pressure driven membrane processes and their application range (adopted from Cui and Muralidhara (2010)).

2.2.1 Dead End and Crossflow Filtrations

Two different basic modes of operation can be distinguished in pressure driven membrane processes: dead end and crossflow modes. Figure 2.2 describes the differences between these two modes schematically. The feed flow direction in dead end mode is perpendicular to the membrane and also there is no retentate stream in this mode. Cake formation is very severe in dead end operations and the membrane should be back washed repeatedly in order that the cake resistance does not increase too much.

In cross flow mode, there are three streams: feed, permeate and retentate. The feed stream is parallel to the membrane surface. The tangential component of the feed velocity makes the particles move in the flow direction. As a result, the cake formation and fouling tendency are less compared to the dead end mode. The parallel feed flow in cross flow mode can be caused by pumping, stirring, bubbling

and moving the membrane relative to the surrounding fluid. It should be mentioned that some modes of membrane filtration cannot be categorized as dead end or cross flow completely and they are a combination of these two modes (Cheryan 1998).

2.2.2 Constant Pressure and Constant Flux Operations

The TMP of a membrane filtration process can be set to a fixed value. This operational condition is called constant pressure filtration. If the TMP is small enough, then an almost constant permeate flux may be achieved. Otherwise the permeate flux would decline to a final steady value (see Figure 2.3a). As can be seen in the figure, this mode of operation is self limiting and the flux would reach a final minimum value called final flux.

Running a filtration process under the constant flux mode will result in an accelerating rise of the TMP if the flux is over a critical value (critical flux, J_{crit}) (Field, et al. 1995). Figure 2.3 shows that the constant flux operation is a self accelerating process. If the filtration is run under the critical flux, then no significant fouling will occur (Howell 1995). The critical flux concept and the methods used to determine the critical flux, are discussed in more details in the next section.

Through comparing the performance of the constant flux and constant pressure processes for water treatment, it was found that the constant flux mode is much more preferable since it prevents an initial high fouling rate which is common under constant pressure mode (Defrance and Jaffrin 1999).

Figure 2.2 Schematic of differences between the modes of operation for pressure driven membrane filtration: (a) dead end and (b) crossflow.

Figure 2.3 Schematic diagram of the operational conditions over time: (a) constant pressure filtration and (b) constant flux filtration.

2.2.3 Concept of Critical Flux

A concept which has been used extensively in the literature of microfiltration processes is the critical flux (J_{crit}). The critical flux hypothesis for microfiltration is

based on the fact that a flux can be found, in constant TMP filtration, that below it the decline of flux over the time is negligible; and above it the fouling is noticeable. Likewise, in constant-flux filtration, an increase in TMP is not observable below the critical value. The value of the critical flux depends on the hydrodynamics, particle size, pore size and probably other variables. The critical flux can be determined experimentally (Field, et al. 1995). For MBR applications, however, the critical flux is not easy to be determined because of the fast adsorption of particles on the surface of the membrane in these applications. To determine J_{crit} in a filtration process, different methods can be used as described in the following.

2.2.3.1 Flux Stepping

In this method, the permeate flux is kept constant in each step within a certain time interval (e.g. 15 minutes), and the TMP is monitored and recorded. For consecutive steps, the flux is increased by a certain value (this flux step can be 5 L/m²h, 10 L/m²h, etc) and the TMP is again monitored. The flux stepping is repeated till a noticeable TMP increase rate, $(\Delta\text{TMP}/\Delta t)_{crit}$, is observed (Wu, et al. 1999). This procedure is schematically depicted in Figure 2.4.

There are differences between the standards which have been used by different researchers to determine the critical flux by flux stepping. These differences include the variations of the time intervals, flux steps and the determination of the critical TMP increase rate (Bacchin, et al. 2006; Cho and Fane 2002; Le Clech, et al. 2003).

Figure 2.4 Determination of critical flux using flux stepping method.

2.2.3.2 Direct Observation through the Membrane (DOTM)

By using high porosity membranes with straight pores (that makes the membrane transparent when it is wet), it is possible to observe the particle deposition and movement close to surface through the membrane (Li, et al. 1998; Li, et al. 2003). In this case, it is possible to estimate the critical flux by observing the particles' deposition on the membrane. In other words, the critical flux is the highest flux before a noticeable deposition can be observed. An example of estimating the critical flux by DOTM is shown in Figure 2.5. In this figure, Li and co-workers monitored the particles' deposition in different fluxes during the filtration of latex particles with diameter of 12 μm in a crossflow channel with constant crossflow velocity (CFV) of 0.4 m/s. They concluded that the fluxes of 35 $\text{L}/\text{m}^2\text{h}$ and 45 $\text{L}/\text{m}^2\text{h}$ were under the critical flux, since no noticeable deposition occurred in these fluxes, and 51 $\text{L}/\text{m}^2\text{h}$ was near or at the critical flux (Li, et al. 1998).

Figure 2.5 Estimating critical flux by monitoring the particle deposition using DOTM performed by Li, et al. (1998).

2.2.3.3 Mass Balance

The mass balance method for the determination of critical flux is based on the fact that the particles' deposition rate (dm/dt) in a filtration process equals to zero for fluxes below the critical flux (Kwon, et al. 2000). Above the critical flux, it has been shown that the particle deposition rate is proportional to the difference of the

flux and critical flux ($J - J_{crit}$), feed concentration (c_b) and membrane area (A) (Chong, et al. 2008; Knutsen and Davis 2006; Zhang, et al. 2006). This can be summarized in the general form of (Zhang, et al. 2010):

$$\frac{dm}{dt} = kc_b(J - J_{crit})A \quad (2.1)$$

Equation (2.1) implies that if we plot the deposition rate (dm/dt) versus the flux (J), then the flux axis intercept of the regression line can be considered as the critical flux (Figure 2.6).

Figure 2.6 Determination of critical flux using mass balance method.

2.3 Mass Transfer in Pressure Driven Membrane Filtration

The permeate flux J in a pressure driven membrane is related to the TMP and total resistance of the membrane R_t by the Darcy's law (Mulder 1996):

$$J = \frac{TMP}{\mu R_t} \quad (2.2)$$

where μ is the viscosity. R_t can be written as the sum of the clean membrane resistance R_m and the resistance due to fouling R_f as follows:

$$R_t = R_m + R_f \quad (2.3)$$

In general, different types of fouling exist. Two main classes of fouling are internal and external fouling. Internal fouling occurs when the particles are smaller than membrane pores. These particles can narrow the pores by absorbing to the pores' wall or they may plug the holes totally. On the other hand, external fouling can arise from the cake or gel formation, and pore blocking and deposition can occur on the surface of the membrane.

2.4 Hydrodynamics in Membrane Processes

Due to the rejection of particles by the membrane, the concentration of rejected particles rises near the membrane surface. This phenomenon is known as concentration polarization (CP). CP is more severe in low pressure membrane applications because of the relatively high permeate flux compared to reverse osmosis (RO) and nanofiltration processes. CP is one of the most important factors that can induce fouling. Therefore, it is essential to lower the CP intensity by means of the hydrodynamics in the filtration system.

The hydrodynamics related to the low pressure membrane applications can be categorized into two different areas:

- 1- The first area relates to the macro hydrodynamics of the system. For instance, the shear rate on the membrane surface (one of the most important

parameters in the membrane filtration systems) should be determined by means of analytical and experimental methods. Also, The washing or secondary flows, which are effective toward reducing CP, should be studied.

- 2- The second area relates to the micro hydrodynamics, or the interaction of particles and fluid near the membrane surface. This can help understand how the back transport of particles from the membrane surface occurs.

Here, we review some of the existing models and experimental methods for the study of hydrodynamics in the membrane processes.

2.4.1 Concentration Polarization (CP) Concept

Membranes are used for the filtration of solutions, colloids and suspensions (generally consist of fluid (liquid) and particles (solid) phase). The particles can be rejected partially ($0 < c_p < c_b$) or completely ($c_p = 0$), where c_p and c_b are the particle concentration values in the permeate and feed side, respectively. In a steady situation, the concentration of particles reaches its maximum value at the surface (c_w) and declines to the feed concentration value (c_b) through a concentration boundary layer with a thickness (δ_c) as shown in Figure 2.7. In the concentration boundary layer, for a membrane with 100% rejection ($c_p = 0$), the convective flux of the particles to the membrane ($J c$) should be equal to the back transport of the particles to the bulk flow due to diffusion. The diffusive flux is $-D \partial c / \partial x$ which D is the diffusion coefficient of the particles and x is the direction normal to the membrane surface (Figure 2.7). Therefore, the governing equation in the concentration boundary layer and the boundary conditions can be formulated as follows (Bowen and Jenner 1995; Mulder 1996):

$$Jc = -D \frac{\partial c}{\partial x} \quad (2.4)$$

$$c = c_w \quad \text{at } x = 0 \quad (2.5)$$

$$c = c_b \quad \text{at } x = \delta_c \quad (2.6)$$

Integrating Equation (2.4) over the concentration boundary layer (i.e. from $x=0$ to $x=\delta_c$), yields:

$$\frac{c_w}{c_b} = e^{\left(\frac{J}{k}\right)} \quad (2.7)$$

where k is the mass transfer coefficient, defined as:

$$k = \frac{D}{\delta_c} \quad (2.8)$$

Figure 2.7 Schematic diagram of CP in a steady state membrane filtration process.

The mass transfer coefficient (k) is the ratio of the diffusion coefficient (D) to the concentration boundary layer thickness (δ_c). To reduce the CP effect, it is necessary

to minimize the concentration of particles at the membrane surface (c_w). Based on Equation (2.7), k should be increased to reduce c_w . For this purpose, either δ_c should be decreased or D should be increased.

In the membrane processes δ_c is a function of the hydrodynamics of the system (Belfort and Nagata 1985; Gekas and Hallström 1990). The effect of hydrodynamics on the mass transfer coefficient (k), for a crossflow channel, is usually presented in the form of a correlation between three non dimensional groups: Sherwood number ($Sh=kd_h/D$), Reynolds number ($Re=ud_h/\nu$) and Schmidt number ($Sc=\nu/D$), where u is the velocity of the bulk flow, ν is kinematic viscosity of the fluid and d_h is the hydraulic diameter of the channel. This correlation is (Mulder 1996):

$$Sh = a Re^b Sc^c \left(\frac{d_h}{L}\right)^d \quad (2.9)$$

where L is the channel length. Empirical values for the constants (a , b , c and d) are available for laminar (Porter 1972) and turbulent flows (Gekas and Hallström 1987) in the literature.

There are also many mechanisms to model the diffusion of particles in the filtration systems (in other words, to determine the diffusion coefficient D). The common mechanisms will be reviewed in the next section.

2.4.2 Particles Back Transport Mechanisms

Many theoretical models have been developed to predict the concentration polarization and steady flux in cross-flow microfiltration processes. For dead end

filtration processes, the only mechanism of particle back transport is Brownian diffusion, which should be negligible compared to the convective migration of the particles toward the membrane (due to the permeate flux). As mentioned before, the tangential flow of the feed in cross flow filtration removes the particles from the membrane surface. In other words, the tangential flow induces a back transport of particles. The particle back transport in cross flow filtration has been described by means of different mechanisms such as Brownian diffusion, shear induced diffusion and inertial lift (Belfort, et al. 1994). Based on the definition of critical flux, it can be concluded that the critical flux occurs when the particles back transport is in balance with the convective migration of particles toward the membrane.

2.4.2.1 Brownian Diffusion Model

The Brownian diffusion model is a mechanism of particle back transport which is dominant with submicron particles and lower ranges of shear rate. The Brownian diffusivity D_0 of particles, which is a function of temperature T , can be calculated by Einstein-Sutherland equation (Belfort, et al. 1994):

$$D_0 = \frac{k T}{f} \quad (2.10)$$

where k is the Boltzmann's constant (1.38×10^{-23} J/mol K) and f (kg/s mol) is the frictional coefficient of the particle, which can be calculated by Stokes law for a laminar flow as:

$$f = 6 \pi \mu a \Omega \quad (2.11)$$

where a is the radius of the particles and Ω (≤ 1 and equals to 1 for spherical particles) is a correcting factor for fractal shape particles (Veerapaneni and Wiesner 1996).

According to the Brownian diffusion model, the steady state flux (J) will be reached when the particles that are transported toward the membrane by convection, are balanced with the particles that diffuse away from the membrane and pass the membrane due to the tangential flow. By integration of this convective-diffusive flow across the membrane length, the steady flow is achieved as follows (Porter 1972):

$$J = 0.81 \left[\frac{\gamma_w D_0^2}{L} \right]^{\frac{1}{3}} \ln \left[\frac{\Phi_w}{\Phi_b} \right] \quad (2.12)$$

L indicates the membrane length, γ_w and Φ_w are the shear rate and particle volume fraction at the edge of the cake layer respectively and Φ_b is the particle volume fraction at the bulk suspension. Substituting Equations (2.10) and (2.11) in Equation (2.12), the steady state flux predicted by Brownian diffusion model is obtained as follows:

$$J = 0.114 \left[\frac{\gamma_w k^2 T^2}{\mu^2 a^2 L} \right]^{\frac{1}{3}} \ln \left[\frac{\Phi_w}{\Phi_b} \right] \quad (2.13)$$

2.4.2.2 Shear-Induced Diffusion Model

It was observed that the steady state flux for cross flow filtration with micron sized particles and intermediate range of shear rate, is noticeably higher than the flux predicted by Brownian diffusion model (Equation (2.13)) (Porter 1972). To explain

this disagreement between the experimental results and model predictions, the shear-induced diffusion model was proposed by Zydney and Colton (1986). This model is based on the fact that particles have a tendency to migrate from layers with higher shear rate to layers with lower shear rate in a flow. As a result, the shear-induced diffusion coefficient D_s is a function of shear rate γ and particles' radius a . A general relationship has been proposed to calculate the D_s (Eckstein, et al. 1977; Li, et al. 2000; Zydney and Colton 1986) as:

$$\frac{D_s}{a^2 \gamma} = c \quad (2.14)$$

In this relation, c is a constant value that depends on the volumetric concentration of particles (Φ). An estimation of D_s was proposed by Zydney and Colton (1986) for a bulk flow concentration Φ_b between 0.2 and 0.45 as:

$$D_s = 0.03 \gamma_w a^2 \quad (2.15)$$

Equation (2.15) can be substituted in Equation (2.12) in order to predict the steady state flux based on the shear-induced diffusion model.

2.4.2.3 Inertial Lift Mechanism

Another approach to model the reverse transport of particles from the surface is to determine the lift force (F_L) that is induced on an individual particle due to the existing shear rate near the surface of the membrane (Drew, et al. 1991; McLaughlin 1991; McLaughlin 1993; Rubin 1977). In this approach, a typical relation is used to predict this force as:

$$F_{bt} = f(\gamma_{wall}, a, \rho, \mu) \quad (2.16)$$

This force is usually compared with other forces such as the drag force (F_D) due to the filtration flux and adhesion force (F_{Ad}) that is caused by electrostatic forces, van-der-Waals interactions and steric effects (Ripperger and Altmann 2002).

$$F_d = F_D + F_{Ad} \quad (2.17)$$

In this equation, F_d is the total deposition force that is induced to a particle. To calculate F_D , the Stokes law for laminar flow can be applied:

$$F_D = 6 \pi \mu a v_f \Omega \quad (2.18)$$

v_f is the flow velocity normal to the surface caused by filtration flux. The forces discussed in Equation (2.17) are shown schematically in Figure 2.8.

Figure 2.8 Forces acting on a particle near the surface of membrane in a filtration system (Ripperger and Altmann 2002).

It is possible to calculate the critical flux theoretically by the inertial lift model. The critical flux can be considered as the flux in which F_d is counterbalanced by F_L on a particle.

2.4.3 Numerical Approaches

With the performance of computers improving significantly day by day, a great deal of interest has been shown in using numerical approaches or computational fluid dynamics (CFD) to simulate the fluid systems in the membrane applications. Most of these simulations have been performed under laminar conditions, though a substantial number of studies have dealt with turbulent conditions (Ghidossi, et al. 2006).

The main purpose of CFD simulations is to investigate the hydrodynamics of membrane systems. Researchers have used CFD to obtain different hydrodynamic parameters in the membrane systems such as the induced shear stresses on the membrane surface, friction loss of the flow passing the membrane module, mixing characteristic of the membrane reactor (like Residence time distribution, RTD), etc. Moreover, CFD can be employed to simulate the hydrodynamics in different kinds of membrane systems like crossflow channels, membrane bioreactors (MBRs) with or without air sparging, vibrating membranes, etc. (Ghidossi, et al. 2006).

Joshi (2001) reviewed comprehensively the past studies on turbulent three-dimensional (3-D) two phase flow in bubble column systems (that are very important in MBR applications). Since then, many efforts have been made to simulate two-phase (air-water) flows in membrane systems with aeration

(Buetehorn, et al. 2011). A complicated simulation of single- and two-phase flows in a submerged hollow fibre system with an irregular moving fibre arrangement at different height of the column (achieved by computer tomography (CT) scan) was performed by Buetehorn, et al. (2011). They considered fluid-structure interactions (FSIs) in their study and found that the regions with higher porosity have higher velocity and lower turbulent local viscosity. Figure 2.1 shows the instantaneous map of fibres in the different heights of the bubbling column taken by a CT scan.

Figure 2.9 CT scan of fibres arrangement at different heights in the bubbling column
(Buetehorn, et al. 2011).

RTD is an effective quantity to measure the mixing and consequently, the biodegradation rate in a membrane plant. Brannock, et al. (2010) used CFD to obtain RTD within two full-scale MBR plants. They found a close agreement between the experimental and simulated results.

The shear rate (and shear stress) on the membrane surface is one of the most important factors that can influence the fouling and CP in any membrane process. Since there are only a few experimental techniques to estimate the shear rate on the membrane surface (which are usually expensive and complicated), most researchers

prefer to calculate the shear rate analytically or numerically (CFD) (Ghidossi, et al. 2006).

Different flow patterns and induced shear rate on the membrane surface were studied using CFD in a membrane channel with 12 different structures of spacers (Santos, et al. 2007). The results were used to design an optimum alignment of spacers in the channel. Sarkar, et al. (2012) simulated the hydrodynamics inside a novel shear enhancing membrane system, called a spinning basket membrane (SBM). They calculated the shear rate and pressure on the membrane surface. To date, very few CFD simulations report the hydrodynamics of vibrating membrane systems. Ahmad, et al. (2010) performed three-dimensional unsteady CFD simulations for a vibrating membrane channel and obtained the shear rate and velocity profile in the channel. As a result they could distinguish five types of velocity profile in a vibrating channel: Poiseuille flow (Figure 2.10a), Couette–Poiseuille flow (Figure 2.10b), plug flow (Figure 2.10c), VSEP flow (Figure 2.10d) and opposite-direction Couette–Poiseuille flow (Figure 2.10e).

Figure 2.10 Different types of velocity profile in a vibrating membrane channel (Ahmad, et al. 2010).

However, the CFD modeling for vibrating hollow fibres bundles, which can determine the effect of different geometrical configurations on the hydrodynamic flow around the fibres, has not been reported so far. In the present study, the CFD modeling for a vibrating fibre bundle is performed for two different configurations of fibres: in-line and staggered. The results of CFD modeling are described in the following chapters.

2.4.4 Particle Image Velocimetry (PIV)

To study the hydrodynamics of a membrane process experimentally, it is essential to monitor the different hydrodynamic parameters of the process when it is operating. Many non-invasive techniques have been developed to do so (Chen, et al. 2004). Optical techniques like DOTM (Hodgson, et al. 1993), electrochemical methods (Miyagi, et al. 2000), constant temperature anemometry (CTA) (Le-Clech, et al. 2006) and impedance spectroscopy (Coster, et al. 1996) are examples of these methods. Particle image velocimetry (PIV) has also been used as a non-invasive method in membrane applications (Yeo, et al. 2006).

PIV can be used to measure 2D real-time velocity fields. To perform PIV, three main components are needed: laser sheet, seeding particles and digital camera. To generate the laser sheet, the laser beam (commonly emitted by Nd:YAG type lasers) should be reshaped to a sheet shape by a cylindrical lens as shown in Figure 2.11. Seeding particles should be able to follow the flow and scatter the laser light so that the particles can be distinguishable in images taken by the digital camera.

The PIV operation is illustrated in Figure 2.11. The target area is divided to several sub-section areas or interrogation areas (IAs). The displacement and consequently the velocity of seeding particles are measured by cross-correlating of the images of particles in each IA between two pulses of lasers (with a certain time intervals Δt).

PIV has been used to study the flow and measure the shear rate on the flat plate and rotating membranes (Gaucher, et al. 2002). Wereley and co-workers used PIV to study the hydrodynamics of a rotating membrane system. They used two different types of seeding particles: smaller particles with diameters in the range of 10-25 microns, and bigger particles with diameters of 150 to 300 microns. They assumed that the smaller particles would follow the flow with a good degree of accuracy, whereas the bigger particles might slip relative to the flow. They found that the slip velocity between big particles and flow can be neglected since the difference between the velocity fields which are achieved by using two different particle types was almost zero (Wereley, et al. 2002).

Figure 2.11 The principles of the PIV operation (DantecDynamics 2012).

PIV was used in submerged hollow fibre membrane systems for measuring the shear rate and finding the flow pattern in a bundle of fibres with air sparging by

Yeo, et al. (2007). It was also used to determine the intensity of turbulence in different membrane applications such as crossflow filtration with turbulence promoter (Gimmelshtein and Semiat 2005) and vibrating submerged hollow fibre membranes (Li, et al. 2013).

2.5 MBR Systems

In an aerobic biological process, organic substances biodegrade into basic compounds such as water, CO_2 , NH_4^+ , etc. The biological cells involved in this biodegradation are called biomass or activated sludge. The amount of biomass increases due to the biodegradation. Therefore, a secondary clarification is needed to separate the sludge from the mixture. In conventional activated sludge processes, this clarification is done by settling tanks (Figure 2.12). A larger volume settling tank can lead to a better sludge separation. On the other hand, using tanks with a larger volume requires more space and equipments and therefore it is more costly (Tchobanoglous, et al. 2003).

Figure 2.12 Schematic of a conventional activated sludge process.

To overcome the space shortage and achieve higher quality treated water, membrane filtration system can be used as an alternative to the clarification tank system. The membrane filtration systems which integrate the biological degradation and membrane separation are known as membrane bioreactors (MBRs). The membrane can retain the sludge totally; therefore, higher quality water can be achieved by MBRs rather than conventional activated sludge systems (Johir, et al. 2012; Muller, et al. 1995). Since higher sludge concentration can be employed in MBRs, a low food to biomass ratio can be sustained; consequently, lower (up to 50% less) sludge production can be achieved (Ghyoot and Verstraete 2000; Mayhew and Stephenson 1998). In terms of chemical oxygen demand (COD), total suspended solids (TSS) and turbidity treatment, MBR systems have shown high efficiencies in municipal and industrial applications (Chang and Kim 2005; Ng and Hermanowicz 2005).

Two main configurations exist for MBRs: the cross flow (side-stream) configuration and the now more commercial submerged configuration (Figure 2.13). In the cross flow configuration, the membrane module is located out of the aeration tank and a retentate stream re-circulates to the aeration tank. In the submerged configuration, the membrane module is immersed in the aeration tank. This configuration was firstly proposed by Yamamoto, et al. (1989). Unlike the cross flow configuration, submerged configuration does not need any re-circulation pump and only needs a suction pump. As a result, less pumping power is consumed in submerged systems (Judd and Judd 2006).

Figure 2.13 Different configurations of a MBR: (a) cross flow configuration, and (b) submerged configuration.

2.5.1 Different Types of Submerged MBRS

Two different modules using in MBR applications are the flat plate submerged MBR and hollow fibre submerged MBR.

Figure 2.14 shows a typical commercial flat plate submerged MBR. For instance, in a commercial submerged flat membrane system developed by the environmental division of Kubota Corporation in Japan, 150 membrane cartridges with approximately 0.8 m^2 surface area for each plate were placed in a rectangular tank. Bubbling was used in order to control the fouling on the membrane surface (Churchouse 1997).

Figure 2.15 shows a typical hollow fibre module used in submerged MBR applications. This module is manufactured by Zenon (Cui, et al. 2003). The hollow fibres are mounted vertically in this module and the permeate can be taken from both ends of the module frame.

Figure 2.14 Schematic diagram of a submerged MBR configuration using flat plate membranes.

2.6 Anti-Fouling Techniques for Submerged MBR Systems

MBR applications usually deal with extremely thick solid suspension fluids. Besides, low pressure and consequently high flux membranes (MF and UF) are usually employed in MBR systems. As a result, the membranes are highly at risk of fouling in these systems. Different techniques can be employed to control the fouling in submerged MBR systems.

These techniques could be categorized into three major methods: chemical, electrical and ultrasonic and hydrodynamic methods (Figure 2.16). Chemical cleaning, membrane surface modification and feed pre-treatment (chlorination, pH adjustment, etc.) are examples of chemical antifouling methods (Fane and Fell 1987; Fane, et al. 1991; Kuzmenko, et al. 2005).

Figure 2.15 A submerged hollow fibre membrane MBR module manufactured by Zenon (Cui, et al. 2003).

The ultrasonic waves can be employed to manipulate the concentration polarization layer near the membrane to reduce the fouling (Simon, et al. 2000). They can also be used to break the cake structure on the membrane in order to remove the foulants from the surface of the membrane (Gonzalez-Avila, et al. 2012). Many attempts to diminish the fouling using an electric field have also been reported (Jurado and Bellhouse 1994; Mameri, et al. 2001).

Back-washing (van de Ven, et al. 2008) and back-pulsing (Ning Koh, et al. 2008) have been used extensively in submerged hollow fibre membrane systems.

Figure 2.16 Classification of anti fouling methods used in MBR applications (Shahnawaz 2009).

Using hydrodynamics to induce shear stresses on the membrane surface and also producing disturbances and secondary flows is the most common anti fouling technique in MBR applications. There are two categories:

- Air sparging (or aeration)
- Dynamic shear enhancing membrane filtration

Some common kinds of shear enhancing systems are rotating cylindrical membrane, rotating disk systems and vibrating membranes (Jaffrin 2008). The scope of this study is on vibrating membranes. This technique and also air sparging (as the most common technique in MBR systems and for the purpose of comparison) are discussed in details in the next sections.

2.6.1 Aeration

It has been proven that employing air sparging is an effective strategy to enhance the flux (i.e. decrease the fouling) in UF (Bellara, et al. 1996; Li, et al. 1998) and

MF applications (Sur and Cui 2005). This flux enhancement can be attributed to different mechanisms. The bubble motion near the surface of the membrane, can induce shear stresses on the surface and therefore help the back transport of supermicron particles to the bulk flow (Cui, et al. 2003). Besides the wakes, which are generated by the movements of bubbles, can produce secondary flows and vortices near the membrane surface resulting in the mixing of the concentration polarization layer and consequently, increasing the mass transfer coefficient (Sur and Cui 2005). The flow disturbances created by bubbles can make the suspended particles to collide and aggregate to bigger particles. These bigger particles are less prone to fouling on the membrane surface (Choir, et al. 2003). For submerged hollow fibres, the bubbles can impact the fibres and push the fibres forth and back. The transverse vibration or movement for loose fibres can produce more secondary and mixing flows (Cui, et al. 2003).

The wakes generated by bubbles have an important role in cleaning the membrane surface. Therefore, it is important to know the different types of bubbles and their wakes. Miyahara, et al. (1988) studied the wakes of a single bubble in three dimensions and classified the bubbles and their wakes into three groups: small bubbles which are spherical and mostly have diameters smaller than 1mm. The flow around them can be considered as Stokes flow and there are no secondary flows or vortices generated by them (Figure 2.17a). The second type of bubbles is ellipsoidal bubbles type with a diameter of 1.5 to 15 mm. The typical movement of these bubbles is moving back and forth while rising in the bubble column as illustrated in Figure 2.17b. Spherical cap bubbles with size of bigger than 15 mm leaves very strong ring type vortices behind as they are rising up (Figure 2.17c).

Although aeration is an effective way to control the fouling, the flux enhancement due to aeration reaches a plateau over a certain superficial air velocity (Bérubé and Lei 2006; Chang and Fane 2001) which is referred to as the optimal superficial air velocity by Xia, et al. (2013). This phenomenon is shown in Figure 2.18. As shown in this figure, the fouling rate ($dTMP/dt$) reaches its minimum value around a superficial air velocity of 1.2 mm/s (stage 3) for two different cases with the membrane module placed at the height of 0.3 and 0.6 m from the bottom of the column (Xia, et al. 2013).

Figure 2.17 Classification of different bubble shapes and associated vortices: (a) Small bubble with Stokes streamline (b) Ellipsoidal bubble with helical vortices (c) Spherical cap bubble with ring type vortices (adopted from Miyahara, et al. 1988).

In terms of energy consumption, aeration for fouling control in MBR systems is very energy consuming. Almost 35 % of the total MBR plant energy consumption is due to the fouling control aeration as shown in Figure 2.19 (Fenu, et al. 2010; Judd and Judd 2006).

To date, most of the commercial MBR plants use the continuous air sparging scheme (Le-Clech, et al. 2006) which can be one of the reasons for the high energy consumption. As a result, some effort has been made to find an alternative aeration scheme which can lead to lower energy consumption. For instance, the eco-aeration scheme has been introduced by Zenon which is based on alternate aeration, and the Mempulse scheme has been employed by Siemens using irregular aeration pulsing (Judd and Judd 2006; Xia, et al. 2013).

Figure 2.18 Fouling rate in different superficial air velocities and the phenomenon of optimal air velocity for the filtration of 0.65 g/l Bentonite solution (Xia, et al. 2013).

Another approach to reduce the energy consumption is to find new alternative techniques which can replace aeration as a fouling control method. One of the promising techniques is the vibrating membrane systems which will be reviewed in the next section.

Figure 2.19 Percentages of energy consumption in a typical MBR plant by different components of the plant (adopted from Fenu, et al. 2010).

2.6.2 Vibrating Systems

2.6.2.1 Vibratory Shear-Enhanced Processing (VSEP)

The original concept of VSEP was introduced by (Armando, et al. (1992); Culkin and Armando 1992). The Company, NewLogic (1987), commercialized this product for industrial applications. A VSEP unit is comprised of a stack of circular flat membranes installed horizontally inside a casing (filter pack). The filter pack is fixed on a vertical torsion shaft which is spun around a vertical axis by a driving motor (Figure 2.20). Different gaskets are used in the filter pack to separate the membranes, and the permeate is collected by permeate channels. Figure 2.21 shows a typical flow diagram of a VSEP system and also illustrates the internal structure of a filter pack in details.

Figure 2.20 Schematic of a VSEP unit series i15 and different parts the vibrating system (NewLogic 1987).

Akoum, et al. (2002) and Jaffrin, et al. (2004) compared the performance of a VSEP with cross-flow filtration in tubular membranes with a rotating disk system. In addition, they calculated the instantaneous shear rate on a membrane surface of VSEP. The local wall shear rate $\gamma_w(r, t)$ is given by:

$$\gamma_w(r, t) = 2r\theta(\pi f)^{1.5}\nu^{-0.5}[\cos(2\pi ft) - \sin(2\pi ft)] \quad (2.19)$$

where f is the oscillation frequency, θ is the angular amplitude of torsional vibration and ν is the fluid kinematic viscosity. The wall shear rate is calculated for a point of a distance r from the vibrating axis. R_1 and R_2 denote the inner and outer radius of the membrane, respectively.

The maximum wall shear rate $\gamma_{w,max}$, over time occurs at the disk's periphery with radius R_2 . This maximum value can be obtained from:

$$\gamma_{w,max} = 2^{0.5} d (\pi f)^{1.5} \nu^{-0.5} \quad (2.20)$$

where d ($=2 \times \text{amplitude}$) is the membrane displacement at the periphery. By averaging the shear rate over a period of oscillation and over the membrane area, the mean wall shear rate $\overline{\gamma_w}$ was obtained as:

$$\overline{\gamma_w} = \frac{2^{1.5} (R_2^3 - R_1^3)}{3\pi R_2 (R_2^2 - R_1^2)} \gamma_{w,max} \quad (2.21)$$

Figure 2.21 Flow diagram of a typical VSEP unit and flow circulation in a filter pack (NewLogic 1987).

Figure 2.22 Schematic view of a vibrating membrane used in a VSEP system.

It is noticeable that the wall shear rate in Equation (2.19) is independent of the distance between two adjacent membranes. In fact, Akoum, et al. (2002) assumed that the boundary layer thickness near a disk is negligible in all cases. This assumption is not very accurate and the wall shear rate should be a function of the distance between two adjacent membranes as well. The flow between two parallel vibrating membranes will be studied in the next chapter and an optimum distance between the membranes will be determined.

Several experimental studies have been carried out to examine the dependence of permeate flux on the shear rate. These experiments focused mostly on finding a correlation between the wall shear rate and the critical flux or steady flux J of a process (Akoum, et al. 2002; Jaffrin, et al. 2004). The most generic correlation which is introduced so far is:

$$J = K \bar{\gamma}_w^m \quad (2.22)$$

where K and m are constants that depend on the fluid property of the system. Akoum, et al. (2002) found that for the micro filtration (MF) of a yeast suspension, m is equal to 0.19 for frequencies below 59.7 Hz and 0.5 for higher frequencies (Figure 2.23).

For ultra filtration (UF) with smaller particles such as bovine albumin solution, m was found equal to 0.426 for all frequencies. It should be noticed that the experiments were done for two different temperatures (i.e. 10 and 35°C), and both m remained unchanged (Figure 2.24). Figure 2.25 also shows the strong hysteresis effect which results when the frequency is reduced and then again raised. This hysteresis indicates irreversible fouling (Akoum, et al. 2002).

Figure 2.23 Variation of permeate flux vs. mean shear rate in log-log coordinate for the MF of a yeast solution (Akoum, et al. 2002).

Low, et al. (2004) used VSEP for the water recovery from a fine carbon loaded wastewater of a TV picture tube plant. The flow diagram of the setup in their study

is shown in Figure 2.26. The filter pack consisted of a single annular membrane with an area of 0.5 ft². Different parameters such as different membrane types, concentration of particles, TMP, vibration amplitude, feed temperature and particle size were considered. They varied these parameters to achieve higher fluxes and less frequent back wash.

Low and his co-workers found that it was undesirable if the membrane pore size and particle size are close to each other. Also, their results implied that the more prone to fouling the membrane is, the more it will benefit from higher amplitudes in vibration to prevent the fouling (Low, et al. 2004).

Figure 2.24 Variation of permeate flux vs. mean shear rate in log-log coordinate for UF of albumin for two different temperatures of 10 and 35°C (Akoum, et al. 2002).

Figure 2.25 Variation of vibration amplitude and filtration flux (Test 1) with frequency in a VSEP system. In Test 2, the frequency was decreased to 58Hz and raised back to its maximum (Akoum, et al. 2002).

Figure 2.26 Schematic flow diagram of the VSEP used by Low, et al. (2004).

2.6.2.2 Vibrating Hollow Fibres

Hollow fibre membranes provide more membrane area per unit volume than flat sheet membranes. To date, not many works on the modeling of hollow fibre membrane systems have been reported.

In 1997, Krantz, et al. (1997) applied axial vibration to a group of silicon hollow tube membranes to achieve higher oxygen mass transfer through the membrane surface. They produced the vibration by shaking the whole membrane bundle relative to the liquid flow inside the tubes. They found that the mass transfer coefficient was raised by a factor of 2.65 when an axial vibration was used. An analytical solution was proposed for the velocity profile of the laminar flow inside the vibrating tube. The method of Fourier-Bessel eigenfunction expansion was used to solve the simplified Navier-Stokes equation in a cylindrical coordinate system (Hildebrand 1962). This solution is however not applicable for submerged hollow fibres because of different boundary conditions. In addition, the internal tube flow was solved by Krantz, et al. (1997) but in MBR applications the external flow of a fibre should be considered.

As mentioned in Chapter 1, different modes of vibration can be applied to a bundle of hollow fibres. Three modes that have been reported in the literature include:

- 1- Axial or lengthwise oscillation: In this mode, the whole bundle and fibres vibrate relative to the external fluid. A schematic design of this type and its components is shown in Figure 2.28.

- 2- Torsional oscillation: When the whole bundle spins around a vertical axis, cross oscillation is applied to each fibre with the amplitude and conditions differing for fibres located from the center to periphery (Figure 2.29) (Low, et al. 2008).
- 3- Combined axial and transverse vibration: By installing horizontal vanes or guides in a chess pattern both transverse and axial vibrations are obtainable among vertical oscillating fibres. This configuration results in higher shear rates on the surface and extra velocity components in other directions in addition to the axial direction, which scatter particles from the surface (Figure 2.30) (Genkin, et al. 2006).

Figure 2.27 A Submerged MBR (SMBR) hollow fibres module with axial vibration (Low, et al. 2005).

Figure 2.28 A Submerged MBR (SMBR) hollow fibres module with axial vibration (Low, et al. 2005).

Figure 2.29 A SMBR hollow fibres module with torsional vibration (Low, et al. 2005).

Low, et al. (2005) carried out a comparison study of the filtration performance using hollow fibres with lengthwise vibration, torsional vibration and VSEP. They discovered that lengthwise oscillation can keep membrane cleaner and permeate

flux higher compared to torsional vibration. Their results showed that the permeate flux decline was 76% for the stationary bundle of fibres, 21% for the torsional vibration motion and 10% for membranes with axial oscillation. The vibrational mean velocity of 0.2 m/s was used in their experiments (Figure 2.31) (Low, et al. 2005).

Figure 2.32 shows a comparison between a VSEP MBR and a SMBR hollow fibre with lengthwise oscillation reported by Low, et al. (2005). They ran the VSEP with a TMP of 15 times higher than the SMBR. The flux in VSEP stabilized at ~70% of the initial flux.

Figure 2.30 (a) The use of chess pattern horizontal vane to induce transverse vibration combined with axial vibration in a submerged hollow fibre system (Genkin, et al. 2006); (b) Side view of the chess pattern for the submerged hollow fibres.

Figure 2.31 Comparison of permeate flux of hollow fibre bundle with no motion, lengthwise and torsional vibration (Low, et al. 2005).

Figure 2.32 Comparison of permeate flux in VSEP and hollow fibre bundle with axial oscillation (Low, et al. 2005).

Beier and co-workers (Beier, et al. 2006; Beier and Jonsson 2006; Beier and Jonsson 2009) used the velocity profile obtained for a vibrating flat surface by Bird, et al. (2002) as follows, to calculate the wall shear rate on the surface of a vibrating fibre:

$$v_z(y, t) = v_0 e^{-\sqrt{\frac{\omega}{2\nu}} y} \cos(\omega t - \sqrt{\frac{\omega}{2\nu}} y) \quad (2.23)$$

where ω (equals to $2\pi f$) is the angular frequency, f is the frequency of vibration, v_0 is the velocity amplitude (equals to $A\omega$), A is the vibration amplitude and ν is the kinematic viscosity of the fluid. In this equation, the z -axis is parallel to the direction of the fibre, and the y -axis is perpendicular to the membrane surface with $y=0$ set at the membrane surface as shown in Figure 2.33, which is similar to a flat surface.

Figure 2.33 Cartesian coordinate system used by Beier, et al. (2006) to calculate the wall shear rate on the hollow fibre membrane surface.

By differentiating Equation (2.23) with respect to y , the shear rate was found by as:

$$\gamma = \frac{dv_z}{dy} = v_0 \sqrt{\frac{\omega}{2\nu}} e^{-\sqrt{\frac{\omega}{2\nu}} y} [\sin\left(\omega t - \sqrt{\frac{\omega}{2\nu}} y\right) - \cos\left(\omega t - \sqrt{\frac{\omega}{2\nu}} y\right)] \quad (2.24)$$

By substituting $y=0$, the shear rate on the membrane surface was obtained as:

$$\gamma_w = v_0 \sqrt{\frac{\omega}{2\nu}} [\sin(\omega t) - \cos(\omega t)] = \gamma_{w,max} \cos\left(\omega t - \frac{3\pi}{4}\right) \quad (2.25)$$

where the maximum shear rate $\gamma_{w,max}$ is:

$$\gamma_{w,max} = v_0 \sqrt{\frac{\omega}{\nu}} = A\omega^{1.5}\nu^{-0.5} \quad (2.26)$$

To date, Equation (2.25) has been commonly used to determine the wall shear rate on the surface of vibrating hollow fibre membranes (Jaffrin 2008). Due to the approximations made, it can be observed in Equation (2.25) that the wall shear rate does not depend on the fibres' diameter. This implies that the surface curvature is unimportant. In order to quantify the wall shear rate more accurately, a solution with more realistic assumptions and using a proper coordinate system needs to be developed.

In this study (Chapter 5), an analysis is performed to relate the velocity profile and the wall shear rate of a vibrating hollow fibre membrane using the cylindrical coordinates. The resulting solution provides a better understanding of the vibrating hollow fibre systems. Some suggestions can also be made about the design and operating parameters by using the results obtained.

Beier, et al. (2006) computed the mean shear rate for a given combination of frequency and amplitude by numerical averaging. The number of time steps is shown in Equation (2.27).

$$\overline{\gamma_w} = \frac{\sum_{i=0}^{1000} \left| \gamma_w(t = \frac{i}{1000}) \right|}{1000} \quad (2.27)$$

Based on these formulations, Beier, et al. (2006) found that at a low frequency (e.g. 10 Hz) and a small amplitude (e.g. 0.2 mm), the fluid velocity was almost negligible at 0.5 mm from the surface. With this fact, they concluded that the effect of fibre vibration on the flow pattern of adjacent fibres can be neglected. For the filtration

performance evaluation, the approach of critical flux was employed in their study. The correlation between the critical flux and mean shear rate was obtained as:

$$J_{crit} = 8.22 (\bar{\gamma}_w)^{0.26} \quad (2.28)$$

This correlation was extracted from the results shown in Figure 2.34.

The effect of axial and transverse vibration simultaneously, and adding coagulant to vibrating membranes as well, were investigated by Genkin, et al. (2006). Critical fluxes of 60-80 L/h m² were achieved for lengthwise vibration in frequencies as low as 10 Hz. Adding transverse vibration to lengthwise vibration (by means of chess pattern vanes) resulted in almost doubling of critical fluxes at the same frequency (130 L/h m²). A 170% improvement in critical flux was observed by adding coagulants to the vibrating system at a low frequency of 100 oscillations per minute or 1.7 Hz. This result is demonstrated in Figure 2.35.

Figure 2.34 Correlation between critical flux and mean shear rate in the filtration of baker's yeast suspension. Results are plotted in a Log-Log diagram (Beier, et al. 2006).

At higher frequencies, by adding coagulant, a lower relative increase in critical flux was obtained. This phenomena probably occurs because of floc breakup due to turbulent conditions induced by fibres at higher frequencies. The effect of frequencies on the critical flux with or without coagulant is described in Figure 2.36 (Genkin, et al. 2006).

Figure 2.35 Critical flux vs. coagulant concentration at frequency of 1.7 Hz (Beier, et al. 2006).

Figure 2.36 Comparison of critical flux vs. frequency in coagulant free and coagulant added suspensions (Genkin, et al. 2006).

In order to obtain the critical flux as a function of frequency, Genkin, et al. (2006) used a similar equation suggested by Beier, et al. (2006) to calculate the wall shear stress (τ_w) on the surface of hollow fibres,

$$\tau_{w,max} = k_1 A f^{1.5} \mu^{0.5} \rho^{0.5} \quad (2.29)$$

where, k_1 is a constant and ρ is fluid density. Also, Genkin and his group assumed that the back transport force (F_{bt}) of a particle is proportional to the wall shear force and square of particle's radius a . This assumption leads to:

$$F_{bt} = k_2 a^2 A f^{1.5} \mu^{0.5} \rho^{0.5} \quad (2.30)$$

The convective drag force induced on a particle due to the permeate flux J , can be calculated by using the Stokes law for laminar flows as:

$$F_d = 3\pi\mu(2a)J \quad (2.31)$$

Finally they considered that the critical flux occurs when, $F_{bt}=F_d$, and found that:

$$J_{crit} = k_3 a A f^{1.5} \nu^{-0.5} \quad (2.32)$$

Genkin, et al. (2006) also conducted experiments to study the effect of frequency on the critical flux. The results are shown in Figure 2.37. As shown in Figure 2.37b, the critical flux had a dependency on frequency by a power of 1.5 (i.e. $f^{1.5}$) above 5 Hz. They suggested that the analogy between experiments and theory shows that the simplifying assumptions, are acceptable in a higher range of frequencies. However, a lower dependency on f is observed for frequencies lower than 5 Hz.

2.7 Conclusion Remarks

Low pressure membrane applications (Mf and UF) and their related definitions are reviewed in this chapter. MF and UF applications have higher permeability and fluxes compared to high pressure applications such as NF and RO. Their

performances are however limited due to CP and fouling phenomena. A possible strategy to control fouling is to manipulate the hydrodynamics of the membrane system. For this purpose, it is necessary to study and model the hydrodynamics of the membrane systems more carefully. Existing models of the transport of particles in the membrane systems and some experimental methods, such as PIV, to study the behavior of particles are reviewed and introduced.

Figure 2.37 (a) Shear rate and critical flux vs. frequency in the axial vibrating hollow fibre system and (b) Log-Log diagram of J_{crit} vs. frequency. Slopes show the power of f in the correlation between J_{crit} and f (Genkin, et al. 2006).

MBR is one of the most common low pressure membrane applications that combines aerobic activated sludge process with membrane treatment in one process. Several anti-fouling methods have been developed for MBR systems. Aeration is an effective and at the same time high energy consuming method. An alternative

method to aeration is vibrating. A few experimental studies have been reported to determine the effect of different vibration parameters on the fouling control. However, there are many areas that need to be studied. Some of them are listed below:

- 1- Developing an analytical solution to understand the hydrodynamics of a longitudinal vibrating hollow fibre membrane system.
- 2- Understanding of the behaviour of supermicron particles in shear flows in order to introduce a more comprehensive parameter rather than critical flux.
- 3- Understanding the hydrodynamics of transverse vibrating hollow fibre membrane systems and the comparison of the longitudinal and transverse vibrating systems in terms of fouling control and energy consumption.
- 4- Understanding the effects of different anti-fouling methods on internal fouling of membranes.
- 5- Examining the behaviour of supermicron particles near the vibrating surface.

These areas are addressed in the present study.

Chapter 3

Materials and Methods

This chapter provides a general description of the experimental apparatus, materials, equipments and experimental methodologies used in this study. More detailed information about different experiments is further explained in its associated chapter.

3.1 Experimental Setup

The schematic diagram and the photograph of the experimental setup of a vibrating flat sheet membrane system are shown in Figure 3.1. The flat sheet membrane holder was submerged in a tank made of glass to be more transparent for PIV tests. The tank dimensions were 400 mm (length) $\times$ 450 mm (width) $\times$ 500 mm (height). A brushless DC motor (VEXTA, Oriental Motor Co. Ltd.) through a slider-crank mechanism vibrated the membrane holder. The permeate were extracted from the membrane holder using a peristaltic pump (Cole-Parmer[®], model 77200-60) which can maintain a constant permeate flux. The TMP and permeate flux variations were monitored by a pressure transmitter (Cole-Parmer[®]) and a digital balance (KERN & Sohn GmbH, model D-72336) respectively. The connections of the different components, are shown with dashed line in Figure 3.1a. A digital multifunction I/O (National Instrument, model USB-660B) with a data logging system (LabVIEW, National Instrument) were incorporated.

Figure 3.1 Vibrating flat sheet membrane experimental setup: (a) schematic diagram and (b) photograph.

The membrane holder was designed so that it can be submerged in the tank, and the permeate side can be sealed completely from the feed side. At the same time, the membrane surface can be exposed to the laser sheet (of PIV tests) and the camera can directly view the membrane surface for the side. These considerations led to a specific design shown in Figure 3.2. Figure 3.2a shows the schematic design of the

holder and Figure 3.2b shows the exploded drawing of the holder. Figure 3.2c is the photograph of the assembled membrane holder with the membrane.

Figure 3.2 The flat sheet membrane holder: (a) schematic representation of the cross-section, (b) exploded view and (c) photograph.

The PIV system was used to study the movements of particles near the vibrating membrane. The principles of PIV were introduced in Chapter 2.

A needle type air sparger was used to generate an air bubble sheet near the membrane surface. The distance of the air bubble sheet and the membrane was adjustable. The air flow was produced by an air blower (WELTCH) and the flow rate was adjusted and metered by a rotameter (DWYER, 0-5 l/min). The front and side view of the air bubble sheet is shown in Figure 3.3.

Figure 3.3 Air bubble sheet generated near the membrane surface: (a) front view and (b) side view.

3.2 Model Fouling Agents

3.2.1 Bentonite

Bentonite (Sigma-Aldrich, 285234) was used as the supermicron model foulant in the experiments. The suspension was prepared by Mili-Q water (Millipore). The particle size distribution for Bentonite particles was measured by a particle size analyzer (Mastersizer 2000, Malvern Instruments) by using laser scattering method (Figure 3.4). The mean particle size for Bentonite particles was 8.5 μm according to Figure 3.4.

3.2.2 Humic Acid

Humic acid was used as the internal fouling agent (for MF membranes) in the experiments. The presence of humic acid particles in the feed and permeate was examined by measuring the total organic carbon (TOC) using TOC analyzer (TOC-

V CSH, Shimadzu). The feed solution was prepared by the Mili-Q water. The average size of the humic acid particles was 231 nm. The size distribution was measured by Zetasizer Nano ZS (Malvern Instruments, UK) and is shown in Figure 3.5.

Figure 3.4 Particle size distribution for Bentonite particles by volume percentage.

Figure 3.5 Particle size distribution for humic acid particles by number percentage.

3.3 Membranes

Polyethersulfone (PES) flat sheet MF membranes (Pall Corporation, model S80610) were used in the experiments to study the effects of anti-fouling methods on the mode of the fouling. The nominal pore size of the MF membranes was 0.1 μm.

In other experiments, PES flat sheet UF membranes (Pall Corporation, model OT100SHEET) were used with a molecular weight cut off (MWCO) of 100 kDa.

In Chapter 6, Polyacrylonitrile (PAN) hollow fibres (Ultrapure Pte Ltd, Singapore) with inner/ outer diameters of 1 mm/ 1.6 mm and nominal pore size of 0.1 μm were used in the experiments. A group of 25 fibres with a length of 18 cm were aligned in parallel with both ends fixed to the C shape holding frame using Araldite epoxy.

3.4 PIV Setup

The principles of PIV were explained in Chapter 2. The following are the specifications of the PIV system (DANTEC Flow-Map system) used in this study.

A green laser sheet (wavelength=532 nm, thickness=1 mm and divergence angle=32°) with vertical orientation was generated by a mini Nd:YAG laser (dual-cavity frequency-doubled Q-switched pulsed). The images were captured by a charged coupled device (CCD) camera (Hi-Sense Mk II, DANTEC) equipped with a 1280×1024 pixels CCD chip.

In the transverse vibration experiments, 20 μm polyamide seeding particles (PSP), with a concentration of 0.1 g/L, were used to track the flow path and determine the velocity field. A 532 nm lens was used to filter off background light other than the scattered laser light from the particles.

In the vibrating flat sheet membrane experiments, the region of interest was very close to the membrane surface. Due to the large amount of reflected light by the

membrane surface, fluorescent polymer particles (FPP) 20 μm were used instead in these experiments. A red lens was used to filter wavelengths larger than 570 nm.

DynamicStudio 3.10 (DANTEC DYANMICS) was the software used for data acquisition, controlling the hardware and analyzing the results. The interrogation area (IA) with a size of 32 $\times$ 32 pixels (50% overlap) was used for the data analysis.

3.5 Pore Size Distribution Analysis Methods

Several techniques can be deployed to measure the pore size distribution (PSD) of membranes in different applications. These techniques can be classified into indirect and direct observation techniques. Molecular weight cut off (MWCO), gas adsorption/desorption (GAD), liquid displacement porometry (LDP) and evapoporometry (EP) are examples of the indirect techniques. Different microscopy techniques such as scanning electron microscopy (SEM), field-emission SEM (FESEM) and atomic force microscopy (AFM) can be used to observe the membrane pores directly. In this study, two indirect techniques, namely LDP and EP, were used to characterize the PSD of clean and fouled membranes. FESEM (as a direct observation method) was also used to verify the trend of the results qualitatively. In the following, the principles and the equipment, used for determining PSD are reviewed briefly.

3.5.1 Liquid Displacement Porometry (LDP)

LDP is an effective technique to measure the pore diameter in membrane applications. This technique can provide pore neck diameter for an individual pore or the PSD for a real membrane sample (Nakao 1994). LDP produces reproducible

and reliable results. However, it also has some drawbacks and limitations. For instance, LDP only can be used for pores larger than 0.01 μm . In addition, LDP deals with high pressures of gas and as a result it may change the membrane structure and the PSD of the membrane (Jena and Gupta 2010).

In a membrane with liquidphilic surface pores, the free energy of solid-gas surface is larger than that of solid-liquid surface. Therefore, the liquid can fill the membrane pores and displace the gas out of the pores spontaneously. To replace the liquid by gas again, the gas should push the liquid back through the pores with a pressure difference (ΔP) as shown in Figure 3.6a. This pressure difference for a wetting liquid with surface tension of γ and contact angle of θ on the surface can be calculated as follows (Jena and Gupta 2001):

$$\Delta P = \gamma \cos \theta \left[\frac{dS}{dV} \right]_{pore} \quad (3.1)$$

where dS and dV are the surface area and volume of the liquid displacement in the pore respectively. For a cylindrical shape pore with diameter of D (Figure 3.6a) and for a wetting liquid with contact angle of zero ($\theta=0$) Equation (3.1) is reduced to:

$$\Delta P = \frac{4\gamma}{D} \quad (3.2)$$

It can be concluded from Equation (3.2) that the larger pores need lower pressure differences for liquid displacement (Figure 3.6b). To determine the PSD in a membrane, the gas pressure is increased step by step and the gas flow rate is measured in different gas pressures for a wet and dry sample of the membrane separately. For the dry sample, the gas flow rate increases linearly by increasing the

gas pressure. For the wet sample, initially the gas flow rate is zero. At a pressure, called the bubble point pressure, the gas starts to flow through the membrane, and the gas displaces the liquid from the largest pore (Figure 3.7). Eventually, when the smallest pore in the membrane is drained, the wet and dry membrane curves become equal (Figure 3.7). The mean flow pressure is the pressure at which the flow rate in the wet sample reaches half of the flow rate in the dry sample (or intersect the half-dry curve) as shown in Figure 3.7. The associated pore diameter at each pressure value can be calculated by Equation (3.2), and the percentage of the gas flow rate through the pores with this diameter can be obtained by comparing the dry and wet curves (Jena and Gupta 2010).

Figure 3.6 Principle of the LDP technique: (a) schematic representation of a draining cylindrical pore and (b) comparison of pores with different diameters.

In this study, the PSD of the clean and fouled membranes was measured by LDP technique with a capillary flow porometer (CFP-1500A, Porous Materials, Inc.). The wetting liquid was Galwick and the non-reacting gas was nitrogen.

Figure 3.7 Gas flow rate versus the differential pressure in LDP (adopted from Jena and Gupta 2010).

3.5.2 Evapoporometry (EP)

Krantz, et al. (2013) introduced EP as a novel technique for characterization of PSD in UF membranes. This technique is based on the depression of vapour pressure in a membrane that is fully wetted with a volatile liquid. The main advantage of EP over the other direct observation (i.e. SEM, FESEM, etc.) and indirect techniques like LDP, is that EP, unlike the mentioned techniques, does not require very expensive instruments. In addition EP does not involve applying high pressures which can deform the structure and as a result PSD of the membrane. In some cases due to the high gas flow rate in LDP technique, it is likely that the gas flow removes the internal fouling from the pores and changes the characteristic of the fouled membrane.

The principle of the EP technique is based on the fact that when a membrane is saturated with a wetting volatile liquid, the vapour pressure of the liquid has

different values in pores with different diameters according to Kelvin equation as follows:

$$\ln \frac{\bar{P}_A}{P_A^\circ} = -\frac{4\gamma V}{DRT} \quad (3.3)$$

$\bar{P}_A$ is the partial pressure of the liquid in a pore (which is draining) with diameter of D and P_A° is the liquid vapor pressure over a flat surface. γ is the surface tension of the liquid on the pore surface. The contact angle (θ) of the liquid is assumed to be zero. V is the molar volume of the vapor, T is the absolute temperature and R is the gas constant. The liquid vapor is assumed to be an ideal gas. By rewriting Equation (3.3) in terms of the mole fraction of vapor, the diameter of draining pores can be calculated from the mole fraction of vapor at the membrane surface (x_{A0}) as bellow:

$$D = -\frac{4\gamma V}{RT \ln \frac{x_{A0}^\circ}{x_{A0}}} \quad (3.4)$$

where x_{A0}° is the mole fraction of the liquid vapor over a free-standing layer of liquid.

Figure 3.8a schematically represents the EP apparatus used in this study. The weight of a test cell (Figure 3.8b) was measured by a microbalance (ME235S, Sartorius) every 10 seconds, and the data was recorded to a computer by SartoCollect software (Sartorius). The test cell and the microbalance were maintained at a constant temperature (31 °C) in an incubator (LE-150D, YIHDER TECHNOLOGY CO., LTD.). To absorb the humidity at the open end of the test cell, silica gel packets were placed at the top of the test cell on a tripod. In order to

isolate the test setup from surrounding disturbances, the incubator was placed on an anti-vibration table. The test cell and its details are depicted in Figure 3.8b. The circular flat membrane sample (diameter of 40 mm) was fixed and sealed in the membrane holder by using two O-rings. The membrane sample was saturated and overlaid by wetting volatile liquid (water here). A fibreglass layer (with thickness of 1 cm) was placed above the free-standing liquid layer to damp the free convection and create a pure controlled diffusion mass transfer.

Figure 3.8 Schematic representations of (a) the EP apparatus and (b) the test cell.

As the water evaporates, three phases of evaporation can be distinguished: 1- primary transient phase, 2- evaporation of the free-standing liquid and 3- evaporation from the pores (Figure 3.9).

Figure 3.9 Three phases of the liquid evaporation in an EP experiment: (a) weight of the test cell versus the time and (b) evaporation rate versus the time.

Equation (3.4) shows that in the phase of evaporation from the pores, the larger pores drain earlier than smaller pores. In other words, the vapor saturation mole fraction (x_{A0}) of smaller pores is smaller than that of larger pores. Therefore, when the liquid vapor is saturated on the surface of a draining pore, it is supersaturated for smaller pores. The highest vapor saturation mole fraction belongs to the free-standing liquid (x_{A0}°) during free-standing liquid evaporation phase. The mass transfer coefficient k_x in the test cell in this phase can be calculated, as follows:

$$k_x = -\frac{4 W_A^{\circ}}{\pi d_c^2 \ln(1 - x_{A0}^{\circ})} \quad (3.5)$$

where W_A° is the free-standing liquid evaporation rate and d_c is the test cell diameter. The mass transfer coefficient k_x is constant when the temperature and pressure are fixed. As a result, the vapor volume fraction (x_{A0}) can be calculated from the instantaneous evaporation rate (W_A) as bellow:

$$x_{A0} = 1 - e^{-\frac{4 W_A}{\pi d_c^2 k_x}} \quad (3.6)$$

The associated pore diameter of any vapor volume fraction can be calculated using Equation (3.4).

3.5.3 Field-Emission Scanning Electron Microscope (FESEM)

For direct observation of the fouled and clean membrane intersections, the FESEM (JSM-6700F, JEOL, Ltd., Japan) was used in this study.

Chapter 4

Prediction of Supermicron Particle Deposition in Crossflow Microfiltration (CFMF)

4.1 Abstract

The concept of a critical permeation flux for the onset of particle deposition in crossflow microfiltration (CFMF) is well-established. However, the critical flux is known to be a function of process parameters such as the particle size, bulk concentration and crossflow velocity. The critical modified Peclet number (Pe_{crit}) is explored here as a generalized criterion for the onset of particle deposition that incorporates the effects of these process parameters as well as axial position along the membrane. Proper determination of Pe_{crit} requires accurate prediction of the concentration polarization boundary layer thickness δ_c and shear-induced diffusion coefficient D_s . The classical Lvque model is adapted to allow for the effect of the permeation flux on the velocity profile. Moreover, the assumptions of a constant concentration at the membrane surface c_w and constant D_s that have been made in prior studies are relaxed in an improved numerical solution to the convective

This chapter is based on: “Generalized criterion for the onset of particle deposition in crossflow microfiltration via DOTM – Modeling And Experimental Validation” by Farhad Zamani, Filicia Wicaksana, Amir H. Taheri, Adrian W.K. Law, Anthony G. Fane, William B. Krantz. Published in Journal of Membrane Science, 457(2014), 128-138.

diffusion equation that is used to predict δ_c and D_s . The critical permeation flux is determined from particle deposition data for 6 and 10 μm latex spheres taken via Direct Observation Through the Membrane (DOTM) characterization. A constant value of $\text{Pe}_{crit} = 4.00 \pm 0.08$ is found to characterize the effects of particle diameter, bulk concentration and crossflow velocity as well as axial position on the onset of particle deposition.

4.2 Introduction

The concept of critical flux is now well established for crossflow microfiltration processes (Field, et al. 1995). Above the critical flux, there is a net transport and deposition of particles (foulant) on the membrane when convection towards the membrane exceeds the diffusive back transport. The various back transport mechanisms, including Brownian diffusion and shear-induced diffusion, are known to be a function of the surface shear in the boundary layer, the relationship between flux and back diffusion points to a characteristic Peclet number (advective transport/diffusive transport) for crossflow microfiltration (CFMF). This approach has been discussed by Bacchin et al. (Bacchin 2004; Bacchin, et al. 2006) who suggested that fouling conditions could be identified by a critical Pe number (ratio of critical flux to the mass transfer coefficient). In this study, we examine this approach using carefully measured particle deposition data for super-micron particles in a well-defined flow channel.

The failure of the Brownian motion diffusivity mechanism to explain the supermicron particle deposition in CFMF (Blatt, et al. 1970; Green and Belfort 1980) resulted in introducing the shear-induced diffusivity (SID) mechanism to

explain the back diffusion behavior of supermicron particles in shear flows (Zydney and Colton 1986). Prior to that, it had been observed that supermicron particles experience lateral migration in shear flows (Eckstein, et al. 1977). Since then, the SID mechanism has been confirmed by observations such as an increase in viscosity of a suspension by shearing it in a Couette flow (Leighton and Acrivos 1987). In addition to SID, other mechanisms such as inertial lift (Altena and Belfort 1984; Green and Belfort 1980) and ‘flowing cakes’ (transport of particles along the surface) (Altmann and Ripperger 1997; Leonard and Vassilieff 1984) have also been proposed for supermicron particle deposition in CFMF (Belfort, et al. 1994). Bacchin and coworkers (Bacchin, et al. 1995) took surface interactions (e.g., electrokinetic effects) into account along with hydrodynamic effects to explain the behavior of colloidal particles near a membrane surface. For the models that consider the motion of a single particle owing to inertial lift and/or transport of the particle along the surface in the flow of a suspension, particle-particle interactions are ignored, which is not a realistic assumption for more concentrated suspensions. The concentration of rejected particles is usually very high close to the membrane surface in CFMF, which is the region of interest for studying the motion of the particles. On the other hand, the shear-induced diffusion coefficient, D_s in the SID models, is an all-inclusive parameter that is a measure of all mechanisms for diffusive particle motion (i.e., perpendicular to the direction of the crossflow). This diffusive motion can arise from mutually induced velocity fields, particle-particle interactions, lift forces and body forces (Cox and Mason 1971; Eckstein, et al. 1977).

The Graetz (Graetz 1883) or Lvque (Lvque 1928) solutions that were originally used for the somewhat analogous heat transfer problem have been widely used to solve the mass transfer in laminar flow CFMF in order to determine the mass transfer coefficient, concentration boundary layer thickness and wall concentration (Li, et al. 2000; Porter 1972; Zydney and Colton 1986). The differences between the various prior studies that used the Lvque solution arise from the use of different diffusion coefficients. Numerical (Chellam, et al. 1992; Singh and Laurence 1979) and computational fluid dynamics (CFD) (Ghidossi, et al. 2006) approaches have also been used to model the momentum and concentration boundary layers in membrane applications. The strengths and weaknesses of these models will be discussed in the next section.

In this study, a comprehensive simulation using a modified SID model (Li, et al. 2000) that is solved by the finite difference method has been employed to predict the wall concentration distribution along the membrane surface. It will be shown that in contrast to the Lvque solution the wall concentration is not the same at different locations along the membrane surface. In addition, based on the results from the DOTM technique the local critical fluxes (J_{crit}) at two different points near the inlet and exit of the crossflow channel have been measured. The experimental data from the DOTM technique combined with the results from the finite difference simulation support the existence of a critical modified Peclet number (Pe_{crit}) concept that has been suggested in prior studies (Bacchin 2004; Bacchin, et al. 2006; Bhattacharya and Hwang 1997).

4.3 Model Development and Numerical Solution

CFMF can be considered to be the flow of an incompressible fluid between parallel flat walls, one of which is porous (i.e., the membrane). To model the mass transfer in this flow, both the velocity and concentration profiles need to be described in some way. Various approximations for the velocity profile have been used in different studies. The velocity profile corresponding to Poiseuille flow that does not consider any effects of the permeation flux through the wall has been used in the Graetz solution (Graetz 1883). The Lvque solution (Lvque 1928) uses a linear approximation of the velocity distribution within a thermal boundary layer that can be employed in the same way for a concentration boundary layer.

In crossflow microfiltration the transverse velocity (due to the permeation) is usually negligible compared to the axial (crossflow) velocity. As a result, the transverse velocity component is usually neglected in solving the equations-of-motion in these systems. However, the concentration polarization boundary layer where the mass transfer of the particles occurs is usually very thin compared to the channel height; hence, very close to the wall, the axial and transverse velocities can be comparable. Therefore, in order to model the mass transfer more accurately, a velocity profile that incorporates the effects of both the transverse and axial components of the velocity field is required.

4.3.1 Velocity Profile in a Channel with Flux through the Membrane

The geometry, coordinate system and other details of the CMFM channel are shown in Fig.1 in which x and y denote the coordinates in the axial and transverse

directions, respectively, and v_w denotes the volumetric permeation flux at the wall. The dimensionless transverse coordinate is denoted by λ (y/h); this implies that λ varies between 0 (the solid wall) and 1 (the membrane surface). When the width of the channel (w) is much larger than the height (h), the flow can be considered to be two-dimensional. A sufficiently long entry region is provided so that the velocity profile within the region of interest can be considered to be fully developed. The flow is assumed to be steady and laminar. The velocity components in the x and y directions are denoted by u and v , respectively. The typical profile of the velocity components (u and v) and mass concentration (c) are shown in Fig. 1. It will be shown later that the particle deposition begins in locations where the modified Peclet number exceeds a critical Peclet value (Pe_{crit}). It also will be explained that the effective wall concentration (c_w) should be distinguished from the deposited cake concentration (c_c) for supermicron particles (Fig. 1). Since the onset of particle deposition near the local critical flux was studied here, the model does not consider any immobile cake layer thickness. Therefore, the axial velocity at the membrane wall was assumed to be zero. As a result, the boundary conditions constitute no-slip and no-permeation at the solid wall ($u, v=0$ at $\lambda=0$) and no-slip and a velocity determined by the permeation flux at the membrane ($u=0, v=v_w$ at $\lambda=1$).

Berman (1953) used a perturbation solution to solve the equations-of-motion that incorporated a transverse velocity component arising from permeation through a porous wall. Details of the perturbation solution for this problem can be found in prior studies (Berman 1953; Chellam, et al. 1992). The perturbation solution which used by Berman (Berman 1953), was also used here in which a no-slip condition was assumed at the membrane surface.

Figure 4.1 Schematic diagram of CFMF showing the parallel plate channel geometry, the axial and transverse velocity profiles, concentration profile, concentration polarization boundary layer, and cake formation layer; particle deposition begins downstream from the channel inlet owing to the local dependence of the critical permeation flux.

From the perturbation solution the velocity components can be calculated from the following (Chellam, et al. 1992):

$$u(x, \lambda) = \left(u_0 - \frac{v_w x}{h} \right) (f'_0(\lambda) + Re_w f'_1(\lambda)) \quad (4.1)$$

and

$$v(\lambda) = v_w (f_0(\lambda) + Re_w f_1(\lambda)) \quad (4.2)$$

where Re_w denotes the wall Reynolds number ($v_w h / \nu$), ν is the fluid kinematic viscosity and u_0 is the mean axial velocity in the channel; $f_0(\lambda)$ and $f_1(\lambda)$ are functions of λ that are obtained from the perturbation solution:

$$f_0(\lambda) = -2\lambda^3 + 3\lambda^2 \quad (4.3)$$

and

$$f_1(\lambda) = \frac{-2}{35}\lambda^7 + \frac{1}{5}\lambda^6 - \frac{3}{10}\lambda^5 + \frac{27}{70}\lambda^3 - \frac{8}{35}\lambda^2 \quad (4.4)$$

This velocity profile, given by Equations (4.1)-(4.4), is an input for the numerical solution for the mass transfer near the membrane surface in the next section.

4.3.2 Mass Transfer of Supermicron Particles near the Membrane Surface

Close to the membrane surface in CFMF applications at a filtration flux below or near the critical flux (Bacchin, et al. 2006; Field, et al. 1995), there is a balance between the convection of particles ($v_w c_w$) toward the membrane and the back-diffusion of rejected particles from the membrane ($D \partial c / \partial y$). This can be written as a boundary condition at the membrane surface as follows:

$$D \frac{\partial c}{\partial y} = v_w c_w \quad (4.5)$$

where y is the normal direction to the membrane. The diffusion coefficient (D) for the rejected particles incorporates both the Brownian-induced and the shear-induced diffusion coefficients, D_B and D_s , respectively (Lee and Clark 1998; Sim, et al. 2012):

$$D = D_B + D_s = \frac{k_B T}{6\pi\mu r_p} + D_s \quad (4.6)$$

where k_B is the Boltzmann constant, T is the temperature, μ is the viscosity and r_p is the particle radius. It has been shown that for supermicron particles, the Brownian diffusion coefficient is negligible compared to the shear-induced diffusion coefficient (i.e., $D_B \ll D_s$) (Eckstein, et al. 1977; Leighton and Acrivos 1987). Different empirical relationships have been used to approximate D_s ; most of these

relationships are based on the results of the experiments conducted by Eckstein et al. (Eckstein, et al. 1977). For suspensions with a feed volume fraction (ϕ_b) in the range of $0.2 < \phi_b < 0.5$ (this range may be applied to the wall volume fraction ϕ_w), Zydney and Colton (Zydney and Colton 1986) approximated D_s by:

$$D_s = 0.03 r_p^2 \gamma_w \quad (4.7)$$

where γ_w denotes the shear rate at the membrane surface. They used this diffusion coefficient in the Lvque solution to obtain the local and average fluxes at the membrane surface. This will be referred to as the SID model.

A modified shear-induced diffusion coefficient was used by Li et al. (Li, et al. 2000) for more dilute suspensions with a wall volume fraction in the range $0 < \phi_w < 0.2$ and is given by:

$$D_s = 0.1 \phi_w r_p^2 \gamma_w \quad (4.8)$$

Note that D_s is dependent on the suspension volume concentration at the wall (ϕ_w). This diffusion coefficient was also used as an input to the Lvque solution. Since in the Lvque solution the wall concentration must be known and constant over the membrane surface, Li et al. assumed a wall volume fraction of 0.2 ($\phi_w=0.2$) (Li, et al. 2000). This will be referred to as the SID-MOD model.

Here, the velocity profile obtained via a perturbation analysis is used that allows for the effect of the permeation flux in a differential mass balance that incorporates shear-induced diffusion as well as convective mass transfer. Realistic flux conditions are applied at the impermeable and permeable solid boundaries. Neither

the concentration nor the shear-induced diffusion coefficient is specified at the boundaries; the local values for both quantities are determined from a finite difference solution. The shear-induced diffusion coefficient is determined from the SID model for high concentrations and from the SID-MOD model for low concentrations:

$$\begin{cases} D_s = 0.1\varphi_w r_p^2 \gamma_w & \text{if } 0 < \varphi_w < 0.2 \\ D_s = 0.03 r_p^2 \gamma_w & \text{if } 0.2 < \varphi_w < 0.5 \end{cases} \quad (4.9a)$$

$$\quad (4.9b)$$

Note that the volume fraction (φ_w) and mass concentration (c_w) at the wall are distinguished from the volume fraction (φ_c) and mass concentration (c_c) of the cake (deposited layers of particles that have no motion relative to each other). That is, because the shear-induced diffusion of particles near the membrane surface is due to particle-particle interactions (Eckstein, et al. 1977; Leighton and Acrivos 1987), there is no flow induced particle-particle interaction within the cake region. Hence, φ_w denotes the volume fraction in the dynamic region close to the membrane surface but above the static region of deposited particles in the cake (i.e., see Figure 4.1). Note that there is a discontinuity in Equation (4.9) at $\varphi_w = 0.2$ that arises from the difference between the SID and SID-MOD models. However, it will be shown in the results section that for this study of CFMF involving dilute suspensions the wall concentration never exceeds much more than 0.2; hence, only Equation (4.9a) was used in the numerical solution. Note that the relation between mass concentration (c_w) and volume fraction (φ_w) is $c_w = \varphi_w \rho_p$ in which ρ_p is the particle density.

In CFMF systems the channel height (h) is much smaller than the channel length (L). Therefore, axial diffusion in the convective diffusion equation is negligible compared to transverse diffusion. By introducing the dimensionless variables $u^* = u/u_0$, $v^* = v/v_w$, $c^* = c/c_0$, $x^* = x/L$ and $\lambda = y/h$, the convective diffusion equation and boundary conditions can be written as follows:

$$\frac{u_0}{L} u^* \frac{\partial c^*}{\partial x^*} + \frac{v_w}{h} v^* \frac{\partial c^*}{\partial \lambda} = \frac{D_s}{h^2} \frac{\partial^2 c^*}{\partial \lambda^2} \quad (4.10)$$

$$\frac{\partial c^*}{\partial \lambda} = 0 \quad \text{at } \lambda = 0 \text{ for } 0 < x^* < 1 \quad (4.11)$$

$$\frac{\partial c^*}{\partial \lambda} = \frac{h}{D_s c_b} v_w c_w \quad \text{at } \lambda = 1 \text{ for } 0 < x^* < 1 \quad (4.12)$$

$$c^* = 1 \quad \text{at } x^* = 0 \text{ for } 0 < \lambda < 1 \quad (4.13)$$

The geometry, boundary conditions and coordinate systems used are shown in Figure 4.1. To discretise the convective diffusion equation and boundary conditions given by Equations (4.10) to (4.13), a backward difference approximation is used for the convective terms on the left-hand side of Equation (4.10) and a central difference approximation is used for the diffusive terms on the right-hand side of Equation (4.10). The number of grid points in the axial direction (x -direction) is denoted by M and the subscript m denotes the grid number in this direction ($m=0$ and $m=M$ for the inlet and exit of the channel, respectively). For the transverse direction (y -direction) the grid number k varies between 0 (the solid wall) and K (the membrane surface); that is, c_{km}^* denotes the dimensionless concentration of the k^{th} row in the y -direction and the m^{th} column in the x -direction. $\Delta x^* = 1/(M-1)$ and $\Delta \lambda = 1/(K-1)$ are the dimensionless grid spacings in the axial and transverse

directions, respectively. The finite difference equations for different grid points in a column, denoted by F_k , can be written as follows:

$$F_1 = \frac{2D_s L}{u_0 h^2 \Delta \lambda^2} c_{1m}^* - \frac{2D_s L}{u_0 h^2 \Delta \lambda^2} c_{2m}^* = 0 \quad \text{for } k = 1 \quad (4.14)$$

$$F_k = \left[\frac{-Lv_w v_{km}^*}{u_0 h \Delta \lambda} + \frac{-D_s L}{u_0 h^2 \Delta \lambda^2} \right] c_{k-1m}^* + \left[\frac{u_{km}^*}{\Delta x^*} + \frac{Lv_w v_{km}^*}{u_0 h \Delta \lambda} + \frac{2D_s L}{u_0 h^2 \Delta \lambda^2} \right] c_{km}^* \quad (4.15)$$

$$+ \left[\frac{-D_s L}{u_0 h^2 \Delta \lambda^2} \right] c_{k+1m}^* + \left[\frac{u_{km}^*}{\Delta x^*} \right] c_{km-1}^* = 0 \quad \text{for } 2 \leq k \leq K-1$$

$$F_K = \left[\frac{-Lv_w}{u_0 h \Delta \lambda} + \frac{-2D_s L}{u_0 h^2 \Delta \lambda^2} \right] c_{K-1m}^* + \left[\frac{-Lv_w}{u_0 h \Delta \lambda} + \frac{2D_s L}{u_0 h^2 \Delta \lambda^2} \right] c_{Km}^* = 0 \quad \text{for } k = K \quad (4.16)$$

From Equation (4.9) it can be seen that $D_s (=0.1 c_{Km}^* c_{bp}^2 \gamma_w / \rho_p$ for $0 < c_{Km}^* c_{bp} / \rho_p < 0.2$) is a function of the local wall concentration (c_{Km}^*). Since Equations (4.14) to (4.16) constitute a system of nonlinear equations, Newton's method is employed (Burden and Faires 2011). The concentration in each column of points (column k) is dependent only on the left column (column $k-1$). Thus, the system of equations is solved for each column whereby the solution for column $k-1$ is used as the input for the system of equations for column k . A block diagram that illustrates the algorithm and protocol for solving the convective diffusion equation using Newton's method is shown in Figure 4.2.

Figure 4.2 Algorithm (Newton's method) used for solving the nonlinear convective diffusion equation.

In Figure 4.2 *tol* refers to the convergence tolerance that is set to 10^{-6} for all the simulations in this study. C_m^* , $F(C_m^*)$ and $J(C_m^*)$ are the dimensionless concentration, finite difference equations and Jacobian, respectively, of the m^{th} column when the solution is cast in the following matrix form:

$$C_m^* = \begin{bmatrix} c_{1m}^* \\ c_{2m}^* \\ \vdots \\ c_{Km}^* \end{bmatrix}, F(C_m^*) = \begin{bmatrix} F_1(C_m^*) \\ F_2(C_m^*) \\ \vdots \\ F_K(C_m^*) \end{bmatrix}, J(C_m^*) = \begin{bmatrix} \frac{\partial F_1(C_m^*)}{\partial c_{1m}^*} & \frac{\partial F_1(C_m^*)}{\partial c_{2m}^*} & \cdots & \frac{\partial F_1(C_m^*)}{\partial c_{Km}^*} \\ \frac{\partial F_2(C_m^*)}{\partial c_{1m}^*} & \frac{\partial F_2(C_m^*)}{\partial c_{2m}^*} & \cdots & \frac{\partial F_2(C_m^*)}{\partial c_{Km}^*} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial F_K(C_m^*)}{\partial c_{1m}^*} & \frac{\partial F_K(C_m^*)}{\partial c_{2m}^*} & \cdots & \frac{\partial F_K(C_m^*)}{\partial c_{Km}^*} \end{bmatrix} \quad (4.17)$$

where $F_1(C_m^*)$ to $F_K(C_m^*)$ are defined by Equations (4.14) to (4.16). $\max(F(C_m^*))$ refers to the largest component of the column matrix $F(C_m^*)$. To choose a proper

grid spacing in the simulation, a grid sensitivity analysis has been performed based on the effect of the grid number on the concentration at the middle of the channel wall on the membrane side. Figure 4.3 shows a plot of the aforementioned concentration as a function of the number of transverse (panel a) and axial grid points (panel b). The legend summarizes the fixed parameters for this sensitivity analysis. Figure 4.3a indicates that the accuracy of the solution depends significantly on the axial grid number (K) but changes by less than 1% for values of $K > 4000$. Figure 4.3b indicates that the accuracy does not depend significantly on M . Hence, the values of M and K are fixed at 1000 and 4000, respectively, in order to ensure a solution within 1% accuracy in the simulations.

Figure 4.3 The effect of the transverse (panel a) and transverse (panel b) grid numbers on the concentration at the middle of the channel wall constituting the membrane.

The principal features of the model developed here and the manner in which it relaxes assumptions made in prior studies are summarized in the following:

1. It employs a velocity profile obtained from a perturbation solution that incorporates the effect of the permeate flux through the membrane on the solution for the concentration profile near the membrane surface; this effect is neglected in the Lvque solution.

2. The wall concentration (c_w) is not specified but rather is predicted by a numerical solution to the describing equations in contrast to the Lvque solution that requires specifying the concentration on the membrane surface.
3. The shear-induced diffusion coefficient is calculated locally via a numerical solution to the nonlinear system of equations in contrast to prior studies that assumed a constant value.

Incorporating these improvements is shown to be important by comparing the predictions of the model developed here to those of the more limiting models developed in prior studies.

4.4 Material and Methods

A schematic of the Direct Observation Through the Membrane (DOTM) setup is shown in Figure 4.4. A gear pump (Cole Parmer) was used to circulate the feed suspension through the CFMF channel (109 mm length x 33.5 mm width x 2 mm height). The membrane module had a built-in chamber which acted as a flow pulsation damper and could damp the pump perturbation. The permeate was extracted using a low capacity peristaltic pump (Minipuls 3, Gilson). The variations of transmembrane pressure (TMP) and flux during the experiment were monitored using a digital balance (PL4002, Mettler) and three pressure transducers (Cole Parmer) connected to a data-logging system (LabVIEW). More details of the DOTM setup and CFMF module are given elsewhere (Wicaksana, et al. 2012).

Figure 4.4 Schematic of the DOTM setup.

Transparent Anopore inorganic disc membranes (Anodisc, Whatman, Germany) with a diameter of 47 mm and a nominal pore size of 0.2 μm were used in this study. In order to facilitate the placement of the membrane in the acrylic CFMF module, the membrane was framed between two sheets of paper that created a square active membrane area (2.7 cm x 2.7 cm) in the middle of the flow channel (Figure 4.5a). Each experiment for a fixed set of system parameters was conducted with using a new membrane. Polystyrene latex beads were used as model particles (Fluka, Sigma Aldrich, USA). Since the concentrations used in this study were very low, the kinematic viscosity, ν , of the suspensions was assumed to be that of pure water (i.e., $10^{-6} \text{ m}^2/\text{s}$)

4.4.1 Experimental Protocol

Flux-stepping tests were conducted by incrementally increasing the flux at 15-minute intervals. A series of filtration runs was performed at crossflow velocities

(CFVs) of 0.07 -0.13 m/s, feed concentrations (c_b) of 0.5 and 1 g/L, and particle sizes of 6 μm and 10 μm (d_p). Five cases defined by different combinations of these parameters were studied as summarized in Table 1. The highest Reynolds number reached in these five cases was 520 (related to Case 2); thus, the flow regime was laminar. In order to investigate the effect of axial distance on particle deposition, DOTM images were captured with a colour video camera (TK-C921BEG, JVC) and AxioVision software (Carl Zeiss) at two locations: 0.7 cm (Point 1) and 2.2 (Point 2) cm from the feed inlet (Figure 4.5a). These locations were pre-set by using a motorized stage (mechanical stage 75 x 50 mot standard, Carl Zeiss) coupled with an electronic coaxial drive. The recorded images then were analysed to determine the rate of particle deposition. The total membrane surface area viewed under the microscope (A) was 280 x 210 μm^2 (Figure 4.5b).

Figure 4.5 Placement of the transparent Anopore membrane in the channel; (b) the total membrane surface area viewed under the microscope.

To determine the local critical flux ($J_{crit}(x)$) for the different cases and axial positions, the following relationship, which is obtained from a particle mass balance (Chong, et al. 2008; Zhang, et al. 2010), was used:

$$\frac{\Delta N}{\Delta t} = \frac{3}{4} \frac{\theta c_b A}{\pi \rho_p r_p^3} (v_w - J_{crit}(x)) \quad (4.18)$$

The local critical flux is shown by $J_{crit}(x)$ to imply that the critical flux is function of the distance (x) from the inlet of the channel as well as other hydrodynamic parameters [2]. N is the number of particles, A is the membrane area and θ is the fractional deposition constant (the fraction of particles convected to the membrane that are deposited on it) (Zhang, et al. 2010). Equation (4.18) relates the particle deposition rate ($\Delta N/\Delta t$) to the difference between the permeate flux and critical flux ($v_w - J_{crit}(x)$). The flux-stepping was continued for at least three more steps after deposition began for each case. At each flux step, the particle deposition rate for both Points 1 and 2 was determined from the images captured at the two time points (t_1 and t_2), as illustrated in Figure 4.6. Equation (4.18) implies that if the particle deposition rate ($\Delta N/\Delta t$) is plotted versus the permeate flux (v_w), the intercept of the regression line with the horizontal axis (flux axis) corresponds to the highest flux at which the particle deposition rate is zero (i.e., the critical flux). The resulting critical fluxes determined in this manner for the five cases are presented and discussed in Section 4.

Table 4.1 Particle diameter (d_p), concentration (c_b) and crossflow velocity (CFV) values for the five cases in this study.

Case No.	d_p (μm)	c_b (g/L)	CFV (m/s)
Case 1	10	0.5	0.07
Case 2	10	0.5	0.13
Case 3	6	0.5	0.075
Case 4	6	1.0	0.075
Case 5	6	1.0	0.1

Figure 4.6 Permeation flux (v_w) and transmembrane pressure (TMP) as a function of time for the flux-stepping protocol; the two micrographs show the particle deposition at 79 and 85 seconds from which the particle deposition rate can be determined as illustrated.

4.5 Results and Discussion

In these experiments involving the use of DOTM in CFMF, the particle deposition at a constant overall permeation flux was found to be a function of axial location. This can be observed in Figure 4.7 that shows the particle deposition at different locations along the membrane at nearly the same time for which the experiment

conditions are given on the figure: left edge or inlet (Figure 4.7a); Point 1 (Figure 4.7b); middle of the channel (Figure 4.7c); Point 2 (Figure 4.7d); and right edge or exit (Figure 4.7e). This suggests that the critical flux should be determined locally to determine the onset of particle deposition in CFMF. These data will be analyzed quantitatively in the subsequent discussion.

Figure 4.7 The membrane surface coverage at the same time at different distances from the channel inlet: (a) left edge or inlet; (b) Point 1; (c) middle of the channel; (d) Point 2; (e) right edge or exit.

Providing a quantitative explanation for this apparent local critical flux in CFMF was a major goal of this study. Prior models could not address this question owing to limiting assumptions. In particular, the model developed in this study does not require specifying the concentration at the membrane surface and allows for the concentration dependence of the shear-induced diffusion coefficient in both the axial and transverse directions. As such, the model can predict the dependence of

the critical flux on the coupled hydrodynamics and mass transfer in the concentration polarization boundary layer. The modelling results for the critical flux can be generalized by casting them in terms of the critical modified Peclet number. The modified Peclet number is the dimensionless ratio of the transverse convection (i.e., owing to the permeation flux) to the diffusion of the rejected particles in crossflow membrane filtration. It was first introduced by Bhattacharya and Hwang (1997) to characterize the concentration polarization boundary layer in nanofiltration and reverse osmosis. A critical Peclet number (Pe_{crit}) in the concentration polarization boundary layer has been suggested by Bacchin and co-workers (Bacchin 2004; Bacchin, et al. 2006) that provides a dimensionless criterion for assessing when the convective flux of particles towards the membrane exceeds their back-diffusion, thereby causing the onset of particle deposition. The critical modified Peclet number is defined as follows:

$$Pe_{crit} = \left(\frac{J_{crit}(x)\delta_c}{D_s} \right)_{crit} \quad (4.19)$$

where δ_c is the concentration polarization boundary layer thickness that can be a function of axial position. This dependence suggests that local particle deposition should occur if $Pe > Pe_{crit} \cong 1$. Moreover, if the critical modified Peclet number is to fundamental significance for CFMF, its value should be independent of the operating conditions (i.e., the conditions for the different cases). This hypothesis will be tested by employing the model developed in this study to determine the local concentration polarization boundary layer thickness and shear-induced diffusion coefficient. The predicted local values of Pe_{crit} will be used to interpret the observed particle deposition determined by the DOTM characterization. The model

developed in this study will be used to assess the error incurred in using the SID and SID-MOD models to predict Pe_{crit} .

4.5.1 Determination of critical fluxes

The method for determining the critical flux was explained in Section 3.1. Figure 4.8a shows the particle deposition rate as a function of the permeation flux for Point 2 for each of the five cases. The intercept of the best fit line for each set of points with the horizontal (permeate flux) axis is identified with the critical flux for that case. The critical fluxes along with the R^2 values for the linear regression obtained via this procedure are shown in the legend of Figure 4.8a.

As expected, a higher CFV, larger particle diameter and a lower feed concentration resulted in a higher critical flux. The same method for calculating the critical flux at Point 1 was used. The results for both Points 1 and 2 are summarized in Figure 4.8b, which clearly shows that the critical fluxes are lower for point 2, which is farther from the channel inlet than Point 1. These results confirm that the critical flux is a local concept whose value is strongly dependent on the hydrodynamics. The critical flux measurements are reproducible with a relative error within $\pm 2.5\%$. These critical fluxes will be used to determine the critical modified Peclet number for the different cases at the two locations.

Figure 4.8 (a) Particle deposition rate as a function of permeate flux at Point 2 from which the critical flux is determined for the different cases; (b) Comparison between the critical fluxes determined at Points 1 and 2 for the different cases.

4.5.2 Comparison between Predictions of the Different Models

Figure 4.9 shows a plot of the shear-induced diffusion coefficient D_s (panel a) and the dimensionless concentration polarization boundary layer thickness δ_c^* ($= \delta_c/h$) (panel b) as a function of the dimensionless distance from the channel inlet for the model developed in this study (dashed line), the SID model (dash-dot line) and the SID-MOD (solid line). The comparison is shown only for Case 1 (Point 1) for which the local critical permeate flux is 41.4 L/m²h (1.15×10^{-5} m/s). Fig. 9a shows

that D_s is constant along the membrane length for both the SID and SID-MOD models owing to the assumption of a constant wall concentration. In contrast, D_s increases with increasing distance from the channel inlet for the model developed in this study since it does not specify the wall concentration but determines it from the numerical solution. The SID and SID-MOD models overestimate D_s and thereby predict a thicker concentration polarization boundary layer thickness δ_c than does the model developed here (Figure 4.9b). In Section 4.3 the critical modified Peclet numbers predicted by the three solutions will be compared.

Figure 4.9 Shear-induced diffusion coefficient D_s (panel a) and the dimensionless concentration polarization boundary layer thickness δ_c^* ($= \delta_c/h$) (panel b) as a function of the dimensionless distance from the channel inlet for the model developed in this study (dashed line), the SID model (dash-dot line) and the SID-MOD (solid line) for Case 1.

4.5.3 Critical Modified Peclet Number

The critical modified Peclet number, Pe_{crit} , has been advanced as a possible key parameter to characterize the mass transfer of supermicron particles in CFMF. The value of Pe_{crit} depends on the method and its associated assumptions used to solve the convective diffusion equation. Figure 4.10 shows a plot of Pe_{crit} based on the

critical flux determined via the procedure shown in Figure 4.8a and based on the values of D_s and δ_c predicted by the SID model at Points 1 and 2 for the five cases. The Pe_{crit} values differ between the five cases as well as at the two points for each case. In principle, Pe_{crit} should be the same irrespective of the operating conditions and the axial position since this dimensionless group characterizes the balance between convection and diffusion when particle deposition begins. Figure 4.11 shows the same plot for Pe_{crit} predicted by the SID-MOD model. Again, the values of Pe_{crit} vary widely for the different cases and the two observation points. This means that the SID and SID-MOD models do not lead to a critical Peclet number. However, Figure 4.12 shows the values of Pe_{crit} predicted by the model developed in this study for the five cases and the two observation points. In contrast to Figure 4.10 and 11, $Pe_{crit} = 4 \pm 0.08$ for all the results shown in Figure 4.12. If Pe_{crit} properly characterizes the conditions defining the onset of particle deposition, its value should be a constant irrespective of the operating conditions. Moreover, the fact that $Pe_{crit} \cong 1$ indicates that this dimensionless group properly characterizes the conditions for which the convection and back-diffusion of particles just balance each other. The model developed in this study predicts a constant value of Pe_{crit} because it more accurately predicts the values of D_s and δ_c that appear in Pe_{crit} owing to relaxing the constraints of a constant c_w and D_s embodied in the SID and SID-MOD models. Hence, in contrast to the critical flux that has been shown to vary locally in these CFMF studies, Pe_{crit} is a global dimensionless parameter whose value characterizes the onset of particle deposition irrespective of axial position, particle diameter, bulk concentration of particles and crossflow velocity.

Figure 4.10 Critical modified Peclet numbers predicted by the SID model at Points 1 and 2 for the five cases corresponding to different operating conditions.

Figure 4.11 Critical modified Peclet numbers predicted by the SID-MOD model at Points 1 and 2 for the five cases corresponding to different operating conditions.

coefficient accurately. In this study the effect of the permeation flux on the velocity profile was incorporated into the model and neither the concentration nor the shear-induced diffusion coefficient was specified along the membrane surface. The resulting nonlinear convective diffusion equation was solved numerically to determine the concentration polarization boundary layer thickness and shear-induced diffusion coefficient as a function of axial distance. These predictions along with the values of the critical flux were used to determine the critical modified Peclet number at two axial positions for five cases involving different values for the particle diameter, bulk particle concentration and crossflow velocity. The resulting critical modified Peclet number was found to be a constant of order one irrespective of axial position or the process parameters for the five cases. This suggests that the critical modified Peclet number provides a global criterion for the inception of particulate fouling in contrast to the critical flux that can depend on the axial position as well as the process parameters.

This study provides strong support for the use of the critical modified Peclet number as a criterion for the onset of particle deposition in CFMF. However, this study considered only the deposition of two different sizes of latex microspheres at two bulk concentrations for five crossflow velocities. The concept of a critical modified Peclet number should apply to different types of particles if the onset of deposition is determined by a balance between convection and diffusion of particles to and from the membrane surface, respectively. However, if additional mechanisms are involved such as eddy diffusion (i.e., turbulent flow), Brownian diffusion or electrostatic interaction between the membrane and the particles, the concept of the critical modified Peclet number as defined in this study undoubtedly

will need to be modified. This study establishes that in the absence of the aforementioned additional mechanisms, the onset of particle deposition in CFMF is determined by a unique value of the modified Peclet number irrespective of the axial position, particle diameter, bulk concentration or crossflow velocity. Further work is required to assess the general applicability of our new modeling approach and the factors influencing Pe_{crit} .

Chapter 5

Hydrodynamic Analysis of Vibrating Hollow Fibre Membranes

5.1 Abstract

Dynamic shear-enhanced filtration through vibration can be an effective method to reduce concentration polarization and membrane fouling in high solids suspension loaded membrane applications such as membrane bioreactors (MBRs). In this approach, the wall shear rate on the membrane surface is one of the most important parameters which can control the fouling in vibrating membrane systems. In the present study, the effects of vibration parameters (i.e. frequency and amplitude) and geometrical parameters (i.e. fibre radius and distance between the fibres in a bundle of fibres) on the wall shear rate at the membrane surface have been studied both analytically and numerically. The analytical solution uses the cylindrical coordinate for the analysis of a vibrating single fibre. The former Cartesian solution for a flat sheet membrane used also for fibres by others, was compared to the new solution. It was found that a relative error of up to 75% can arise comparing the two solutions

This chapter is based on: "Hydrodynamic Analysis of Vibrating Hollow Fibre Membranes" by Farhad Zamani, Adrian W.K. Law, A.G. Fane. Published in Journal of Membrane Science, 429 (2013) 304-312.

within a realistic range of hollow fibre diameters. The results also showed that fibres with smaller radii are more effective for the vibrating system. Computational Fluid Dynamics simulations were also performed to examine the optimal configuration and distance between fibres for different configurations. The computational results with two remote fibres were first obtained and compared with the analytical results of a single vibrating fibre. The comparison was satisfactory and shows the compatibility of the modeling and analytical results. Subsequently, the CFD analysis was conducted for a fibre bundle with both staggered and in-line arrangements and the former was found to be marginally more responsive to vibrations.

5.2 Introduction

Dynamic shear-enhanced filtration through vibration could be an effective method (Jaffrin 2008; Jaffrin, et al. 2004) to reduce the concentration polarization and membrane fouling in high solid suspension loaded membrane applications such as membrane bioreactors (MBRs). It could be of particular interest for anaerobic MBRs where fouling control by bubbling is difficult. In the vibration approach, the membrane is moved relative to the surrounding fluid in order to induce wall shear on the membrane surface. Common types of shear-enhanced systems include the rotating cylindrical membranes, rotating disk systems and vibrational membranes (Jaffrin 2008). Different modes of vibration can be employed in dynamic shear-enhanced filtration. For instance, a flat membrane system can be vibrated torsionally around a vertical axis, which is the original idea of the vibratory shear-enhance processing (VSEP) proposed by Armando, et al. (1992). Also, a hollow

fibre system can be vibrated longitudinally, transversely, torsionally or with a combination of these motions (Genkin, et al. 2006; Low, et al. 2005). The main interest of the present study is the longitudinally vibrating hollow fibre membrane system.

A few experimental studies had been reported in the literature on the effect of wall shear rate on the resulting filtration flux in vibrating membrane systems (Akoum, et al. 2002; Beier, et al. 2006; Genkin, et al. 2006). However, theoretical modeling and simulation of vibrating systems have not been addressed sufficiently to date. The modeling and simulation of vibrating systems is a twofold problem that needs to include:

1. Modeling of the flow and hydrodynamics of the system to predict the shear rate on the membrane surface and flow characterization near the membrane.
2. Studying and modeling of the reverse transport mechanism of the particles away from the membrane surface in an oscillatory shear flow that is caused by a periodic movement of the membrane.

The literature on shear rate of vibrating membranes was reviewed in Chapter 2. This study focuses on the analytical and computational fluid dynamics (CFD) hydrodynamic modeling of a longitudinally vibrating hollow fibre system. The prior studies are reviewed first in the following section. Asymptotic cases such as a single vibrating hollow fibre and two adjacent vibrating flat surfaces are then solved analytically. For a more complex system of a bundle of hollow fibres, computational fluid dynamics (CFD) modeling is performed and the results are

presented and compared with the analytical results. Finally, brief practical conclusions are drawn from the study.

5.3 Hydrodynamic Analysis

5.3.1 Analytical Solution for the Hydrodynamics of a Sinusoidal Vibrating Single Fibre

The laminar flow around the vibrating fibre is considered in this analysis. The continuity and Navier-Stokes equations are the governing equations for the problem. The boundary conditions consist of a vibrating cylindrical surface (fibre) and a hydrostatic boundary far away from the fibre. A cylindrical coordinate system is chosen to solve the problem (Figure 5.1).

Figure 5.1 Schematic diagram of geometry, boundary conditions and coordinate system for an axial vibrating fibre.

Because of axisymmetry, the dependence on the θ -direction can be omitted. It can be shown that the velocity in the r -direction (due to the suction through the membrane) is negligible in comparison with velocity in the z -direction (u) for

common MBR applications. Therefore, the governing equations and boundary conditions can be reduced to:

$$\frac{\partial u}{\partial t} = \nu \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial u}{\partial r} \right) \right] \quad (5.1)$$

$$B.C.1: \text{ at } r = r_o, \quad u = A\omega \cos(\omega t) \quad (5.2)$$

$$B.C.2: \text{ at } r \rightarrow \infty, \quad u = 0 \quad (5.3)$$

By scale analysis and nondimensionalizing, the governing equations and boundary conditions can be simplified to:

$$\alpha \frac{\partial u^*}{\partial t^*} = \frac{1}{r^*} \frac{\partial}{\partial r^*} \left(r^* \frac{\partial u^*}{\partial r^*} \right) \quad (5.4)$$

$$B.C.1: \text{ at } r^* = 1, \quad u^* = \cos(t^*) \quad (5.5)$$

$$B.C.2: \text{ at } r^* \rightarrow \infty, \quad u^* = 0 \quad (5.6)$$

where, $u^* = u/A\omega$, $r^* = r/r_o$ and $t^* = t\omega$ are dimensionless variables. r_o is the outer radius of the fibre, and t stands for time. A parameter, *Fibre roundness factor* (α), can be defined as:

$$\alpha = \frac{r_o^2 \omega}{\nu} \quad (5.7)$$

With larger values of α , the fibre behaviour approaches that of a flat surface.

To solve Equation (5.4), a separation of variables is used as follows with a periodic variation in time:

$$u^*(r^*, t^*) = \Re(u^{*\circ}(r^*)e^{it^*}) \quad (5.8)$$

where, $\Re$ denotes the real part of a complex function and $u^{*\circ}$ is a complex function of r^* . Substituting into Equation (5.4) yields:

$$\alpha \Re(iu^{*\circ} e^{it^*}) = \Re\left(\left[\frac{1}{r^*} \times \frac{d u^{*\circ}}{dr^*} + \frac{d^2 u^{*\circ}}{dr^{*2}}\right] e^{it^*}\right) \quad (5.9)$$

Hence, we can extract from Equation (5.9):

$$\alpha i u^{*\circ} = \frac{1}{r^*} \times \frac{d u^{*\circ}}{dr^*} + \frac{d^2 u^{*\circ}}{dr^{*2}} \quad (5.10)$$

Multiplying the equation by r^{*2} and using the change of variable $r^{**} = \beta r^*$, where $\beta^2 = -\alpha i$, Equation (5.10) can be rearranged to a Bessel type differential equation as below:

$$r^{**2} \frac{d^2 u^{*\circ}}{dr^{**2}} + r^{**} \frac{d u^{*\circ}}{dr^{**}} + r^{**2} u^{*\circ} = 0 \quad (5.11)$$

With the following boundary conditions:

$$B.C.1: \text{ at } r^{**} = \beta, \quad u^{*\circ} = 1 \quad (5.12)$$

$$B.C.2: \text{ at } r^{**} \rightarrow \infty, \quad u^{*\circ} = 0 \quad (5.13)$$

The general solution of this equation is in the form of:

$$u^{*\circ} = C J_0(\beta r^*) + D Y_0(\beta r^*) \quad (5.14)$$

where, J_0 and Y_0 are 0th order Bessel's functions of the first and second kind, respectively. In Equation (5.14) C and D are complex constants, so each of them consists of 2 unknowns. Consequently, 4 unknowns are to be found in total: c_1 , c_2 , d_1 and d_2 , where:

$$\begin{cases} C = c_1 + c_2 i \\ D = d_1 + d_2 i \end{cases} \quad (5.15)$$

Also, it should be noted that $(\beta.r^*)$ and β are both complex arguments, resulting in two components for the Bessel functions and two equations for each boundary condition. Substituting Equations (5.14) and (5.15) in Equations (5.12) and (5.13) yields:

$$\begin{bmatrix} \Re(J_0(\beta)) & -Im(J_0(\beta)) & \Re(Y_0(\beta)) & -Im(Y_0(\beta)) \\ Im(J_0(\beta)) & \Re(J_0(\beta)) & Im(Y_0(\beta)) & \Re(Y_0(\beta)) \\ \lim_{r^* \rightarrow \infty} \Re(J_0(\beta r^*)) & -\lim_{r^* \rightarrow \infty} Im(J_0(\beta r^*)) & \lim_{r^* \rightarrow \infty} \Re(Y_0(\beta r^*)) & -\lim_{r^* \rightarrow \infty} Im(Y_0(\beta r^*)) \\ \lim_{r^* \rightarrow \infty} Im(J_0(\beta r^*)) & \lim_{r^* \rightarrow \infty} \Re(J_0(\beta r^*)) & \lim_{r^* \rightarrow \infty} Im(Y_0(\beta r^*)) & \lim_{r^* \rightarrow \infty} \Re(Y_0(\beta r^*)) \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ d_1 \\ d_2 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (5.16)$$

where, Equation (5.16) is the matrix form of the boundary conditions. The boundary conditions approaching infinity (i.e. the last two B.C.s in Equation (5.16)) can be used to find the constants. By using the approximations of Bessel functions for large complex arguments [11], it can be shown that:

$$\lim_{r^* \rightarrow \infty} \Re(J_0(\beta r^*)) = -\lim_{r^* \rightarrow \infty} Im(Y_0(\beta r^*)) \quad (5.17)$$

$$\lim_{r^* \rightarrow \infty} \Re(Y_0(\beta r^*)) = \lim_{r^* \rightarrow \infty} Im(J_0(\beta r^*)) \quad (5.18)$$

Substituting Equations (5.17) and (5.18) in the third and fourth boundary conditions in Equation (5.16), d_1 and d_2 can be obtained as:

$$d_1 = c_2 \quad (5.19)$$

$$d_2 = -c_1 \quad (5.20)$$

As a result, only two unknown constants remain which can be calculated from the two first boundary conditions of Equation (5.16) for different values of β . After finding C and D for a given α , the final solution for u^* can be obtained by Equation (5.14). Differentiating u^* with respect to r^* gives us the dimensionless shear rate γ^* :

$$\gamma^* = \Re([C\beta J_{-1}(\beta r^*) + D\beta Y_{-1}(\beta r^*)]e^{it^*}) \quad (5.21)$$

where, J_{-1} and Y_{-1} are -1st order Bessel functions of the first and second kind, respectively. The dimensionless shear rate on the surface of the membrane, γ_w^* , can then be computed by setting $r^* = 1$:

$$\gamma_w^* = \Re([C\beta J_{-1}(\beta) + D\beta Y_{-1}(\beta)]e^{it^*}) \quad (5.22)$$

Equation (5.22) can be recast to a more physically understandable form as follows:

$$\gamma_w^* = \gamma_{w,max}^* \cos(t^* - \varphi) \quad (5.23)$$

where the maximum dimensionless wall shear rate $\gamma_{w,max}^*$ is:

$$\gamma_{w,max}^* = \sqrt{\Re^2([C\beta J_{-1}(\beta) + D\beta Y_{-1}(\beta)]) + Im^2([C\beta J_{-1}(\beta) + D\beta Y_{-1}(\beta)])} \quad (5.24)$$

and the phase delay φ of the wall stress relative to the wall velocity is:

$$\varphi = \tan^{-1} \frac{Im(C\beta J_{-1}(\beta) + D\beta Y_{-1}(\beta))}{\Re(C\beta J_{-1}(\beta) + D\beta Y_{-1}(\beta))} \quad (5.25)$$

The wall shear rate can be calculated from the dimensionless shear rate as follows:

$$\gamma_w = \frac{A\omega}{r_0} \gamma_w^* \quad (5.26)$$

The maximum dimensionless wall shear $\gamma_{w,max}^*$ rate and the phase delay φ are calculated for different values of α . and the results are compared with the results from the Cartesian solution (Equation (2.25)) in the results section.

5.3.2 Analytical Solution for Optimizing the Distance between Two Vibrating Surfaces

Here, another asymptotic case of the flow between two vibrating flat surfaces is solved analytically to examine the effect of the distance between two surfaces on the resulting wall shear rate. The geometry, boundary conditions and Cartesian coordinate system used, are schematically shown in Figure 5.2. The flow can be considered as unidirectional flow and the only component of velocity is u in the direction of x . The continuity and Navier-Stokes equations reduce to:

$$\frac{\partial u}{\partial t} = \nu \frac{\partial^2 u}{\partial y^2} \quad (5.27)$$

With the following boundary conditions:

$$B.C.1: \text{ at } y = 0, \quad \frac{\partial u}{\partial y} = 0 \quad (5.28)$$

$$B.C.2: \text{ at } y = H, \quad u = A\omega \cos(\omega t) \quad (5.29)$$

$$B.C.3: \text{ at } y = -H, \quad u = A\omega \cos(\omega t) \quad (5.30)$$

Figure 5.2 Schematic diagram of geometry, boundary conditions and coordinate system for two parallel vibrating surfaces.

Using $u^* = u/A\omega$, $y^* = y/H$, $t^* = t\omega$ and $\lambda = H^2\omega/\nu$ as dimensionless variables, and employing a separation of variables (similar to the case of a single hollow fibre) as follows:

$$u^*(y^*, t^*) = \Re(u^{*\circ}(y^*)e^{it^*}) \quad (5.31)$$

Equation (5.27) can then be recast to the following form:

$$\frac{d^2 u^{*\circ}}{dy^{*2}} - \lambda i u^{*\circ} = 0 \quad (5.32)$$

with the boundary conditions:

$$B.C. 1: \text{ at } y^* = 0, \quad \frac{du^{*\circ}}{dy^*} = 0 \quad (5.33)$$

$$B.C. 2: \text{ at } y^* = 1, \quad u^{*\circ} = 1 \quad (5.34)$$

$$B.C. 3: \text{ at } y^* = -1, \quad u^{*\circ} = 1 \quad (5.35)$$

The general solution of Equation (5.32) is in the form of:

$$u^{*\circ} = C_1 e^{\sqrt{\frac{\lambda}{2}}(1+i)y^*} + C_2 e^{-\sqrt{\frac{\lambda}{2}}(1+i)y^*} \quad (5.36)$$

where, C_1 and C_2 are complex constants. Substituting Equation (5.36) into the boundary conditions (Equations (5.33) to (5.34)) yields:

$$C_1 = C_2 = C = C_0 e^{i\theta} = \frac{1}{e^{\sqrt{\frac{\lambda}{2}}(1+i)} + e^{-\sqrt{\frac{\lambda}{2}}(1+i)}} \quad (5.37)$$

where, C_0 and θ are the magnitude and phase of C , respectively. After finding C for a given λ , by substituting Equation (5.36) in Equation (5.32), the final solution for u^* is obtained as:

$$u^*(y^*, t^*) = \Re([C e^{\sqrt{\frac{\lambda}{2}}(1+i)y^*} + C e^{-\sqrt{\frac{\lambda}{2}}(1+i)y^*}] e^{it^*}) \quad (5.38)$$

The dimensionless shear rate on the surface of the membrane can now be calculated by differentiating u^* with respect to y^* at $y^* = l$:

$$\gamma_w^* = \Re([C \sqrt{\frac{\lambda}{2}}(1+i) e^{\sqrt{\frac{\lambda}{2}}(1+i)y^*} - C \sqrt{\frac{\lambda}{2}}(1+i) e^{-\sqrt{\frac{\lambda}{2}}(1+i)y^*}] e^{it^*}) \quad (5.39)$$

The maximum wall shear rate for different values of amplitude A , frequency ω and membranes separation distance H is calculated and shown in the results section.

5.4 CFD Modeling

5.4.1 Computational Domain

Three-dimensional (3D) CFD simulations were performed in this study using the software FLUENT v6, to investigate the wall shear rate of a vibrating fibre bundle. Two different configurations, in line (Figure 5.3a) and staggered (Figure 5.3b), were examined. The cross sections of the computational domains are shown in Figure 5.3. Due to symmetry, only the hatched areas in the figure need to be considered as the computational domain.

Figure 5.3 Cross section of (a) in-line and (b) staggered layout of hollow fibres. Hatched areas are the computational domains for CFD modeling.

The GAMBIT software was used to mesh the domain of computation. Structured meshing is used to produce the meshes for both the cross section and longitudinal coordinates of the computational domain (Figure 5.4). Finer meshes were constructed near the membrane surface in order to resolve the wall shear with a higher level of accuracy. The length of the domain was 40 cm and the outer radius of the fibre r_o was 0.4 mm. The simulations were performed for different distances between the fibres, therefore different domains and meshes were developed for different distance cases.

For instance, the distance of 1.4 mm between two neighbour fibres (i.e. domain radial length is 0.7 mm) nodes were typically 1 mm apart along the domain in the z direction (Figure 5.4c) and the smallest distance between two adjacent nodes was almost 0.05 mm on the domain face. This case and the boundary conditions used in the model are also shown in Figure 5.4.

For the case of 0.06 mm (distance of 1.2 mm), 5 cells are used in the radial direction (i.e. the cell size of 0.012 in average). In the longitudinal direction, even smaller cell sizes were used (smaller than 1mm) to keep the aspect ratio in a reasonable

range. For other cases (0.4, 0.6, 1, 1.4 and 10 mm), minimally 8 cells were used in the r-direction.

Figure 5.4 Meshing and boundary conditions.

5.4.2 Solution Description

Unsteady state simulations were required to solve the continuity and Navier-Stokes equations in the computational domain because of the periodic nature of the flow. The flow regime was considered to be laminar. The segregated (pressure based) solver was chosen for the discretization of the governing equations. The pressure implicit with splitting of operators (PISO) algorithm was applied to couple the velocity and pressure parameters. To discretize the governing equations in space and time domains, first-order implicit and second-order upwind schemes were chosen respectively.

As shown in Figure 5.4, the surface of the hollow fibre was considered as the moving wall boundary condition that was vibrating with amplitude (A) of 1 cm and frequency (f) of 5 Hz. To set a periodic velocity for this wall, a user defined function (UDF) was written and “hooked” to the CFD model using the ‘DEFINE_PROFILE’ predefined macro.

5.5 Results and Discussion

5.5.1 Wall Shear Rate of a Vibrating Fibre

Dimensionless shear rates on the surface of a membrane (γ_w^*) are calculated for given values of α via Equation (5.30). To compare the cylindrical and Cartesian solutions (C.S.), the C.S. for the wall shear rate in Equation (2.25) is non-dimensionalized and rearranged as follows:

$$\frac{r_o \gamma_w}{A\omega} = \frac{v_0}{A\omega} \sqrt{\frac{\omega r_o^2}{\nu}} \cos\left(\omega t - \frac{3}{4} \pi\right) \quad (5.40)$$

Using the same dimensionless scale factors in Section 5.3.1, Equation (5.40) can be rewritten as:

$$\gamma_w^* = \alpha^{0.5} \cos\left(t^* - \frac{3}{4} \pi\right) \quad (5.41)$$

Thus, we can conclude that the C.S. maximum wall shear $\gamma_{w,max}^*$ is:

$$\gamma_{w,max}^* = \alpha^{0.5} \quad (5.42)$$

and the phase delay (φ) of wall shear rate relative to the wall velocity is:

$$\varphi = \frac{3}{4}\pi \quad (5.43)$$

The maximum dimensionless wall shear rates $\gamma^*_{w,max}$ obtained by the cylindrical solution and C.S. are listed in Table 5.1 and shown with respect to α in Figure 5.5 in Log-Log scale. It is evident again that with large values of α , the cylindrical solution approaches the Cartesian solution, and the assumption of a flat membrane surface is valid. For small values of α , however, relative errors up to 75% can be observed among the realistic range of parameters tested. The phase delay φ of the wall shear relative to the wall velocity is also listed in Table 5.1.

The phase delay between shear rate and the velocity of the membrane affects the hydrodynamic response of the system. The most important parameter that it influences is the energy dissipation in the flow (i.e. the amount of energy which is transferred to the flow from the vibrating surface due to the friction). The dissipation power (energy over the time) $P_{Dissipation}$ can be calculated by integrating over a complete cycle (T is the period of the vibration) as follows:

$$P_{Dissipation} = \frac{\int_t^{t+T} u \cdot \tau \cdot dt}{T} = \frac{\mu A^2 \omega^2}{2 r_o} \gamma^*_{max} \cos \varphi \quad (5.44)$$

which is proportional to cosine of phase delay ($\cos(\varphi)$).

Figure 5.5 $\gamma_{w,max}^*$ vs. α obtained from the cylindrical solution and Cartesian solution in Log-Log scale.

The analytical solution, presented in Section 5.3.1, can also be used to investigate the effect of fibres' diameter on the resulting surface shear rate due to vibration in different frequencies. Table 5.2 presents some computed results in more accessible units. The comparison is between a small hollow fibre (diameter 0.6mm) and a large hollow fibre (diameter 3mm), for a given amplitude (10mm) at various frequencies. It is evident that the vibration of fibres with smaller diameter can lead to higher wall shear rates at a given amplitude and frequency. The effect is most pronounced at low frequencies with 1 Hz yielding a 34% enhancement that drops to 16% and 12% at frequencies of 5 and 10 Hz respectively. This unexpected advantage of smaller fibres may be worth exploiting but needs to be balanced against the increased lumen-side pressure drop and membrane integrity issues.

Table 5.1 Maximum wall shear rate obtained from the cylindrical solution $\gamma_{w,max}^*$ and C.S. $\alpha^{0.5}$ and the phase delay of wall shear rate (ϕ).

α	$\sqrt{\alpha}$	$\gamma_{w,max}^*$	ϕ	α	$\sqrt{\alpha}$	$\gamma_{w,max}^*$	ϕ
0.2	0.45	0.79	0.85π	9	3.00	3.36	0.78π
0.3	0.55	0.9	0.84π	10	3.16	3.53	0.78π
0.4	0.63	0.99	0.84π	20	4.47	4.83	0.77π
0.5	0.71	1.06	0.83π	30	5.48	5.84	0.77π
0.6	0.77	1.13	0.83π	40	6.32	6.69	0.77π
0.7	0.84	1.20	0.82π	50	7.07	7.43	0.76π
0.8	0.89	1.25	0.82π	60	7.75	8.11	0.76π
0.9	0.95	1.31	0.82π	70	8.37	8.73	0.76π
1	1.00	1.36	0.82π	80	8.94	9.30	0.76π
2	1.41	1.78	0.80π	90	9.49	9.85	0.76π
3	1.73	2.10	0.80π	100	10.00	10.36	0.76π
4	2.00	2.36	0.79π	200	14.14	14.50	0.76π
5	2.24	2.60	0.79π	300	17.32	17.68	0.76π
6	2.45	2.81	0.79π	400	20.00	20.35	0.76π
7	2.65	3.01	0.78π	500	22.36	22.70	0.76π
8	2.83	3.19	0.78π				

It can be seen in Table 5.2 that the assumed kinematic viscosity is $10^{-6} \text{ m}^2/\text{s}$. This value is almost the kinematic viscosity of pure water in 25°C . In MBR applications, the kinematic viscosity remains unchanged (almost 10^{-6}) lower than a critical value of mixed liquor suspended solids (MLSS). Higher than this critical value of MLSS the viscosity increases rapidly [13]. For typical MBR applications the MLSS is between 10 and 20 gr/L. In this range the kinematic viscosity may raise up to twice that of pure water (i.e. $2.0 \times 10^{-6} \text{ m}^2/\text{s}$). The effect of kinematic viscosity on the resulting shear rate on the hollow fibre's surface, and the relative error of Cartesian solution with different assumed kinematic viscosity are presented in Table 5.3.

These results of for hollow fibres with outer diameter of 1mm, a given amplitude (10mm) at various frequencies and with kinematic viscosities of 2.0×10^{-6} and 10^{-6} .

Table 5.2 Resulting wall shear rates for two vibrating fibres with different radii for different frequencies.

$A(mm)$	$r(mm)$	$f(Hz)$	$\nu(m^2/s)$	α	$\gamma_w(I/s)$
10	0.3	1	10^{-6}	0.565	232.4779
10	1.5	1	10^{-6}	14.137	172.6619
10	0.3	5	10^{-6}	2.827	2136.283
10	1.5	5	10^{-6}	70.686	1834.69
10	0.3	10	10^{-6}	5.655	5738.643
10	1.5	10	10^{-6}	141.372	5127.079

Table 5.3 shows that higher viscosities which mean smaller α values would result in higher errors (up to 40%) compared to fluids close to pure water in terms of viscosity.

5.5.2 Optimum Distance between Two Vibrating Surfaces

To evaluate the effect of the separation distance between two vibrating plates on the resulting wall shear rate of each plate, the wall shear rate is calculated by Equation (5.38). The maximum wall shear rate $\gamma_{w,max,two\ plates}^*$ is also compared with the maximum wall shear rate of a single vibrating plate $\gamma_{w,max,single\ plate}^*$, which can be calculated by Equation (2.26). The ratio of these two wall shear rates is plotted for different frequencies versus H in Figure 5.6.

Table 5.3 Resulting wall shear rates for a vibrating fibre with different kinematic viscosities for different frequencies.

$A(mm)$	$r(mm)$	$f(Hz)$	$\nu(m^2/s)$	α	$\gamma_w (1/s)$	<i>Relative error of Cartesian solution (%)</i>
10	0.5	1	$2 \cdot 10^{-6}$	0.785	156.64	40.7
10	0.5	1	10^{-6}	1.57	203.15	29
10	0.5	5	$2 \cdot 10^{-6}$	3.925	1474.1	18.4
10	0.5	5	10^{-6}	7.85	1989.45	13
10	0.5	10	$2 \cdot 10^{-6}$	7.855	3978.9	13
10	0.5	10	10^{-6}	15.71	5435.96	9.2

Figure 5.6 Effect of the distance between two vibrating plates on the resulting wall shear rate.

Figure 5.6 shows that an optimum distance exists between two vibrating plates in terms of the maximum wall shear rate. Thus, by adjusting the distance between two vibrating plates, up to 15% increase in wall shear rate can be achieved. Also, the amount of this increase is almost independent of the frequency of the vibration, although the optimum occurs at different distances for different frequencies.

5.5.3 CFD Simulations of Vibrating Bundles of Fibres

The average wall shear rate on the vibrating surface in the computational domain, which was introduced in Section 5.4, is obtained from the CFD simulations and presented in this section. The simulations were done for both the staggered and in-line configurations for different distances between the fibres in the configuration (0.12, 0.4, 0.6, 1, 1.4 and 10 mm). The results are presented in Figure 5.7. In this figure, the wall shear rate in the bundle of fibres and the wall shear rate of a single vibrating fibre, which can be calculated by Equation (5.24) (analytical solution), are plotted versus the distance between the fibres in the bundle for the staggered and in line configurations.

Similar to the case of vibration with two parallel flat-sheet membranes, it can be observed from Figure 5.7 that an optimum distance between the fibres in the fibres bundle exists that yields the maximum shear rate. Also, it is noticeable that when the fibres are far from each other (for instance $D-d=10$ mm), the CFD results agree with the analytical solution for a single vibrating fibre. Thus, the CFD results are validated by the analytical solution in these figures.

Another important point is that when the fibres are too close to each other, the wall shear rate decreases significantly. To avoid this decrease, the distance between the fibres should be kept larger than a specific value which can be obtained from the figure. The staggered configuration provides higher wall shear rate rather than the in line configuration with the optimum distance of fibres.

Figure 5.7 The wall shear rate for fibre bundles with staggered and in line configuration vs. the distance between the fibres.

Figure 5.8 displays that the shear rate distribution on the surface of the vibrating fibres in a bundle, for different distances between the fibres. As shown in Figure 5.8a and b, for the distance of 0.12 mm between adjacent fibres both in Inline and staggered configurations, the shear rate at the ends of the domains, where the distance to the adjacent fibres is smallest, is significantly smaller than the average over the whole surface. The same situation occurs for the distance of 0.4 mm between the fibres but in a smaller range (Figure 5.8c and d). By making the distance between the adjacent fibres big enough (ex. 1 mm), the shear rate becomes relatively uniform over the membrane surface as shown in Figure 5.8e and f. Therefore, the shear rate in bundles with high packing density (small distance between fibres), varies significantly with position. This means that when using high packing density in vibrating fibre bundles some parts of the fibres' surface would not benefit from vibrations and the wall shear rate would be up to 40% lower than the average; these regions would be the potential points to be fouled.

Figure 5.8 Membrane wall shear stress distribution for frequency of 5 Hz and fibre's radius of 0.4 mm for the following distances between the fibres and configuration: (a) staggered-0.12 mm (b) Inline-0.12 mm (c) staggered-0.4 mm (d) Inline-0.4 mm (e) staggered-1 mm (f) Inline-1 mm.

5.6 Conclusions

This study examines analytically and numerically the flow characteristics around vibrating membranes and the associated wall shear rates. The following conclusions can be drawn:

- (a) An analytical solution was developed for laminar flows around a vibrating hollow fibre. The solution was expressed in a dimensionless form with a dimensionless factor α . The Cartesian solution for a flat sheet membrane used by others as approximation, was compared to the new solution. It was found that for large α (i.e. large r_o), the new solution approaches the Cartesian solution, thus, the use of the Cartesian solution and its associated assumptions are acceptable. With small α (small fibres and mixtures with

high viscosity), however, a relative error of up to 75% (ex. $\alpha=0.2$) can arise with the Cartesian solution with the typical range of parameters tested. The phase delay of the wall shear rate relative to the wall velocity was also calculated for different values of α . In addition, the analytical solution clearly illustrates that the vibration of fibres with smaller diameters can lead to higher wall shear rates.

- (b) In a system that contains two vibrating flat sheet membranes, the analytical result shows that an optimum distance exists that can achieve the maximum wall shear rate. The trend of the analytical results for two vibrating flat membranes is similar to CFD results for vibrating fibres in a bundle.
- (c) The CFD simulations of a hollow fibres bundle show that the wall shear rate depends significantly on the distance between the fibres. Based on the results, high density packed bundles would not be recommended for dynamic shear-enhanced filtration. Regarding the configuration, the staggered configuration with the optimum distance of fibres in general provides higher wall shear rates than the in line configuration, but this impact is minor and exists for distances less than 1.4 mm.

Chapter 6

Hydrodynamic Analysis of Transverse Oscillating Hollow Fibre Membranes

6.1 Abstract

Membrane systems are now widely used in water treatment processes. To reduce membrane fouling, a possible approach is to oscillate the membranes so that the membrane surface is subjected to surface shear stresses. The oscillation of the membrane can be done longitudinally or transversely. For transverse oscillation, in addition to the shear flow around the membrane fibres, some secondary flows also exist. These secondary flows have been neglected for fouling analysis in oscillating membrane systems in the current literature, but they are very important as they act in a manner similar to cross flow filtration, i.e. the secondary flow helps wash the particles outside the concentration boundary layer and reduce deposition.

In this study, the secondary flows induced by transversely oscillating membrane fibres were analysed numerically. The governing equations of the system were solved using the Fluid Flow module of COMSOL Multiphysics (Version 4.3). The two-dimensional Time Dependant solver was used, and a grid sensitivity analysis was performed to ensure that the results were independent of the grid size.

The computation results consisted of the velocity profile, shear rate, pressure and flow circulation around the fibre. In addition, the hydrodynamics of different membrane fibre layouts, such as bundle and curtain, were studied and compared.

To validate the CFD simulation results, the velocity along the oscillating axis and the flow circulation were compared with the experimental data acquired using the laser imaging technique of Particle Image Velocimetry (PIV) in the laboratory at different Reynolds numbers. The computational results generally showed a good agreement with the experimental observations.

6.2 Introduction

It has been proven that the shear rate on the surface of the membrane is the key factor for the back transport of supermicron particles (larger than 3 μm) in crossflow microfiltration (Belfort, et al. 1994; Li, et al. 2000; Zydney and Colton 1986). Similarly, for the oscillating membrane systems, many studies have recently been made to determine the shear rate as the dominant factor for the fouling control (Jaffrin 2008). The shear rate has been calculated near the longitudinal oscillating membrane surface for flat membranes (Beier, et al. 2006) and hollow fibres membranes (Zamani, et al. 2013).

One factor that receives less attention for the fouling control in oscillating membrane systems, is the role of secondary flows which can act as the washing stream or the mixing flow. For cross flow filtration, the bulk flow induces the shear rate near the membrane surface and washes the particles outside the concentration boundary layer simultaneously. Figure 6.1 illustrates these two roles schematically.

The velocity varies from zero (on the membrane surface) to the bulk flow velocity U (out of the momentum boundary layer with thickness δ_M) and the concentration varies from wall concentration c_w to the bulk flow concentration c_b (out of the concentration boundary layer with thickness δ_C). As shown in this figure, the back transport by diffusion with the coefficient of D exists in the momentum boundary layer due to the velocity gradient, or that is the shear rate. There is also another washing off due to the fluid velocity at some distance from the surface. This stream is not very effective close to surface because of the no slip condition at the membrane surface; on the other hand, the back transport diffusion coefficient has its largest value at the surface. It should be noted that for mass transport in liquids, Schmidt number ($Sc=\mu/\rho D$) is mostly much larger than 1 and thus the concentration boundary layer thickness (δ_C) is usually much smaller than the momentum boundary layer thickness (δ_M) (Deen 1998).

Figure 6.1 Schematic diagram of mechanisms involved in the fouling control in a crossflow filtration process.

To diminish the concentration polarization of supermicron particles two hydrodynamic conditions are required:

- 1- Sufficiently high induced shear rate on the membrane surface to produce back diffusion of the particles away from the surface.
- 2- Continuous and steady washing or secondary flows that can keep moving particles from the regions near the membrane surface back to the bulk fluid environment. It should be noted that these flows cannot have a periodic nature, otherwise the washing effect would be ineffective.

For a longitudinal oscillating surface (of a flat membrane or a hollow fibre membrane), the oscillation is parallel to the surface. The fluid velocity profile (caused by the vibrating surface) is thus periodic and has a general form of (Zamani, et al. 2013):

$$u(y, t) = u_{max}(y) \cos(\omega t - \varphi) \quad (6.1)$$

The geometry, boundary conditions and coordinate system are shown in Figure 6.2. $u_{max}(y)$ is the velocity amplitude of the fluid at a distance of y from the surface. It varies from $A\omega$ to zero in the region of influence of the vibration surface with thickness of δ_M (Krantz 2007). Hence, the membrane surface is vibrating with velocity of $A\omega \cos(\omega t)$.

The velocity for an ideal longitudinal vibration in this boundary layer is periodic, and the average velocity is zero over an oscillation period. Thus, a net washing flow does not exist (Beier, et al. 2006; Zamani, et al. 2013). Therefore, although there is a back transport diffusion mechanism because of the existence of shear rate in the region of the influence, as the particles are pushed back to the bulk flow they come toward the membrane again due to the convection of permeate flux. The reason is

that the shear rate exists up to a certain distance (inside the region of influence) but the permeate effect is effective even outside this region (Figure 6.2). As a result, the thickness of the concentration polarization layer increases continuously and the deposition of particles on the surface occurs very fast. In this case, a pure longitudinal vibrating membrane filtration is similar to a dead-end filtration unless there are some other secondary flows to wash off the particles in outer distances.

Figure 6.2 Schematic representation of the vibration membrane surface and the region of influence of vibration, growing concentration polarization layer and associated boundary conditions.

The theory and prior studies on transverse vibrating cylinder and fibres are reviewed in the next section. To study the hydrodynamics of transverse vibrating fibres specifically in membrane applications, some criteria will be suggested and the results will be presented.

6.3 Theory and Prior Studies

When a cylinder oscillates transversely (perpendicularly to its axis) in a stationary fluid or a flow oscillating about a fixed cylinder, a relative unsteady streaming flow occurs around the cylinder that can exert a reaction force on the cylinder. This type of flows is of interest to many areas of engineering such as heat exchangers design, offshore engineering, aerodynamics and most recently membrane technology.

Figure 6.3 shows a cylinder (with diameter of d) that oscillates transversely and sinusoidally with an absolute velocity of $A\omega \cos(\omega t)$. For a long enough cylinder and in laminar flow regime, the flow around the cylinder can be considered as two-dimensional streaming flow with vortices and secondary flows that are schematically shown in Figure 6.3. In this case, by choosing a non-inertial Cartesian coordinate system fixed to the centre of the cylinder cross section (Figure 6.3), the governing equations (continuity and Navier-Stokes equations can be written as follows:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (6.2)$$

$$\rho \frac{\partial u}{\partial t} + \rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} = -\frac{\partial p}{\partial x} - \rho(-A\omega^2 \sin(\omega t)) + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \quad (6.3)$$

$$\rho \frac{\partial v}{\partial t} + \rho u \frac{\partial v}{\partial x} + \rho v \frac{\partial v}{\partial y} = -\frac{\partial p}{\partial y} + \mu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) \quad (6.4)$$

where u and v are the velocity components in x - and y -directions, p is the pressure, μ and ρ are the dynamic viscosity and density of the fluid respectively. The second term of the right side of Equation (6.3), namely $-\rho(-A\omega^2 \sin(\omega t))$, is due to the

acceleration of the non-inertial coordinate system. This term has the form of $(-\rho a)$ where a is the acceleration of the coordinate system and equals to $-A\omega^2 \sin(\omega t)$ for this system. The boundary conditions of this system relative to the chosen coordinate system are as follows:

$$u, v = 0 \quad \text{at } x^2 + y^2 = \frac{d^2}{4} \quad (6.5)$$

$$u = -A\omega \cos(\omega t), v = 0 \quad \text{as } x^2 + y^2 \rightarrow \infty \quad (6.6)$$

By introducing dimensionless variables $x^*=x/d$, $y^*=y/d$, $t^*=t/T$, $u^*=u/A\omega$, $v^*=v/A\omega$ and $p^*=p/\rho A^2 \omega^2$, the governing equations change to:

$$\frac{\partial u^*}{\partial x^*} + \frac{\partial v^*}{\partial y^*} = 0 \quad (6.7)$$

$$\frac{1}{KC} \frac{\partial u^*}{\partial t^*} + u^* \frac{\partial u^*}{\partial x^*} + v^* \frac{\partial u^*}{\partial y^*} = -\frac{\partial p^*}{\partial x^*} + \frac{2\pi}{KC} \sin(2\pi t^*) + \frac{1}{Re} \left(\frac{\partial^2 u^*}{\partial x^{*2}} + \frac{\partial^2 u^*}{\partial y^{*2}} \right) \quad (6.8)$$

$$\frac{1}{KC} \frac{\partial v^*}{\partial t^*} + u^* \frac{\partial v^*}{\partial x^*} + v^* \frac{\partial v^*}{\partial y^*} = -\frac{\partial p^*}{\partial y^*} + \frac{1}{Re} \left(\frac{\partial^2 v^*}{\partial x^{*2}} + \frac{\partial^2 v^*}{\partial y^{*2}} \right) \quad (6.9)$$

with the following boundary conditions:

$$u^*, v^* = 0 \quad \text{at } x^{*2} + y^{*2} = \frac{1}{4} \quad (6.10)$$

$$u^* = -\cos(2\pi t^*), v^* = 0 \quad \text{as } x^{*2} + y^{*2} \rightarrow \infty \quad (6.11)$$

It can be inferred from Equations (6.8) and (6.9) that the flow is governed by two dimensionless groups (parameters): Keulegan-Carpenter number ($KC=2\pi A/d$) and Reynolds number ($Re=\rho A\omega d/\mu$). In some studies, the ratio of Re and KC (i.e., Re/KC) has been used as one of the dominant parameters that can influence the hydrodynamics. This parameter is called the Stokes number ($St=f d^2/\mu$). However,

only two of these three parameters (i.e., Re , KC and St) are needed to describe the problem. Equations (6.7) to (6.11) are used as the governing equations in the numerical solution in this study.

Figure 6.3 Oscillating cylinder in a stationary fluid: the geometry, oscillating non-inertial coordinate system chosen in this study and two-dimensional streaming flow and vortices and simplified secondary flows around the cylinder in quarter 4.

Prior studies on this subject, namely perpendicular oscillating flows relative to a cylinder, typically had two main focuses: to calculate the force exerted on the cylinder by the flow (Bearman, et al. 1985; Borthwick 1989; Keulegan and Carpenter 1958; Morison, et al. 1950; Sarpkaya 1986; Stokes 1851; Wang 1968) and to qualitatively investigate the flow pattern around the cylinder in different flow regimes (Borthwick 1989; Honji 1981; Keulegan and Carpenter 1958; Lam, et al. 2010; Sarpkaya 1986; Tatsuno and Bearman 1990; Williamson 1985).

Stokes (1851) showed that the force exerted on an oscillating pendulum in a viscous fluid comprises of a drag component, which involves the acceleration of the oscillating body, and an inertia component, which involves the velocity of the body. Morison, et al. (1950) developed a general formulation for the force on a stationary cylindrical pile in an oscillating flow as follows:

$$F = \frac{1}{2}\rho d C_D u^2 + \frac{1}{4}\rho \pi d^2 C_M \frac{du}{dt} \quad (6.12)$$

where F is the exerted force on the pile per unit length, d is the pile diameter, u is the velocity of flow perpendicular to the pile axis, du/dt is the acceleration of the flow, C_D and C_M are the drag and inertia coefficients, respectively. Since then, many researchers tried to determine the values of C_D and C_M experimentally and theoretically. Keulegan and Carpenter (1958) showed that C_D and C_M , for an oscillating cylinder in a stationary fluid depends on KC and Re numbers using dimensional reasoning. In other words, they introduced the KC dimensionless group as an important parameter on the hydrodynamics of this problem. Wang (1968) used outer and inner expansion for vibrating cylinders to examine the validity of the Stokes solution at low Reynolds numbers. Bearman, et al. (1985) compared the theoretical and experimental results of the exerted force on cylinders in small amplitude (i.e., small KC values) oscillating flows, and found that the theoretical results match the experimental results at small KC numbers and moderately high values of St number. Sarpkaya (1986) compared the experimental results for C_D and C_M with the theoretical predictions by Stokes (1851) and Wang (1968), and showed that the KC number at which C_D deviates from Stokes and Wang predictions is very close to the critical KC number at which flow instability occurs. Borthwick (1989)

performed some experiments to measure the forces on a sinusoidally oscillating cylinder in a stationary fluid, for Re numbers between 50000 and 300000 and KC number between 0.8 and 12.1. He showed that the vortex shedding and the increase in C_D coefficient occur for KC numbers larger than 5 (Borthwick 1989).

In terms of the flow patterns induced by an oscillating cylinder, many researchers tried to explore repeatable flow patterns in different ranges of KC and Re numbers. Keulegan and Carpenter (1958) examined the flow pattern around a cylinder in an oscillating flow by injecting a coloured liquid jet near one side of the cylinder for different values of KC number. Honji (1981) performed several experiments to study the streaked flow patterns induced around an oscillating cylinder. He found that at large values of oscillation amplitude, three-dimensional mushroom shape vortices were produced in the direction of oscillation. Williamson (1985) identified four repeatable flow patterns around an oscillating cylinder: pairing of attached vortices, single pair, double pairs and three and more pairs. The first pattern, namely pairing of attached vortices (which can be considered as a laminar symmetric attached stable two-dimensional flow) occurred at $0 < KC < 4$ and in a fixed $St=730$ (i.e., $0 < Re < 2900$). Similarly, Sarpkaya (1986) classified the flow patterns, induced by oscillating flow around a cylinder, into 4 types. The critical Re number for separation of flow and vortex shedding was around $Re=750$ at low KC numbers (Sarpkaya 1986). Tatsuno and Bearman (1990) identified eight different flow regimes in different ranges of KC number.

By using relatively more modern techniques such as particle image velocimetry (PIV), researchers are enabled to investigate quantitatively the induced velocity

field in oscillating systems. Lam, et al. (2010) studied the flow pattern around a vibrating cylinder in more details for KC number between 8 and 36 and with a constant Re number kept at 2400. Different modes of flow patterns were identified by them. Iwai, et al. (2004) found that for oscillating flows around a cylinder with large KC numbers (i.e., $63 < KC < 240$), the flow remains laminar and with Re numbers smaller than 810.

Oscillating submerged hollow fibre membranes, either longitudinally or transversely, has been proven to be an effective approach to mitigate the membrane fouling. Kola, et al. (2012) used transverse vibration in a submerged hollow fibre membrane system, and investigated the effect of vibration on the fouling rate in the system. They used Equation (6.12) to calculate the force variation over an oscillation period as well as the required energy to generate the oscillation. However, there is still a lack of study on the quantitative flow characteristics around a transversely oscillating hollow fibre membrane (or an oscillating bundle of fibres) including the pressure distribution (p), shear rate on the membrane surface (γ), streaming flow and secondary flows magnitude. To study the streaming flow around a transverse oscillating fibre quantitatively, the time-mean velocity ($\bar{u}$) over a period of an oscillation on the x -axis (axis of oscillation direction as shown in Figure 6.3) needs to be determined. $\bar{u}$ is defined as follows:

$$\bar{u} = \frac{\int_{t_0}^{t_0+T} u dt}{T} \quad (6.13)$$

where t_0 is an arbitrary time. It will be shown that $\bar{u}$ on the x -axis has non-zero values away from the fibre (unlike the longitudinal oscillation) which implies a

continuous streaming away from a transverse oscillating fibre that can help wash off the rejected particles from the fibre.

The time-mean circulation ($\bar{\Gamma}$) over an oscillation period is used in this study as a measure of the existence of secondary flows (or vortices) and their intensity. The time-mean circulation ($\bar{\Gamma}$) is calculated around a square which is placed in only one of the quarters of the domain (Figure 6.3). Due to symmetry, if the circulation is calculated over the whole domain, the resulting value will be zero. Here, $\bar{\Gamma}$ is calculated only around the square with dimensions of $0 < x < 5d$ and $0 < y < 5d$, as shown in Figure 6.4. The mean circulation can be calculated either by using line integral:

$$\bar{\Gamma} = \oint_{\text{Line 1}} u \, dx + \oint_{\text{Line 2}} v \, dy + \oint_{\text{Line 3}} -u \, dx + \oint_{\text{Line 4}} -v \, dy \quad (6.14)$$

or by using surface integral over the square surface:

$$\bar{\Gamma} = \iint_{\text{Square}} \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) dS \quad (6.14)$$

where the term $(\partial v / \partial x - \partial u / \partial y)$ is the two-dimensional vorticity and dS is the area element of the surface integration over the square.

In this study, computational fluid dynamics (CFD) was used to simulate the flow around different submerged hollow fibre systems and to calculate the induced quantities (i.e., time-mean velocity, circulation and surface-averaged shear rate at the oscillating cylinder surface) in these systems. Some of the CFD results were verified by comparing them with experimental results obtained by PIV. Moreover,

the hydrodynamics of different fibre layouts (single fibre, curtain of fibres and bundle of fibres) was compared, and the best layout was suggested. Eventually, a transverse oscillating fibre system and a longitudinal oscillating fibre system were compared in terms of the hydrodynamic parameters, fouling rate and energy consumption by using CFD and experimental results.

More details about the CFD modeling and experimental apparatus are given in the following sections.

Figure 6.4 Schematic representation of calculating the time-mean circulation around a square located in Quarter 1 as a measure of the intensity of the vortices around the oscillating fibre.

6.4 Materials and Methods

6.4.1 PIV Experimental Apparatus

The PIV technique was successfully employed to obtain the 2D velocity field for the cross-section of the flow around an oscillating rod. The PIV apparatus used in this chapter was similar to the one described in Chapter 3 with some differences

which is explained here. The schematic diagram of the PIV experiment is shown in Figure 6.5a. The photograph of the experimental apparatus is shown in Figure 6.5b.

A polyethylene dark rod with a diameter of 1 cm (Figure 6.5c) and length of 25 cm was submerged in a water tank with dimensions of 400 mm (length) $\times$ 450 mm (width) $\times$ 500 mm (height). The rod was fixed horizontally to a holder which was oscillating vertically by a slider-crank mechanism running by a DC brushless motor (VEXTA, Oriental Motor Co. Ltd.). The laser sheet intersected the middle of the vibrating rod perpendicularly as shown in Figure 6.5a. A picture captured by the CCD camera, for calibration purpose, is shown in Figure 6.5c.

To study an unsteady flow, several sets of double frame images can be taken as needed. In this study, 8 sets of double frame images were taken in each period of the rod oscillation (totally 300 sets). To remove the possible incorrect velocity vectors in the velocity vector maps, the results were post-processing using three validation methods of “range validation”, “moving-average validation” and “peak validation” (Raffel, et al. 1992).

6.4.2 Vibrating Hollow Fibre Experiments

The performances of the systems with transversely and longitudinally oscillating submerged hollow fibres were compared in this study. The setup included the vibration mechanism and the permeate measurement equipment. The vibrating setup was similar to the PIV experiment. Longitudinal or transverse vibrations were obtained by positioning the fibres vertically or horizontally, respectively. The centre positions of the vertical and horizontal fibres were identical. The membrane module

holder was driven by a brushless DC motor (BXM 6200-A, Oriental Motor Co., Ltd) with a crank moving mechanism. The vibration amplitude was set at either 24 or 28 mm, while the vibration frequency could be varied from 1 to 2 Hz. The permeate flow was controlled by a master flex peristaltic pump (Cole-Parmer Instrument Company) together with a needle valve (Swagelok). The suction pressure was measured with a pressure transducer (Precision digital), and the permeate flux with a digital balance (UX 6200H, Shimadzu).

Figure 6.5 (a) Schematic diagram of the PIV experiment; (b) photograph of the oscillating mechanism, the rod holder, rod and glass tank; (c) the rod from the CCD camera point of view.

PAN hollow fibres were used in these experiments as explained in Chapter 3.

Inorganic Bentonite (Sigma-Aldrich) was adopted as the fouling agent. It represented an inorganic feed and has been widely used in the microfiltration. The formula of Bentonite is $\text{H}_2\text{Al}_2\text{O}_6\text{Si}$, with the molecular weight is 180.1 g/mol. The average particle diameter was 5.83 μm in the experiments with a relative density of 2.4 g/cm^3 . Before the experiments, Bentonite particles were added to tap water and mixed with a magnetic stirrer at 300 rpm for 30 min. After complete mixing, they were diluted to make a 4 g/L suspension (pH 6.0-9.0).

6.4.3 CFD Simulation

The flow around the oscillating cylinder was assumed laminar, stable, unsteady and two-dimensional (2D) as shown in Figure 6.3. By comparing the experimental and CFD results, it will be shown that these assumptions are valid for a certain range of Reynolds number. The fluid flow module of Comsol 4.3 multi-physics was employed to build the geometry, mesh and solve the system of equations. In fact, COMSOL has the capability of using moving coordinate systems and employing the equations in non-inertial coordinate systems. An oscillating coordinate system is non-inertial as it does not have a constant velocity. If FLUENT is used instead, moving boundaries and moving meshes need to be established which require a very long computational time. As a result, COMSOL was employed for this simulation.

Time-dependent simulations were conducted for all cases using the direct solver (PARDISO), ‘nested dissection multithreaded’ for reordering algorithm, and ‘Auto’ for scheduling method provided by Comsol. The time steps and iterations for

the variables were controlled automatically by the software to reach the event tolerance of 0.01.

6.4.3.1 Computational Domain and Boundary Conditions

Many cases with different geometry and sizes were studied. To give a better illustration of the computational domain and meshing, the domain of a single vibrating fibre is shown in Figure 6.6a. An unstructured mesh with triangular elements was used to discretize the computational domain. Finer graded meshes were located at the surroundings of membrane fibres (Figure 6.6b). This was necessary in order to capture the hydrodynamic behaviour of the flows near the fibres. A size function was utilized to ensure a smooth growth of the grid size in highly curved regions. This meshing strategy improved the mesh quality, and also reduced the mesh quantity and thereby saved computing time.

Figure 6.6 The geometry, meshing and boundary conditions for a simulation case: (a) the whole domain; (b) close to the oscillating fibre.

The domain was considered liquid (water) at the room temperature of 25 °C and incompressible. For the initial conditions, the liquid water and membrane fibre were still, in other words, the velocity for the domain was specified as 0. Moving wall condition was specified on the membrane surface by setting the moving velocity derived from the vibrating amplitude and frequency (Figure 6.6b). The domain boundaries were specified as open boundaries in the present simulations.

6.4.3.2 Grid independence test

As the simulation results can be highly dependent on the grid strategy, it is thus critically important that the results are grid independent in a numerical simulation. Hence, a grid independence test was conducted using nine predefined meshing sizes which are listed in Table 6.1. In the mesh independency evaluation, tests were performed for a single transverse oscillating fibre (with outer diameter of 2mm) which oscillated with amplitude of 1 cm and frequency of 2 Hz. Since the shear rate at the fibre surface was too sensitive to the grid size, the surface-averaged shear rate ($\bar{\gamma}$) over the surface of the vibrating fibre was chosen and reported within the forth oscillation period (between $t=4T$ and $t=5T$) using different meshing schemes. The results were compared in Figure 6.7. It is noted that from the mesh scheme of ‘fine’ and onward to ‘extremely fine’, the numerical average shear rate tended to stabilize with only slight differences. Hence, to ensure a solution within 1% accuracy in the simulations, ‘extra fine’ scheme was used in all the simulations.

Table 6.1 Mesh properties of grid independence test for studied case.

Mesh Scheme	Minimum Element Size (m)	Number of Elements
Extremely coarse	7e-04	402
Extra coarse	5e-04	538
Coarser	4e-04	888
Coarse	3e-04	1576
Normal	2e-04	1996
Fine	1e-04	3464
Finer	4e-05	4576
Extra fine	1.5e-05	7218
Extremely fine	2e-06	18960

Figure 6.7 Grid independence test for surface-averaged shear rate on the oscillating fibre surface within the 4th oscillation period.

6.5 Results and Discussion

As mentioned before, the continuous streaming and secondary flows (in contrast with periodic streaming and secondary flows) can help wash off the rejected

particles from the membrane surface. For a transverse oscillating fibre membrane, this continuous streaming flow exists. The hydrodynamics of such a system was studied here experimentally using the PIV method and numerically. Figure 6.8 shows the continuous streaming flows away from the vibrating fibre (regardless the instantaneous velocity of the fibre which is shown in the legend of the Figure 6.8). Figure 6.8a and b show the results from the CFD simulations and PIV experiments for the same oscillating cylinder case. The vortices, which can help mix the concentrated fluid near the membrane surface with less concentrated fluid away from the membrane surface, can be observed in Figure 6.8.

Figure 6.8 The streaming flows away from the vibrating surface and the induced vortices at two different times: (a) PIV experiments; (b) CFD simulations.

To study the streaming flows and vortices and other hydrodynamic parameters quantitatively, some criteria have been introduced in the previous sections. The results are presented here.

6.5.1 Validation of CFD Simulations by PIV Results

The time-mean velocity ($\bar{u}$) and time-mean circulation ($\bar{\Gamma}$), obtained by CFD simulations and PIV experiments, for an oscillating rod (with diameter of 1 cm) are compared and summarized in Figures 6.9 and 6.10. The rod oscillated with an amplitude (A) of 1 cm and frequencies (f) of 15, 30, 60, 90, and 120 rpm (or $f=0.25$, 0.5, 1, 1.5 and 2 Hz). The time-mean parameters (i.e., $\bar{u}$ and $\bar{\Gamma}$) were calculated within the 4th oscillation (i.e., between $t=4T$ and $t=5T$). Since the rod was moving, it was too difficult to measure the velocities very close to the rod surface in PIV experiments. Hence, the shear rates cannot be determined directly from the PV experiments.

Figure 6.9 shows the changes of $\bar{u}$ (averaged for $4T < t < 5T$) along the vibrating axis (x -axis). In the figure, the data points started from $x=0.005$ m (i.e., the surface of oscillating rod) to $x=0.05$ m (i.e., 5 times the rod diameter). In Figure 6.9a-c, namely for $f = 15, 30$ and 60 rpm, the CFD simulation results were in qualitative agreement in terms of the flow pattern (having two peaks) and the maximum values (having relative errors less than 10 %). In Figure 6.9d ($f = 90$ rpm) a 30 % relative error existed between the maximum values of CFD and PIV results. However, the flow pattern remained similar. Figure 6.9e ($f = 120$ rpm) shows that the CFD results were inconsistent with the PIV results, which implied that the flow assumptions made for the CFD simulation, namely being laminar, stable and two-dimensional,

were invalid for this case. It means that flow in higher frequencies such as 120 rpm may become unstable and turbulent.

Figure 6.10 confirms the trend observed in Figure 6.9. In other words, for frequencies up to 60 rpm, the $\bar{I}$ values (averaged within $4T < t < 5T$) calculated over a square in Quarter 1 with dimension of $5d$ ($0 < x < 5d$ and $0 < y < 5d$ as shown in Figure 6.4) were consistent between the CFD simulations and PIV experiments with relative errors less than 10 %. For $f = 90$ rpm, the relative error was over 35% and for $f = 120$ rpm, the relative error exceeded 70 %.

Overall, the assumption of laminar, stable and two-dimensional (2D) flow around the oscillating rod proved to be valid for frequencies up to 60 rpm, which was equivalent to Reynolds number (Re) values up to 600 (associated Re value with frequency of 60 rpm as $Re = \rho A \omega d / \mu = 1000 \text{ (kg/m}^3) \times 0.01 \text{ (m)} \times 2\pi \times 0.01 \text{ (m)} / 10^{-3} \text{ (kg/m s)} \approx 628$). For a typical oscillating fibre membrane system (with a typical diameter of 2 mm), the Re number would be much smaller than 600. Therefore, laminar 2D CFD simulations can be used accurately to study the hydrodynamics around oscillating hollow fibre membranes.

6.5.2 Gauge Pressure Variation for an Oscillating Fibre Membrane

In membrane applications, the permeate flux through the membrane is directly proportional to the transmembrane pressure (TMP) which is the pressure difference between two sides of the membrane (lumen and feed sides). For a transverse oscillating submerged hollow fibre, the pressure at the surface of the membrane

(feed side) fluctuates over the time duration because of the fibre motion relative to the still fluid.

CFD simulations were carried out to determine the pressure variations over the surface of the membrane and over time. For this purpose, a typical fibre membrane diameter (2 mm) that oscillated with $A=1$ cm and $f = 300$ rpm (which can be considered a high frequency) was considered.

Figure 6.9 CFD and PIV results of time-mean velocity $\bar{u}$ (averaged for $4T < t < 5T$) along the vibrating axis (x -axis) for an oscillating rod with diameter of 1 cm, amplitude (A) of 1cm and frequencies of: (a) 15; (b) 30; (c) 60; (d) 90 and (e) 120 rpm.

Figure 6.11 represents the variations of gauge pressure over the surface of the oscillating fibre (at different points specified at the legend of the figure) and for different times within the 4th oscillation. It should be noted that the gauge pressure

charts for $t = 4T$ and $t = 5T$ were the same, overlapping each other. The variation of the gauge pressure over the fibre surface and over the time period was less than 65 Pa. Thus, for a typical microfiltration application with a typical TMP of 10 kPa the variation of the gauge pressure is less than 1% of the applied TMP which is negligible.

Figure 6.10 CFD and PIV results and relative errors for time-mean circulation $\bar{\Gamma}$ (averaged for $4T < t < 5T$) in Quarter 1 and over an square with dimension of $5d$ for an oscillating rod with diameter of 1 cm and amplitude (A) of 1cm in different frequencies.

Figure 6.11 Gauge pressure distribution around the oscillating fibre for different times within the 4th oscillation period.

6.5.3 Hydrodynamic Comparison of Oscillating Fibre Membranes with Different Layouts

The hydrodynamics around oscillating fibres with different layouts are studied here by CFD simulations. The geometry, oscillation modes, chosen coordinate system and results of these simulations are summarized and presented in Table 6.2. Four different layouts of a transverse oscillating single fibre, curtain of fibres (with transverse in-plane oscillation), curtain of fibres (with transverse out-plane oscillation) and bundle of fibres (with transverse oscillation) were simulated.

The fibre diameter (d) was 2 mm, the oscillation amplitude (A) was 1 cm and the oscillation frequency (f) was 60 rpm. The distances between fibres in each layout are shown in Table 6.2.

The hydrodynamic parameters in the different layouts can be compared to that in the single fibre case as reference. The second column of Table 6.2 represents the time-mean velocity $\bar{u}$ (averaged over the 4th oscillation) contour for different layouts in the domain which is specified in the first column by dashed rectangle. The results show that the streaming flows for a single fibre and the curtain (with out-plane oscillation) were almost similar and noticeable. For the curtain (with in-plane oscillation) and the bundle of fibres, the streaming flows were significantly damped among adjacent fibres.

Table 6.2 Hydrodynamic comparison of oscillating fibre membranes with different layouts.

Fibre Layout	$\bar{u}$ Distribution	$\bar{\Gamma}(\text{m}^2/\text{s})$	$\bar{\gamma}_{\max} (1/\text{s})$
<p>Single:</p>		2.76×10^{-4}	606.6
<p>Curtain (in-plane oscillation):</p>		5.79×10^{-5}	553.3
<p>Curtain (out-plane oscillation)</p>		2.09×10^{-4}	608.5
<p>Bundle:</p>		2.70×10^{-5}	411.5

The values for the time-mean circulation $\bar{\Gamma}$ (calculated over a square dimension of $5d$ and averaged within $4T < t < 5T$) for different layouts are listed in the third column of Table 6.2. It can be seen again that the circulation, which was a measure of the secondary flows and vortices around the oscillating fibre, was nearly identical

for a single fibre and a curtain with out-plane oscillation. However, for a curtain with in-plane oscillation and for a bundle of fibres, the vortices were significantly damped in the domain around the fibres. The surface-averaged shear rate $\bar{\gamma}$ (averaged around the fibre) was calculated for different layouts, and the maximum values over an oscillation period $\bar{\gamma}_{max}$ are listed in the forth column of Table 6.2. It can be seen again that for all cases, $\bar{\gamma}_{max}$ values were similar. However, the single fibre and the curtain with out-plane oscillation had higher surface shear rate compared to the two other layouts.

In real applications, using single fibres or a bundle of fibres with large distances between fibres is not practical. However, a curtain of fibres with large distances between curtains and using out-plane oscillation can produce the same hydrodynamics as a single oscillating fibre, and the system can benefit from the transverse oscillation.

6.5.4 Comparison of Longitudinal and Transverse Oscillating Membranes

To prove that the existence of streaming and secondary flows is very important for fouling control in membrane applications, the performances of longitudinal oscillating fibres and transverse oscillating fibres were compared experimentally in terms of the TMP rise (which is a measure of the fouling rate).

Four cases, which are listed in Table 6.3, were studied experimentally and the TMP rises are reported here. The filtration experiments were all carried out under constant flux mode with flux of 25 LMH. The diameter of the fibres was 1.6 mm.

For the transverse oscillation tests, the curtain layout (with out-plane oscillation) was used which is very similar to a single oscillating fibre case hydrodynamically.

The longitudinal oscillating experiments were considered as the case without net streaming flows and vortices (washing flow) close to the membrane surface, whereas, it was shown earlier that the washing flow exists near the transverse oscillating membranes.

The longitudinal and transverse oscillations were compared in terms of the energy consumption and maximum shear rate here. These parameters for the longitudinal oscillating membranes were calculated by using the analytical solution developed by Zamani, et al. (2013). The energy consumption, needed to produce the transverse vibrating motion, and $\bar{\gamma}_{max}$ were calculated by CFD simulations.

Table 6.3 Comparison of transverse and longitudinal oscillation modes in terms of the TMP rise, surface maximum shear rate and power consumption.

Case No.	f (rpm)	A (cm)	Oscillation Mode	Δ TMP (kPa)	Washing Flow	$\bar{\gamma}_{max}$ (1/s)	Power/Length (mW/m)		
							P_{osc}	$P_{\Delta TMP}$	P_{tot}
Case 1	1	2.4	Transverse	5.4	✓	1954.8	2.688	0.094	2.782
			Longitudinal	23	✗	377.9	0.101	0.401	0.503
Case 2	2	2.4	Transverse	0.7	✓	4023.9	21.22	0.012	21.23
			Longitudinal	16.4	✗	1069.1	0.573	0.286	0.859
Case 3	1	2.8	Transverse	4.2	✓	2327.3	4.253	0.073	4.326
			Longitudinal	21.8	✗	440.9	0.138	0.380	0.518
Case 4	2	2.8	Transverse	0.6	✓	4652.0	33.59	0.010	33.60
			Longitudinal	9.2	✗	1247.3	0.780	0.161	0.941

The consuming power per unit length of an oscillating fibre (P_{tot}) is considered to consist of two components: the required power for generating oscillation (P_{osc}) and the power consumption due to the TMP rise ($P_{\Delta TMP} = \Delta TMP \times V/2\Delta t$), where V is the total permeate volume which is extracted from the membrane in time duration of Δt . The oscillation power (P_{osc}) can be calculated by:

$$P_{osc} = \frac{1}{\Delta t} \int F(t)u(t)dt \quad (6.15)$$

where $F(t)$ which is exerted by the fluid to the oscillating fibre and $u(t)$ is the fibre velocity. These power consumptions per unit length of the fibre are listed in Table 6.3 in mW. The results show that the transverse oscillation mode consumes much more energy than longitudinal oscillation mode. In terms of the TMP rise, transverse oscillating membranes perform significantly better than longitudinal oscillating membranes. The better performance of the transverse oscillating membrane can be attributed to the higher shear rate (induced by the oscillation) and the existence of the washing flows.

Overall, the results suggest that the transverse oscillation mode is a better choice rather than the longitudinal oscillating mode, though it has higher energy consumption.

6.6 Conclusions

The hydrodynamics around transverse oscillating submerged hollow fibre membrane was studied. The time-mean velocity ($\bar{u}$) and time-mean circulation ($\bar{\Gamma}$), obtained by CFD simulations and PIV experiments for an oscillating rod (with

diameter of 1 cm) were reported and compared. The experimental results and CFD simulations showed good agreement for cases with Re number smaller than 600, which the flow around the oscillating cylinder can be considered as laminar.

CFD simulations were also carried out to determine the pressure variations over the surface of the membrane and over the time period for a typical transverse oscillating membrane fibre. It was found that the pressure variations due to the oscillation were negligible compared to the typical TMP values for the membrane applications.

The hydrodynamics of four different fibre layouts were compared. The streaming flow and vortices were found to be damped in bundle of fibres or curtain of fibres with in-plane oscillation. However, a curtain of fibres with large distances between curtains and out-plane oscillation can produce the same hydrodynamics as a single oscillating fibre, and the system can benefit from the transverse oscillation.

The comparison of longitudinal and transverse oscillating cases suggested that the transverse oscillation mode is a better choice rather than longitudinal oscillating mode, although it has higher energy consumption.

Chapter 7

Comparison of Different Anti-Fouling Techniques, in terms of Membrane Rejection and Fouling Mode

7.1 Abstract

In this study, different anti-fouling techniques, including aeration, vibration, aeration plus vibration and relaxation (plus aeration and vibration), in terms of the membrane rejection and fouling modes (i.e., internal or external modes) in a submerged flat sheet microfiltration system were compared. We used humic acid, as a model of natural organic matter (NOM), and bentonite, as a model of supermicron particles, as the fouling agents. The internal fouling of the membranes was assessed using different techniques, including liquid displacement porometry (LDP), evapoporometry (EP) and field-emission scanning electron microscopy (FESEM). The results suggested that using vibration may have adverse effects on the performance of the membrane when internal fouling matters.

7.2 Introduction

Low pressure membrane applications, such as microfiltration (MF) and ultrafiltration (UF), have been widely employed in wastewater treatment systems

This study was performed in collaboration with Ebrahim akhondi from SMTC.

like membrane bioreactors (MBRs). The main challenge in these applications is the rapid fouling rate of the membranes, due to the high fluxes and heavily loaded feed solutions. The industry has developed several techniques to prevent or reduce the fouling rate during the membrane filtration process. One of the most common techniques is to use air bubbling, in order to induce turbulence and scrub the surface of the membrane (Brindle, et al. 2000; Cui, et al. 2003). From a hydrodynamic point of view, air bubbling provides unsteady and fluctuating stresses on the membrane surface and induces additional flows in different directions that scatter particles from the surface (Cabassud, et al. 2001).

It is well known that high shear rates on the surface of a membrane can reduce concentration polarization (CP), cake build-up and, consequently, fouling in membrane systems. Vibrating the membrane is an effective method to enhance the shear rate at the membrane surface (Jaffrin 2008). The method, called vibratory shear-enhanced processing (VSEP), was introduced and used by (Armando, et al. (1992); Culkin and Armando 1992) for circular flat-sheet membranes. Vibration has also been employed for different membrane systems, such as submerged hollow fibre systems with different modes of vibration (e.g., transversely and longitudinal) (Genkin, et al. 2006; Krantz, et al. 1997; Le Clech, et al. 2003; Li, et al. 2013; Low, et al. 2004; Low, et al. 2005).

Relaxation (by stopping and starting the permeation intermittently) effectively diminishes fouling under specific conditions (but not always) for crossflow filtration and submerged systems (Defrance and Jaffrin 1999; Hong, et al. 2002;

Wu, et al. 2008; Zsirai, et al. 2012). Here, we combined relaxation with vibration and aeration to remove the fouled cake layer more effectively.

Foulants of different sizes can be found in real wastewater treatment processes. Two main components of feed solutions in typical wastewater processes are natural organic matter (NOM) and supermicron particles (e.g., microorganisms). Different materials and particles have been used to model these foulants under laboratory conditions. Several studies have used humic acid as the foulant model for NOM (Demneh, et al. 2011; Hashino, et al. 2011; Katsoufidou, et al. 2008; Xiao, et al. 2011). Bentonite is also a well-known particulate substance that has been used by many researchers as a model of supermicron particles in membrane studies. Bentonite can be used in binary suspensions and as the foulant model for supermicron particles (Ye, et al. 2011). We used a binary bentonite/humic acid mixture for this study. Bentonite was used as the supermicron particle, which can form the cake (external fouling) on the membrane surface, while humic acid was used as a fouling agent, which can cause internal fouling, due to its small size and particular shape (with string-type macromolecules).

In this study, we aimed to investigate the effect of different anti-fouling techniques, namely aeration, vibration, aeration plus vibration and relaxation (combined with aeration and vibration), on the selectivity and internal fouling of the membrane. The results were compared with a dead-end filtration case as a reference. The selectivity of the membrane was evaluated by measuring the total organic carbon (TOC) of the feed and the permeate flows. We assessed the total membrane resistance (including internal and cake resistances) by monitoring the rise in TMP. We then employed the

LDP, EP and FESEM methods to evaluate the degree of the membrane's internal fouling.

7.3 Materials and Methods

7.3.1 Experimental Apparatus and Protocol

We used the vibrating flat sheet membrane setup, which is described in Section 3.1, to perform filtration while the membrane vibrated. The schematic diagram of the experimental setup is shown in Figure 3.1a. The flat sheet membrane holder was vibrated at a frequency of 180 rpm and amplitude of 10 mm. All experiments involving aeration used an air flow rate of 2 l/min.

All of the filtration experiments were carried out for 60-minute periods with constant flux of 40 l/m²h. For the relaxation experiment, the periodical permeation relaxation (combined with vibration and aeration) was conducted for 1-minute periods after every 10 minutes of filtration. The filtration test employed no vibration or aeration during the dead-end test.

7.3.2 Model Foulant

We used bentonite (Sigma-Aldrich, 285234) as the supermicron model foulant in our experiments. The suspension was prepared using Mili-Q water (Millipore). The mean particle size of the bentonite particles was 8.5 µm, as shown in Figure 3.4.

We used humic acid as the internal fouling agent (for MF membranes) in our experiments. The presence of humic acid particles in the feed and permeate was examined by measuring the total organic carbon (TOC) using a TOC analyzer

(TOC-V CSH, Shimadzu). The feed solution was prepared with Mili-Q water. The average particle size of the humic acid particles was 231 nm. The size distribution of the humic acid particles is shown in Figure 3.5.

We used a mixture of bentonite (1 g/l) and humic acid (50 mg/l) as the feed solution in each experiment.

7.3.3 Pore Size Distribution Analysis Methods

In this study, we used a capillary flow porometer (CFP-1500A, Porous Materials, Inc.) and the LDP technique to measure the pore size distribution (PSD) of the clean and fouled membranes. The wetting liquid was galwick, and the non-reacting gas was nitrogen. In addition, we used Mili-Q water (Millipore) as the wetting liquid for the EP experiments. The principals and the setup of the EP method are explained in Chapter 3.

We used a FESEM (JSM-6700F, JEOL, Ltd., Japan) in this study to observe the fouled and clean membrane intersections directly.

7.4 Results and Discussion

7.4.1 TMP Rise Monitoring

Figure 7.1 shows the TMP rise versus time for different anti-fouling techniques. Each technique could diminish the rise in TMP rise, when compared to the dead-end filtration mode. This means that each technique can mitigate overall fouling (internal and external). Aeration resulted in the minimum TMP rise, whereas vibration had the closest TMP rise to that of the dead-end mode. The results show

that aeration plus vibration had a higher TMP rise than aeration alone. It should be noted that aeration plus vibration had a higher shear rate value than that of the vibration and aeration modes separately. Therefore, this interesting result suggests that vibration can cause some internal fouling (absorption and pore blocking) because internal fouling cannot be eliminated by higher shear rate values.

Figure 7.1 TMP rise versus time for different anti-fouling techniques at permeate flux of $40 \text{ l/m}^2\text{h}$.

7.4.2 TOC-Level Analysis

In all cases, we evaluated the selectivity of the membrane by measuring the TOC values in the feed and permeate flows. The TOC values of the different cases are shown in Figure 7.2 and were compared with the feed solution TOC as the reference. A large portion of humic acid, suspended in the feed flow, was rejected by the membrane in all of the filtration tests. However, the TOC values for permeation were still significant. The lowest TOC levels were found in the cases that used aeration (i.e., aeration alone and aeration plus vibration). This result implies that the air stream in the tank can produce a net flow near the membrane

surface, which can wash the particles (including the bentonite and humic acid particles) away from the regions near the membrane surface (in the concentration polarization layer) to the outer regions in the tank. However, a strong net flow cannot be generated by vibration alone. In the dead-end and relaxation modes, no continuous circulation and mixing flows exist; this creates a highly concentrated layer near the membrane surface, which reduces the selectivity of the membrane.

Figure 7.2 TOC level in the permeate of the filtration tests with different anti-fouling techniques.

7.4.3 Pore Size Distribution Analysis

The largest and average pore diameters are represented in Figure 7.3. The results in Figure 7.3 show that the pore sizes of the fouled membranes were, in all cases, noticeably smaller than those of the clean membrane. This reduction in pore size is a measure of the internal fouling in the membranes. Therefore, it can be inferred that pore constriction occurred in all filtration tests, regardless of which anti-fouling method had been used. The smallest pore constriction was achieved by using aeration as the anti-fouling method.

One drawback of the LDP method is that LDP deals with high pressures of gas and, as a result, may change the membrane structure and the PSD of the membrane (Jena and Gupta 2010). Similarly, applying high pressures in the LDP method may result in pushing the fouled particles out of the membrane pores and breaking the fouled layer attached to the surface of the membrane. This can explain the similar average pore sizes measured by the LDP method for each of the filtration tests using the different anti-fouling techniques.

Figure 7.3 Largest and average pore diameters (measured by LDP) of clean and fouled membranes; effect of different anti-fouling techniques.

The average pore sizes of the fouled and clean membranes that were measured with the EP technique are shown in Figure 7.4. The average pore sizes of the fouled membranes are clearly smaller than the clean membrane, which confirms the occurrence of internal fouling in all of the filtration tests.

Figure 7.4 Average pore diameter (measured by EP) of clean and fouled membranes; effect of different anti-fouling techniques.

Among all of these tests, aeration caused the least change to the pore size, which suggests that aeration is effective in mitigating cake formation. The fouled membrane had the greatest reduction in pore size in the filtration tests using vibration. This results confirms that vibration can loosen the cake structure, which itself acts as a barrier to the humic acid molecules and increases internal fouling. To validate the LDP and EP results, a cross-section of the fouled and clean membranes were observed directly by FESEM. The FESEM images are shown in Figure 7.5.

Internal fouling is clearly observable in the samples from the filtration tests with vibration and aeration plus vibration (see Figure 7.5c and e). Unlike the vibration samples, only an attached (to the membrane surface) fouled layer can be seen in the other fouled samples (from the aeration, relaxation and dead-end modes). The dead-end and relaxation samples look very similar.

7.5 Conclusions

Different anti-fouling methods have been introduced previously in the literature. Most of these studies showed the effectiveness of their methods in terms of the fouling control by monitoring the TMP changes. However, very few studies addressed the comparison of these anti-fouling methods in terms of the fouling mechanism and membrane selectivity, which is performed in this study.

Membrane anti-fouling techniques can change the fouling mechanisms and consequently influence membrane performance. Aeration is an effective technique for improving membrane selectivity and diminishing membrane fouling (both internal fouling and cake formation). On the other hand, vibration can allow smaller particles (humic acid molecules) to enter the membrane pores and cause some internal fouling, although vibration mitigates the concentration polarization of the supermicron particles.

The vibration technique can be used with relaxation and aeration (in the intermittent form), which do not cause severe internal fouling.

These results and trends may be specific to the membrane and foulants used in this study, and more studies can be conducted using tighter ultrafiltration membranes.

Figure 7.5 FESEM images of the cross-section of the membranes: (a) clean membrane and membranes used in filtration tests in different modes: (b) aeration; (c) vibration; (d) relaxation; (e) aeration plus vibration; (f) dead-end.

Chapter 8

Preliminary Observation of Supermicron Particles

Polarization near a Vibrating Surface

8.1 Abstract

In this chapter, the movement of the particles near a vibrating surface, with different frequencies, was evaluated using particle image velocimetry (PIV) measurements by calculating the time-averaged velocity components in the area of observation. The back transport of accumulated particles on the membrane surface was measured, and three cases were compared: vibration alone, aeration alone, and vibration plus aeration. Results show that to keep particles from making a cake on the membrane surface, shear rate (induced by vibration) and washing flows (generated by aeration) both are needed.

8.2 Introduction

Vibration of the membrane has been found to be effective for back transport of supermicron particles (larger than 3 μm) and, consequently, diminishing the concentration polarization and cake formation (Jaffrin 2008). Many efforts have recently been made to study and model the hydrodynamics around the vibrating membranes. As the most important factor in fouling control, the shear rate at the membrane surface has been calculated for flat sheet vibrating membranes (Akoum,

et al. 2002; Jaffrin, et al. 2004). The hydrodynamics around the longitudinal vibrating hollow fibres was studied in Chapter 5. Chapter 6 tried to study the hydrodynamics around transverse oscillating fibres using computational fluid dynamics (CFD) simulations and PIV experiments.

The PIV technique has been used in the study of membrane applications. The prior studies using PIV in membrane applications were reviewed in Chapter 2.

Permeation flow has usually been neglected in studying the motion of supermicron particles around vibrating membranes. This is because of the small ratio of the permeation velocity (velocity of the fluid through the membrane) to the vibrating velocity (velocity of the fluid parallel to the vibrating membrane). However, it should be noted that when there is a permeation flow through the membrane and using suspension (e.g., water and seeding particles) as the feed flow, the particles will accumulate on the membrane surface and there will be high concentration regions near the membrane surface. By applying vibration and consequently inducing a shear rate on the membrane surface, there will be a back transport of accumulated particles to the bulk flow, due to the shear induced diffusivity (Zydney and Colton 1986). In order to evaluate this back transport of particles, the permeation and vibration should be performed at the same time.

Another point about oscillating flows is that the nature of velocity for an ideal longitudinal vibration in this boundary layer is periodic, and the average of the velocity is zero over an oscillation period (T). Also, a net washing flow does not exist in the direction of membrane's length or in other directions (Beier, et al. 2006; Zamani, et al. 2013). Therefore, to determine if there is any net washing flow and

back transport flow near a real vibrating surface, the velocities of the particles should be averaged over the period of the vibration. For this purpose, the time-averaged velocity components, namely $\bar{u}$ and $\bar{v}$ in the x - and y -directions, respectively, as shown in Figure 8.1, were measured and reported. In fact, $\bar{u}$ is a measure of net movement of particles parallel to the vibrating surface and $\bar{v}$ represents the back transport of particles from the region near the membrane surface to the bulk flow.

In this chapter, the movement of the particles near a vibrating surface, with different frequencies, was evaluated by PIV measurements. Then, $\bar{u}$ and $\bar{v}$ were measured for three cases of vibration alone, aeration alone, and vibration plus aeration were. The results were compared.

Figure 8.1 The schematic representation of the vibration membrane surface and the region of influence of vibration, coordinate system and time-averaged velocity components.

8.3 Materials and Methods

Figure 8.2a shows a three-dimensional (3D) schematic diagram of the vibrating membranes and the PIV setup. The vibrating and filtration apparatus was explained earlier in Chapter 3. Figure 8.2b shows the area that is captured by the CCD camera for calibration purpose. This area is in the middle of the vibrating surface, and all results that will be reported are in this area.

As shown in Figure 8.2b, the region of interest was very close to the membrane surface. Due to the large amount of reflected light by the membrane surface, the reflected light by the PSP particles is not distinguishable by the camera. Therefore, fluorescent polymer particles (FPP) 20 μm were used in these experiments. A red lens was used to filter wavelengths larger than 570 nm.

In all experiments, PES flat sheet UF membranes (Pall Corporation, model OT100SHEET) were used with a molecular weight cut off (MWCO) of 100 kDa.

All the experiments were carried out with permeation by a constant flux of 30 $\text{l/m}^2\text{h}$. For the experiments of a vibrating surface with different frequencies (f), the amplitude (A) of the vibration was kept constant and equal to 10 mm. Five different frequencies of 15, 30, 60, 90, and 120 rpm were used.

In the experiments, for comparing the three modes of aeration, vibration, and aeration plus vibration, the vibration had an amplitude of 15 mm and frequency of 30 rpm. The air flow rate for aeration was kept at 2 l/min .

Figure 8.2 (a) 3D schematic diagram of the vibrating membranes and the PIV setup; (b) PIV camera point of view.

8.4 Results and Discussion

The $\bar{u}$ and $\bar{v}$ values are shown in Figure 8.3 for different frequencies. In each panel of Figure 8.3, there is a column bar that shows the variation limits and the zero point of each contour map. It can be seen that both $\bar{u}$ and $\bar{v}$ values are zero near the surface of the membrane. This implies that there was no net particle movement parallel to the membrane surface very close to the membrane surface. Also, there was no back transport of accumulated particles back to bulk low away from the surface. For smaller frequencies (i.e., 15 and 30 rpm in Figure 8.3a and b), the time-averaged velocity components values were close to zero, even away from the surface. This means that the flow circulation produced by the vibrating membrane holder was not big enough to get close to the membrane surface. It also meant that

the region of influence of the vibrating surface had a higher thickness (δ_M) for smaller frequencies. Theoretically, δ_M is proportional to $\sqrt{\nu/f}$, where ν is the kinematic viscosity of the flow. Thus, larger δ_M exists for smaller frequencies (f), which is consistent with experimental results. However, for higher frequencies of 60, 90, and 120 rpm (Figure 3c-e), the flow circulation produced by vibrating membrane holder in the tank was quite noticeable. However, the values of $\bar{u}$ and $\bar{v}$ were still close to zero for regions very close to the membrane surface.

Three modes of vibration, aeration, and aeration plus vibration were compared to each other in terms of particle movement. Firstly, the membrane was kept stationary and the permeation was started. After 5 minutes of permeation, the accumulation of seeding particles could be clearly observed on the surface of the membrane (Figure 8.4a). After the vibration went on for two minutes, the accumulated particles were still attached to membrane surface (Figure 8.4b). At the next stage, after the vibration stopped and two minutes into the aeration mode, no significant change was observed in the situation of accumulated particles at the surface (Figure 8.4c). It should be noted that the air column was adjusted so that bubbles could not touch the membrane surface. When vibration started again (while aeration was still on as well) all the accumulated particles were washed off from the membrane surface after 10 seconds (Figure 8.4d).

Figure 8.3 $\bar{u}$ and $\bar{v}$ contours near vibrating membrane with different frequencies: (a) 15; (b) 30; (c) 60; (d) 90; (e) 120 rpm.

In order to study this phenomena quantitatively, the values of $\bar{u}$ and $\bar{v}$ were measured and calculated exactly after each of the mentioned modes started. Figure 8.5 shows the results for all three modes. It can be seen that for aeration (Figure 8.5a) or vibration (Figure 8.5b) alone, the $\bar{u}$ and $\bar{v}$ values were close to zero near the membrane surface. This means there was no back transport of particles (or washing streams) near the membrane surface. However, for the aeration plus vibration mode (Figure 8.5c), higher values of $\bar{v}$ can be seen near the membrane surface, Hence, some net back transport of particles occur near the membrane, and the particles were washed off by the aeration stream.

Figure 8.4 Accumulation of seeding particles on the membrane surface in different filtration modes: (a) dead-end; (b) vibration; (c) aeration; (e) vibration plus aeration.

8.5 Conclusions

The existence of net washing flows and back transport of particles near the vibrating membranes were evaluated by measuring and calculating the time-averaged velocities within the period of the vibration. The pure vibration of a completely flat sheet membrane will not produce any significant net parallel and back transport stream of particles. On the other hand, if the vibration can be

combined with aeration, the back transport of accumulated particles near the vibrating surface can be significant.

Figure 8.5 $\bar{u}$ and $\bar{v}$ contours for filtration tests with different modes: (a) aeration; (b) vibration; (c) aeration plus vibration.

Chapter 9

Conclusions and Recommendations

9.1 Conclusions

Based on the results of this study, the following conclusions were drawn and summarized in this chapter.

9.1.1 Introducing a Generalized Criterion for Particle Deposition in CFMF Using DOTM Results

A new numerical method has been developed to simulate the mass transfer of supermicron particles in a crossflow membrane system. This method has been compared with prior methods (SID and SID-MOD models), and it has been shown that the more realistic assumptions in the new model improve the analysis of data.

The mass balance and DOTM methods were used to measure the local critical fluxes for different cases and for different distances from the inlet of a membrane channel. Combining the results from the experiments and simulation, the Peclet numbers (Pe) were calculated for different cases with different hydrodynamic conditions at their corresponding local critical flux. It was also found that the Peclet numbers in all of the cases were close to a unique, “critical” value ($Pe_{crit} \approx 4$). The SID and SID-MOD models had limitations in estimating accurate local Peclet

numbers due to their non-realistic assumptions, which arose from using the Lvque solution as their base for solving the mass-transfer equation.

9.1.2 Hydrodynamic Analysis of Longitudinal Vibrating Hollow Fibre Membranes

The laminar flow around a longitudinal vibrating hollow fibre was solved analytically. It was found that the hydrodynamics around the longitudinal fibre depend on a dimensionless group (α). The Cartesian solution for a flat-sheet membrane, used in prior studies, was compared to the new solution. It was found that for large α (i.e., bigger fibres), the new solution approaches the Cartesian solution, thus the use of the Cartesian solution and its associated assumptions are acceptable. However, for small values of α (small fibres), a relative error of up to 75% (ex. $\alpha=0.2$) can arise with the Cartesian solution with the typical range of parameters tested.

The wall-shear rate on the surface of the membranes of a bundle was obtained by performing CFD simulations. It was found that the shear rate significantly depends on the distance between the fibres. Based on the results, packed bundles of fibres with not very high density would be recommended for dynamic shear-enhanced filtration. It was also found that a staggered configuration generally provides higher wall-shear rates than an in-line configuration with the optimum distance.

9.1.3 Hydrodynamic Analysis of Transverse Oscillating Hollow Fibre Membranes

The hydrodynamics around a transverse oscillating submerged hollow fibre membrane were studied numerically and experimentally. The time-mean velocity ($\bar{u}$) and time-mean circulation ($\bar{\Gamma}$), obtained by CFD simulation and PIV experiment, for an oscillating rod with diameter of 1 cm were reported and compared. The experimental results and CFD simulation results showed a good agreement, and it was found that for cases with Re number values smaller than 600, the flow around the oscillating cylinder can be considered laminar and 2D, and the results of CFD simulation are acceptable with good accuracy.

CFD simulations were carried out to determine the pressure variations over the surface of the membrane and over time for a typical transverse oscillating membrane fibre. It was found that the pressure variations due to the oscillation were negligible compared to the typical TMP values for the membrane applications.

The hydrodynamics of four different fibre layouts were compared. The streaming flow and vortices might be damped in a bundle of fibres or curtain of fibres with in-plane oscillation. However, using curtains of fibres with large distances between curtains with out-plane oscillation can produce the same hydrodynamics as a single oscillating fibre, which the system can benefit from the transverse oscillation.

The experimental and CFD comparison of longitudinal and transverse oscillating cases suggested that, the transverse oscillation mode is a better choice than the longitudinal oscillation mode, though it has higher energy consumption.

9.1.4 Effects of Different Anti-Fouling Techniques on the Fouling Mechanism

Using different anti-fouling techniques, different fouling mechanisms may occur. Among all the methods, aeration was found the most effective technique for improving the membrane selectivity and diminishing the membrane fouling (both internal fouling and cake formation). Unlike aeration, vibration may cause some internal fouling, although vibration can mitigate the concentration polarization of supermicron particles.

To benefit from the vibration technique, it can be used along with relaxation and aeration (in the intermittent form), which does not cause severe internal fouling.

9.1.5 Supermicron Particles Polarization near a Vibrating Surface

The Existence of net washing flows and back transport of particles near the vibrating membranes can be evaluated by measuring and calculating the time-averaged velocities within the period of vibration.

Pure vibration for a completely flat sheet membrane did not produce any significant net parallel or back transport stream of particles. On the other hand, where the vibration was combined with aeration, the back transport of accumulated particles near the vibrating surface was significant.

9.2 Recommendations

The following recommendations are suggested as potential directions for future research works:

- The concept of critical Peclet number may be used for submerged systems with different anti-fouling methods such as aeration, vibration, and relaxation.
- CFD simulations may be performed by coupling the mass-transfer equations with the Navier-Stokes equations for vibrating membranes (longitudinal and transverse). In this case the permeation of the fluid through the membrane should be considered so that the accumulation of the particles at the membrane surface can be simulated.
- For transverse oscillating fibre membranes, a series of CFD simulations and experiments can be carried out to find out the optimum frequency and amplitude in order to achieve the minimum energy consumption with the same rate of fouling.
- The effect of different anti-fouling methods on the internal fouling can be examined for membranes with different pore sizes.
- The internal fouling experiments may be carried out using real wastewater samples in order to study more realistic systems.

References

- Ahmad, A. L., Ban, Z. H., and Ooi, B. S. (2010), "A Three-Dimensional Unsteady Hydrodynamic Profile of a Reciprocating Membrane Channel", Journal of Membrane Science, vol. 365, pp. 426-437.
- Akoum, O. A., Jaffrin, M. Y., Ding, L., Paullier, P., and Vanhoutte, C. (2002), "An Hydrodynamic Investigation of Microfiltration and Ultrafiltration in a Vibrating Membrane Module", Journal of Membrane Science, vol. 197, pp. 37-52.
- Altena, F. W. and Belfort, G. (1984), "Lateral Migration of Spherical Particles in Porous Flow Channels: Application to Membrane Filtration", Chemical Engineering Science, vol. 39, pp. 343-355.
- Altmann, J. and Ripperger, S. (1997), "Particle Deposition and Layer Formation at the Crossflow Microfiltration", Journal of Membrane Science, vol. 124, pp. 119-128.
- Armando, A. D., Culkin, B., and Purchas, D. B., "New Separation System Extends the Use of Membranes," in *Euromembrane '92*, Paris, 1992, p. 459.
- Bacchin, P. (2004), "A Possible Link between Critical and Limiting Flux for Colloidal Systems: Consideration of Critical Deposit Formation Along a Membrane", Journal of Membrane Science, vol. 228, pp. 237-241.
- Bacchin, P., Aimar, P., and Field, R. W. (2006), "Critical and Sustainable Fluxes: Theory, Experiments and Applications", Journal of Membrane Science, vol. 281, pp. 42-69.
- Bacchin, P., Aimar, P., and Sanchez, V. (1995), "Model for Colloidal Fouling of Membranes", AIChE Journal, vol. 41, pp. 368-376.
- Bearman, P. W., Downie, M. J., Graham, J. M. R., and Obasaju, E. D. (1985), "Forces on Cylinders in Viscous Oscillatory Flow at Low Keulegan-Carpenter Numbers", Journal of Fluid Mechanics, vol. 154, pp. 337-356.
- Beier, S. P., Guerra, M., Garde, A., and Jonsson, G. (2006), "Dynamic Microfiltration with a Vibrating Hollow Fiber Membrane Module: Filtration of Yeast Suspensions", Journal of Membrane Science, vol. 281, pp. 281-287.
- Beier, S. P. and Jonsson, G. (2006), "Dynamic Microfiltration with a Vibrating Hollow Fiber Membrane Module", Desalination, vol. 199, pp. 499-500.
- Beier, S. P. and Jonsson, G. (2009), "A Vibrating Membrane Bioreactor (Vmbr): Macromolecular Transmission--Influence of Extracellular Polymeric Substances", Chemical Engineering Science, vol. 64, pp. 1436-1444.

- Belfort, G., Davis, R. H., and Zydney, A. L. (1994), "The Behavior of Suspensions and Macromolecular Solutions in Crossflow Microfiltration", Journal of Membrane Science, vol. 96, pp. 1-58.
- Belfort, G. and Nagata, N. (1985), "Fluid Mechanics and Cross-Flow Filtration: Some Thoughts", Desalination, vol. 53, pp. 57-79.
- Bellara, S. R., Cui, Z. F., and Pepper, D. S. (1996), "Gas Sparging to Enhance Permeate Flux in Ultrafiltration Using Hollow Fibre Membranes", Journal of Membrane Science, vol. 121, pp. 175-184.
- Berman, A. S. (1953), "Laminar Flow in Channels with Porous Walls", Journal of Applied Physics, vol. 24, pp. 1232-1235.
- Bérubé, P. R. and Lei, E. (2006), "The Effect of Hydrodynamic Conditions and System Configurations on the Permeate Flux in a Submerged Hollow Fiber Membrane System", Journal of Membrane Science, vol. 271, pp. 29-37.
- Bhattacharya, S. and Hwang, S.-T. (1997), "Concentration Polarization, Separation Factor, and Peclet Number in Membrane Processes", Journal of Membrane Science, vol. 132, pp. 73-90.
- Bird, R. B., Stewart, W. E., and Lightfoot, E. N. (2002), Transport Phenomena, second ed.: John Wiley & Sons Inc.
- Blatt, W., Dravid, A., Michaels, A., and Nelsen, L., "Solute Polarization and Cake Formation in Membrane Ultrafiltration: Causes, Consequences, and Control Techniques," in *Membrane Science and Technology*, J. Flinn, Ed., ed: Springer US, 1970, pp. 47-97.
- Borthwick, A. G. L. (1989), "Pressure and Force Measurements on a Cylinder Oscillated Sinusoidally at Low and Intermediate Keulegan-Carpenter Numbers ", Journal of Fluids and Structures, vol. 3, pp. 509-528.
- Bowen, W. R. and Jenner, F. (1995), "Theoretical Descriptions of Membrane Filtration of Colloids and Fine Particles: An Assessment and Review", Advances in Colloid and Interface Science, vol. 56, pp. 141-200.
- Brannock, M., Wang, Y., and Leslie, G. (2010), "Mixing Characterisation of Full-Scale Membrane Bioreactors: Cfd Modelling with Experimental Validation", Water Research, vol. 44, pp. 3181-3191.
- Brindle, K., Passe, D., Wilkes, S., Wilkes, S., and Judd, S. J. (2000), "Performance and Economic Evaluation of a Submerged Membrane Bioreactor on Large Diameter Hollow Fiber Membrane for the Treatment of Raw Sewage", presented at the 8th World Filtration Congress, Brighton
- Buethorn, S., Volmering, D., Vossenkaul, K., Wintgens, T., Wessling, M., and Melin, T. (2011), "Cfd Simulation of Single- and Multi-Phase Flows through

Submerged Membrane Units with Irregular Fiber Arrangement", Journal of Membrane Science, vol. 384, pp. 184-197.

Burden, R. L. and Faires, J. D. (2011), Numerical Analysis, 9th ed.: Boston, MA : Brooks/Cole, Cengage Learning, c2011.

Cabassud, C., Laborie, S., Durand-Bourlier, L., and Lainé, J. M. (2001), "Air Sparging in Ultrafiltration Hollow Fibers: Relationship between Flux Enhancement, Cake Characteristics and Hydrodynamic Parameters", Journal of Membrane Science, vol. 181, pp. 57-69.

Chang, I.-S. and Kim, S.-N. (2005), "Wastewater Treatment Using Membrane Filtration—Effect of Biosolids Concentration on Cake Resistance", Process Biochemistry, vol. 40, pp. 1307-1314.

Chang, S. and Fane, A. G. (2001), "The Effect of Fibre Diameter on Filtration and Flux Distribution — Relevance to Submerged Hollow Fibre Modules", Journal of Membrane Science, vol. 184, pp. 221-231.

Chellam, S., Wiesner, M., and Dawson, C. (1992), "Slip at a Uniformly Porous Boundary: Effect on Fluid Flow and Mass Transfer", Journal of Engineering Mathematics, vol. 26, pp. 481-492.

Chen, V., Li, H., and Fane, A. G. (2004), "Non-Invasive Observation of Synthetic Membrane Processes – a Review of Methods", Journal of Membrane Science, vol. 241, pp. 23-44.

Cheryan, M. (1998), Ultrafiltration and Microfiltration Handbook: Technomic Pub. Co.

Cho, B. D. and Fane, A. G. (2002), "Fouling Transients in Nominally Sub-Critical Flux Operation of a Membrane Bioreactor", Journal of Membrane Science, vol. 209, pp. 391-403.

Choir, S.-i., Kim, S.-g., Yoon, J., Ahn, K., and Lee, S.-h. (2003), "Particle Behavior in Air Agitation Submerged Membrane Filtration", Desalination, vol. 158, pp. 181-188.

Chong, T. H., Wong, F. S., and Fane, A. G. (2008), "Implications of Critical Flux and Cake Enhanced Osmotic Pressure (Ceop) on Colloidal Fouling in Reverse Osmosis: Experimental Observations", Journal of Membrane Science, vol. 314, pp. 101-111.

Churchouse, S. (1997), "Membrane Bioreactors for Wastewater Treatment -- Operating Experiences with the Kubota Submerged Membrane Activated Sludge Process", Membrane Technology, vol. 1997, pp. 5-9.

Coster, H. G. L., Chilcott, T. C., and Coster, A. C. F. (1996), "Impedance Spectroscopy of Interfaces, Membranes and Ultrastructures", Bioelectrochemistry and Bioenergetics, vol. 40, pp. 79-98.

Cox, R. G. and Mason, S. G. (1971), "Suspended Particles in Fluid Flow through Tubes", Annual Review of Fluid Mechanics, vol. 3, pp. 291-316.

Cui, Z. F., Chang, S., and Fane, A. G. (2003), "The Use of Gas Bubbling to Enhance Membrane Processes", Journal of Membrane Science, vol. 221, pp. 1-35.

Cui, Z. F. and Muralidhara, H. S. (2010), Membrane Technology: Butterworth-Heinemann.

Culkin, B. and Armando, A. D. (1992), "New Separation System Extends the Use of Membranes", Filtration & Separation, vol. 29, pp. 376-378.

Dantec Dynamics, <http://www.dantecdynamics.com>

Deen, W. M. (1998), Analysis of Transport Phenomena / William M. Deen: New York : Oxford University Press, 1998.

Defrance, L. and Jaffrin, M. Y. (1999), "Comparison between Filtrations at Fixed Transmembrane Pressure and Fixed Permeate Flux: Application to a Membrane Bioreactor Used for Wastewater Treatment", Journal of Membrane Science, vol. 152, pp. 203-210.

Demneh, S. M. G., Nasernejad, B., and Modarres, H. (2011), "Modeling Investigation of Membrane Biofouling Phenomena by Considering the Adsorption of Protein, Polysaccharide and Humic Acid", Colloids and Surfaces B: Biointerfaces, vol. 88, pp. 108-114.

Drew, D. A., Schonberg, J. A., and Belfort, G. (1991), "Lateral Inertial Migration of a Small Sphere in Fast Laminar Flow through a Membrane Duct", Chemical Engineering Science, vol. 46, pp. 3219-3224.

Eckstein, E. C., Bailey, D. G., and Shapiro, A. H. (1977), "Self-Diffusion of Particles in Shear Flow of a Suspension", Journal of Fluid Mechanics, vol. 79, pp. 191-208.

Fane, A. G. and Fell, C. J. D. (1987), "A Review of Fouling and Fouling Control in Ultrafiltration", Desalination, vol. 62, pp. 117-136.

Fane, A. G., Fell, C. J. D., Hodgson, P. H., Leslie, G., and Marshall, K. C. (1991), "Microfiltration of Biomass and Biofluids: Effects of Membrane Morphology and Operating Conditions", Filtration & Separation, vol. 28, pp. 332-331.

Fenu, A., Roels, J., Wambecq, T., De Gussem, K., Thoeye, C., De Gueldre, G., and Van De Steene, B. (2010), "Energy Audit of a Full Scale Mbr System", Desalination, vol. 262, pp. 121-128.

Field, R. W., Wu, D., Howell, J. A., and Gupta, B. B. (1995), "Critical Flux Concept for Microfiltration Fouling", Journal of Membrane Science, vol. 100, pp. 259-272.

- Gander, M., Jefferson, B., and Judd, S. (2000), "Aerobic Mbrs for Domestic Wastewater Treatment: A Review with Cost Considerations", Separation and Purification Technology, vol. 18, pp. 119-130.
- Gaucher, C., Legentilhomme, P., Jaouen, P., Comiti, J., and Pruvost, J. (2002), "Hydrodynamics Study in a Plane Ultrafiltration Module Using an Electrochemical Method and Particle Image Velocimetry Visualization", Experiments in Fluids, vol. 32, pp. 283-293.
- Gekas, V. and Hallström, B. (1987), "Mass Transfer in the Membrane Concentration Polarization Layer under Turbulent Cross Flow : I. Critical Literature Review and Adaptation of Existing Sherwood Correlations to Membrane Operations", Journal of Membrane Science, vol. 30, pp. 153-170.
- Gekas, V. and Hallström, B. (1990), "Microfiltration Membranes, Cross-Flow Transport Mechanisms and Fouling Studies", Desalination, vol. 77, pp. 195-218.
- Genkin, G., Waite, T. D., Fane, A. G., and Chang, S. (2006), "The Effect of Vibration and Coagulant Addition on the Filtration Performance of Submerged Hollow Fibre Membranes", Journal of Membrane Science, vol. 281, pp. 726-734.
- Ghidossi, R., Veyret, D., and Moulin, P. (2006), "Computational Fluid Dynamics Applied to Membranes: State of the Art and Opportunities", Chemical Engineering and Processing: Process Intensification, vol. 45, pp. 437-454.
- Ghyoot, W. and Verstraete, W. (2000), "Reduced Sludge Production in a Two-Stage Membrane-Assisted Bioreactor", Water Research, vol. 34, pp. 205-215.
- Gimmelshtein, M. and Semiat, R. (2005), "Investigation of Flow Next to Membrane Walls", Journal of Membrane Science, vol. 264, pp. 137-150.
- Gonzalez-Avila, S. R., Prabowo, F., Kumar, A., and Ohl, C.-D. (2012), "Improved Ultrasonic Cleaning of Membranes with Tandem Frequency Excitation", Journal of Membrane Science, vol. 415-416, pp. 776-783.
- Graetz, L. (1883), "Ueber Die Wärmeleitungsfähigkeit Von Flüssigkeiten", Annalen der Physik und Chemie, vol. 18, pp. 79-94.
- Green, G. and Belfort, G. (1980), "Fouling of Ultrafiltration Membranes: Lateral Migration and the Particle Trajectory Model", Desalination, vol. 35, pp. 129-147.
- Hashino, M., Hiram, K., Katagiri, T., Kubota, N., Ohmukai, Y., Ishigami, T., Maruyama, T., and Matsuyama, H. (2011), "Effects of Three Natural Organic Matter Types on Cellulose Acetate Butyrate Microfiltration Membrane Fouling", Journal of Membrane Science, vol. 379, pp. 233-238.
- Hildebrand, F. B. (1962), Advanced Calculus for Applications. Englewood Cliffs, NJ: PrenticeHall.

- Hodgson, P. H., Pillay, V. L., and Fane, A. G., "Visual Study of Crossflow Microfiltration with Inorganic Membranes: Resistance of Biomass and Particulate Cake," in *Sixth World Filtration Congress*, Nagoya, 1993, pp. 607-610.
- Hong, S. P., Bae, T. H., Tak, T. M., Hong, S., and Randall, A. (2002), "Fouling Control in Activated Sludge Submerged Hollow Fiber Membrane Bioreactors", *Desalination*, vol. 143, pp. 219-228.
- Honji, H. (1981), "Streaked Flow around an Oscillating Circular Cylinder", *Journal of Fluid Mechanics*, vol. 107, pp. 509-520.
- Howell, J. A. (1995), "Sub-Critical Flux Operation of Microfiltration", *Journal of Membrane Science*, vol. 107, pp. 165-171.
- Iwai, H., Mambo, T., Yamamoto, N., and Suzuki, K. (2004), "Laminar Convective Heat Transfer from a Circular Cylinder Exposed to a Low Frequency Zero-Mean Velocity Oscillating Flow", *International Journal of Heat and Mass Transfer*, vol. 47, pp. 4659-4672.
- Jaffrin, M. Y. (2008), "Dynamic Shear-Enhanced Membrane Filtration: A Review of Rotating Disks, Rotating Membranes and Vibrating Systems", *Journal of Membrane Science*, vol. 324, pp. 7-25.
- Jaffrin, M. Y., Ding, L.-H., Akoum, O., and Brou, A. (2004), "A Hydrodynamic Comparison between Rotating Disk and Vibratory Dynamic Filtration Systems", *Journal of Membrane Science*, vol. 242, pp. 155-167.
- Jena, A. and Gupta, K. (2001), "An Innovative Technique for Pore Structure Analysis of Fuel Cell and Battery Components Using Flow Porometry", *Journal of Power Sources*, vol. 96, pp. 214-219.
- Jena, A. and Gupta, K. (2010), "Advances in Pore Structure Evaluation by Porometry", *Chemical Engineering & Technology*, vol. 33, pp. 1241-1250.
- Johir, M. A. H., George, J., Vigneswaran, S., Kandasamy, J., Sathasivan, A., and Grasmick, A. (2012), "Effect of Imposed Flux on Fouling Behavior in High Rate Membrane Bioreactor", *Bioresource Technology*, vol. 122, pp. 42-49.
- Joshi, J. B. (2001), "Computational Flow Modelling and Design of Bubble Column Reactors", *Chemical Engineering Science*, vol. 56, pp. 5893-5933.
- Judd, S. and Judd, C. (2006), *The Mbr Book*. Oxford: Elsevier Science.
- Jurado, J. and Bellhouse, B. J. (1994), "Application of Electric Fields and Vortex Mixing for Enhanced Ultrafiltration", *Filtration & Separation*, vol. 31, pp. 273-268.
- Katsoufidou, K., Yiantsios, S. G., and Karabelas, A. J. (2008), "An Experimental Study of Uf Membrane Fouling by Humic Acid and Sodium Alginate Solutions: The Effect of Backwashing on Flux Recovery", *Desalination*, vol. 220, pp. 214-227.

Keulegan, G. H. and Carpenter, L. H. (1958), "Forces on Cylinders and Plates in an Oscillating Fluid", Journal of Research of the National Bureau of Standards, vol. 60, pp. 423-440.

Knutson, J. S. and Davis, R. H. (2006), "Deposition of Foulant Particles During Tangential Flow Filtration", Journal of Membrane Science, vol. 271, pp. 101-113.

Kola, A., Ye, Y., Ho, A., Le-Clech, P., and Chen, V. (2012), "Application of Low Frequency Transverse Vibration on Fouling Limitation in Submerged Hollow Fibre Membranes", Journal of Membrane Science, vol. 409–410, pp. 54-65.

Krantz, W. B. (2007), Scaling Analysis in Modeling Transport and Reaction Processes [Electronic Resource] : A Systematic Approach to Model Building and the Art of Approximation: Hoboken : John Wiley & Sons, Inc., 2007.

Krantz, W. B., Bilodeau, R. R., Voorhees, M. E., and Elgas, R. J. (1997), "Use of Axial Membrane Vibrations to Enhance Mass Transfer in a Hollow Tube Oxygenator", Journal of Membrane Science, vol. 124, pp. 283-299.

Krantz, W. B., Greenberg, A. R., Kujundzic, E., Yeo, A., and Hosseini, S. S. (2013), "Evaporimetry: A Novel Technique for Determining the Pore-Size Distribution of Membranes", Journal of Membrane Science, vol. 438, pp. 153-166.

Kuzmenko, D., Arkhangelsky, E., Belfer, S., Freger, V., and Gitis, V. (2005), "Chemical Cleaning of Uf Membranes Fouled by Bsa", Desalination, vol. 179, pp. 323-333.

Kwon, D. Y., Vigneswaran, S., Fane, A. G., and Aim, R. B. (2000), "Experimental Determination of Critical Flux in Cross-Flow Microfiltration", Separation and Purification Technology, vol. 19, pp. 169-181.

Lam, K. M., Hu, J. C., and Liu, P. (2010), "Vortex Formation Processes from an Oscillating Circular Cylinder at High Keulegan–Carpenter Numbers", Physics of Fluids, vol. 22, p. 015105.

Le-Clech, P., Cao, Z., Wan, P. Y., Wiley, D. E., and Fane, A. G. (2006), "The Application of Constant Temperature Anemometry to Membrane Processes", Journal of Membrane Science, vol. 284, pp. 416-423.

Le-Clech, P., Chen, V., and Fane, T. A. G. (2006), "Fouling in Membrane Bioreactors Used in Wastewater Treatment", Journal of Membrane Science, vol. 284, pp. 17-53.

Le Clech, P., Jefferson, B., Chang, I. S., and Judd, S. J. (2003), "Critical Flux Determination by the Flux-Step Method in a Submerged Membrane Bioreactor", Journal of Membrane Science, vol. 227, pp. 81-93.

Lee, Y. and Clark, M. M. (1998), "Modeling of Flux Decline During Crossflow Ultrafiltration of Colloidal Suspensions", Journal of Membrane Science, vol. 149, pp. 181-202.

- Leighton, D. and Acrivos, A. (1987), "The Shear-Induced Migration of Particles in Concentrated Suspensions", Journal of Fluid Mechanics, vol. 181, pp. 415-439.
- Leonard, E. F. and Vassilieff, C. S. (1984), "The Deposition of Rejected Matter in Membrane Separation Processes", Chemical Engineering Communications, vol. 30, pp. 209-217.
- Lévêque, M. A. (1928), "Les Lois De La Transmission De Chaleur Par Convection", Annales des Mines, Memoires, Series 12, vol. 13, pp. 201-299, 305-362, 381-415.
- Li, H., Fane, A. G., Coster, H. G. L., and Vigneswaran, S. (1998), "Direct Observation of Particle Deposition on the Membrane Surface During Crossflow Microfiltration", Journal of Membrane Science, vol. 149, pp. 83-97.
- Li, H., Fane, A. G., Coster, H. G. L., and Vigneswaran, S. (2000), "An Assessment of Depolarisation Models of Crossflow Microfiltration by Direct Observation through the Membrane", Journal of Membrane Science, vol. 172, pp. 135-147.
- Li, H., Fane, A. G., Coster, H. G. L., and Vigneswaran, S. (2003), "Observation of Deposition and Removal Behaviour of Submicron Bacteria on the Membrane Surface During Crossflow Microfiltration", Journal of Membrane Science, vol. 217, pp. 29-41.
- Li, Q. Y., Ghosh, R., Bellara, S. R., Cui, Z. F., and Pepper, D. S. (1998), "Enhancement of Ultrafiltration by Gas Sparging with Flat Sheet Membrane Modules", Separation and Purification Technology, vol. 14, pp. 79-83.
- Li, T., Law, A. W.-K., Cetin, M., and Fane, A. G. (2013), "Fouling Control of Submerged Hollow Fibre Membranes by Vibrations", Journal of Membrane Science, vol. 427, pp. 230-239.
- Low, S. C., Cheong, K. T., Tan, K. K., and Lim, D. (2008), "A Vibration Membrane Bio-Reactor", presented at the IWA regional Conference, Moscow, Russia.
- Low, S. C., Han, H. J., and Jin, W. X. (2004), "Characteristics of a Vibration Membrane in Water Recovery from Fine Carbon-Loaded Wastewater", Desalination, vol. 160, pp. 83-89.
- Low, S. C., Jin, W. X., and Tan, M. (2004), "Characteristics of Particle and Membrane Pore Sizes in the Performance of Water Recovery from a Fine Carbon Loaded Wastewater Using a Vibration Membrane System", Desalination, vol. 167, pp. 217-226.
- Low, S. C., Juan, H. H., and Siong, L. K. (2005), "A Combined Vsep and Membrane Bioreactor System", Desalination, vol. 183, pp. 353-362.

Mameri, N., Oussedik, S. M., Khelifa, A., Belhocine, D., Ghrib, H., and Lounici, H. (2001), "Electric Fields Applied in the Ultrafiltration Process", Desalination, vol. 138, p. 291.

Mayhew, M. and Stephenson, T. (1998), "Biomass Yield Reduction: Is Biochemical Manipulation Possible without Affecting Activated Sludge Process Efficiency?", Water Science and Technology, vol. 38, pp. 137-144.

McLaughlin, J. B. (1991), "Inertial Migration of a Small Sphere in Linear Shear Flows", Journal of Fluid Mechanics, vol. 224, pp. 261-274.

McLaughlin, J. B. (1993), "The Lift on a Small Sphere in Wall-Bounded Linear Shear Flows", Journal of Fluid Mechanics, vol. 246, pp. 249-265.

Miyagi, N., Kimura, M., Shoji, H., Saima, A., Ho, C.-M., Tung, S., and Tai, Y.-C. (2000), "Statistical Analysis on Wall Shear Stress of Turbulent Boundary Layer in a Channel Flow Using Micro-Shear Stress Imager", International Journal of Heat and Fluid Flow, vol. 21, pp. 576-581.

Miyahara, T., Tsuchiya, K., and Fan, L. S. (1988), "Wake Properties of a Single Gas Bubble in Three-Dimensional Liquid-Solid Fluidized Bed", International Journal of Multiphase Flow, vol. 14, pp. 749-763.

Morison, J. R., O'Brien, M. P., Johnson, J. W., and Schaaf, S. A. (1950), "The Force Exerted by Surface Waves on Piles", Petroleum Transactions, AIME, vol. 189, pp. 149-154.

Mulder, M. (1996), Basic Principles of Membrane Technology, 2nd ed. Dordrecht ; Boston: Kluwer Academic.

Muller, E. B., Stouthamer, A. H., and van Verseveld, H. W. (1995), "A Novel Method to Determine Maximal Nitrification Rates by Sewage Sludge at a Non-Inhibitory Nitrite Concentration Applied to Determine Maximal Rates as a Function of the Nitrogen Load", Water Research, vol. 29, pp. 1191-1197.

Nakao, S.-i. (1994), "Determination of Pore Size and Pore Size Distribution: 3. Filtration Membranes", Journal of Membrane Science, vol. 96, pp. 131-165.

New Logic Research Inc., <http://www.vsep.com>

Ng, H. Y. and Hermanowicz, S. W. (2005), "Membrane Bioreactor Operation at Short Solids Retention Times: Performance and Biomass Characteristics", Water Research, vol. 39, pp. 981-992.

Ning Koh, C., Wintgens, T., Melin, T., and Pronk, F. (2008), "Microfiltration with Silicon Nitride Microsieves and High Frequency Backpulsing", Desalination, vol. 224, pp. 88-97.

Porter, M. C. (1972), "Concentration Polarization with Membrane Ultrafiltration", Product R&D, vol. 11, pp. 234-248.

Raffel, M., Leitzl, B., and Kompenhans, J., "Data Validation for Particle Image Velocimetry," in *6th International Symposium on Applications of Laser Techniques to Fluid Mechanics*, Lisbon, Portugal, 1992.

Ripperger, S. and Altmann, J. (2002), "Crossflow Microfiltration – State of the Art", *Separation and Purification Technology*, vol. 26, pp. 19-31.

Rubin, G. (1977), "Widerstands-Und Auftriebsbeiwerte Von Ruhenden, Kugelförmigen Partikeln in Stationären, Wandnahen Laminaren Grenzschichten", *PhD*, University of Karlsruhe,

Santos, J. L. C., Geraldes, V., Velizarov, S., and Crespo, J. G. (2007), "Investigation of Flow Patterns and Mass Transfer in Membrane Module Channels Filled with Flow-Aligned Spacers Using Computational Fluid Dynamics (Cfd)", *Journal of Membrane Science*, vol. 305, pp. 103-117.

Sarkar, A., Moulik, S., Sarkar, D., Roy, A., and Bhattacharjee, C. (2012), "Performance Characterization and Cfd Analysis of a Novel Shear Enhanced Membrane Module in Ultrafiltration of Bovine Serum Albumin (Bsa)", *Desalination*, vol. 292, pp. 53-63.

Sarpkaya, T. (1986), "Force on a Circular Cylinder in Viscous Oscillatory Flow at Low Keulegan-Carpenter Numbers", *Journal of Fluid Mechanics*, vol. 165, pp. 61-71.

Shahnawaz, H. M. (2009), "Ac Electrokinetic Manipulation of Colloids During Filtration", *Ph.D. Dissertation*, Mechanical Engineering, University of Alberta, Edmonton, Canada.

Sim, S. T. V., Chong, T. H., Krantz, W. B., and Fane, A. G. (2012), "Monitoring of Colloidal Fouling and Its Associated Metastability Using Ultrasonic Time Domain Reflectometry", *Journal of Membrane Science*, vol. 401–402, pp. 241-253.

Simon, A., Penpenic, L., Gondrexon, N., Taha, S., and Dorange, G. (2000), "A Comparative Study between Classical Stirred and Ultrasonically-Assisted Dead-End Ultrafiltration", *Ultrasonics Sonochemistry*, vol. 7, pp. 183-186.

Singh, R. and Laurence, R. L. (1979), "Influence of Slip Velocity at a Membrane Surface on Ultrafiltration Performance—II. Tube Flow System", *International Journal of Heat and Mass Transfer*, vol. 22, pp. 731-737.

Stokes, G. G. (1851), "On the Effect of the Internal Friction of Fluids on the Motion of Pendulums", *Transactions of the Cambridge Philosophical Society*, vol. 9, pp. 8-106.

Sur, H. W. and Cui, Z. F. (2005), "Enhancement of Microfiltration of Yeast Suspensions Using Gas Sparging – Effect of Feed Conditions", *Separation and Purification Technology*, vol. 41, pp. 313-319.

Tatsuno, M. and Bearman, P. W. (1990), "A Visual Study of the Flow around an Oscillating Circular Cylinder at Low Keulegan-Carpenter Numbers and Low Stokes Numbers", Journal of Fluid Mechanics, vol. 211, pp. 157-182.

Tchobanoglous, G., Burton, F. L., Stensel, H. D., Metcalf, and Eddy (2003), Wastewater Engineering: Treatment and Reuse. New York: McGraw-Hill.

van de Ven, W. J. C., Pünt, I. G. M., Zwijnenburg, A., Kemperman, A. J. B., van der Meer, W. G. J., and Wessling, M. (2008), "Hollow Fiber Ultrafiltration: The Concept of Partial Backwashing", Journal of Membrane Science, vol. 320, pp. 319-324.

Veerapaneni, S. and Wiesner, M. R. (1996), "Hydrodynamics of Fractal Aggregates with Radially Varying Permeability", Journal of Colloid and Interface Science, vol. 177, pp. 45-57.

Wang, C. Y. (1968), "On High-Frequency Oscillatory Viscous Flows", Journal of Fluid Mechanics, vol. 32, pp. 55-68.

Wereley, S. T., Akonur, A., and Lueptow, R. M. (2002), "Particle-Fluid Velocities and Fouling in Rotating Filtration of a Suspension", Journal of Membrane Science, vol. 209, pp. 469-484.

Wicaksana, F. (2006), "Submerged Hollow Fibre Membranes in Bubbling Systems", Ph.D. Dissertation, School of Chemical Engineering and Industrial Chemistry, The University of New South Wales, Sydney.

Wicaksana, F., Fane, A. G., Pongpairroj, P., and Field, R. (2012), "Microfiltration of Algae (*Chlorella Sorokiniana*): Critical Flux, Fouling and Transmission", Journal of Membrane Science, vol. 387-388, pp. 83-92.

Williamson, C. H. K. (1985), "Sinusoidal Flow Relative to Circular Cylinders", Journal of Fluid Mechanics, vol. 155, pp. 141-174.

Wu, D., Howell, J. A., and Field, R. W. (1999), "Critical Flux Measurement for Model Colloids", Journal of Membrane Science, vol. 152, pp. 89-98.

Wu, J., Le-Clech, P., Stuetz, R. M., Fane, A. G., and Chen, V. (2008), "Effects of Relaxation and Backwashing Conditions on Fouling in Membrane Bioreactor", Journal of Membrane Science, vol. 324, pp. 26-32.

Xia, L., Law, A. W.-K., and Fane, A. G. (2013), "Hydrodynamic Effects of Air Sparging on Hollow Fiber Membranes in a Bubble Column Reactor", Water Research, vol. 47, pp. 3762-3772.

Xiao, K., Wang, X., Huang, X., Waite, T. D., and Wen, X. (2011), "Combined Effect of Membrane and Foulant Hydrophobicity and Surface Charge on Adsorptive Fouling During Microfiltration", Journal of Membrane Science, vol. 373, pp. 140-151.

- Yamamoto, K., Hiasa, M., Mahmood, T., and Matsuo, T. (1989), "Direct Solid-Liquid Separation Using Hollow Fiber Membrane in an Activated Sludge Aeration Tank", Water Science and Technology, vol. 21, pp. 43-54.
- Ye, Y., Chen, V., and Le-Clech, P. (2011), "Evolution of Fouling Deposition and Removal on Hollow Fibre Membrane During Filtration with Periodical Backwash", Desalination, vol. 283, pp. 198-205.
- Yeo, A. P. S., Law, A. W. K., and Fane, A. G. (2006), "Factors Affecting the Performance of a Submerged Hollow Fiber Bundle", Journal of Membrane Science, vol. 280, pp. 969-982.
- Yeo, A. P. S., Law, A. W. K., and Fane, A. G. (2007), "The Relationship between Performance of Submerged Hollow Fibers and Bubble-Induced Phenomena Examined by Particle Image Velocimetry", Journal of Membrane Science, vol. 304, pp. 125-137.
- Zamani, F., Law, A. W. K., and Fane, A. G. (2013), "Hydrodynamic Analysis of Vibrating Hollow Fibre Membranes", Journal of Membrane Science, vol. 429, pp. 304-312.
- Zhang, Y. P., Fane, A. G., and Law, A. W. K. (2006), "Critical Flux and Particle Deposition of Bidisperse Suspensions During Crossflow Microfiltration", Journal of Membrane Science, vol. 282, pp. 189-197.
- Zhang, Y. P., Law, A. W. K., and Fane, A. G. (2010), "Determination of Critical Flux by Mass Balance Technique Combined with Direct Observation Image Analysis", Journal of Membrane Science, vol. 365, pp. 106-113.
- Zsirai, T., Buzatu, P., Aerts, P., and Judd, S. (2012), "Efficacy of Relaxation, Backflushing, Chemical Cleaning and Clogging Removal for an Immersed Hollow Fibre Membrane Bioreactor", Water Research, vol. 46, pp. 4499-4507.
- Zydney, A. L. and Colton, C. K. (1986), "A Concentration Polarization Model for the Filtrate Flux in Cross-Flow Microfiltration of Particulate Suspensions", Chemical Engineering Communications, vol. 47, pp. 1 - 21.