Vibration of hollow fibre membranes in submerged membrane bio-reactors (SMBRs)

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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

**VIBRATION OF HOLLOW FIBRE MEMBRANES
IN SUBMERGED MEMBRANE BIO-REACTORS
(SMBRs)**

LI TIAN

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

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(SMBRs)**

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SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

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SUMMARY

In this study, the improvement of fouling control of submerged hollow fibre membrane filtration with mechanical sinusoidal vibration was examined experimentally in the dead-end filtration of inorganic Bentonite and organic yeast suspensions, as well as mixed liquor collected from a local water reclamation plant. The hollow fibre membranes were submerged in the reactor and vibrated both longitudinally and transversely.

Experiments with longitudinal vibration in both Bentonite and yeast suspensions showed that the membrane performance could be greatly improved when vibration frequency or vibration amplitude was increased beyond a threshold magnitude. In addition, small degree of fibre looseness could further reduce membrane fouling under vibration. A comparison of vibrating the hollow fibres with and without the holding frame was also carried out to determine the effects of turbulence generated by the vibrating holding frame used in the experimental setup. Particle Image Velocimetry (PIV) measurements were performed to quantify the associated turbulence inside the membrane reactors. It was confirmed that the turbulence generated by the vibrating frame was more apparent at a high vibration frequency, but its contribution to the fouling reduction was minor. In addition, the energy consumption for vibration was significantly less than aeration with a comparable fouling rate, which could be due to the fact that only the boundary fluid layers around the fibres are mobilized in vibration and thus the energy dissipation is much reduced.

Experiments with transverse vibration indicated that membrane fouling could be further reduced as compared to longitudinal vibration, and could be attributed to the separation of boundary layers and generation of secondary flows. A small degree of fibre looseness was also found to further reduce the membrane fouling by the transverse vibration. Experiments with varying packing densities of membrane bundles with transverse vibration showed that at larger vibration amplitudes, a high packing density

of fibres could be operated with little membrane fouling, which indicated that the secondary flows generated could overcome the strong permeate flux competition within the bundle. The inclusion of vibration relaxation suggested that a short relaxation time was more favourable in the half vibration/relaxation mode. PIV measurements indicated that vortices could be generated by transverse vibration. Finally, the measurement of energy consumption indicated that transverse vibration was more efficient and effective for fouling control than longitudinal vibration.

The effect of transverse vibration was further investigated for both short and long operating time in mixed liquor. For the short duration operation, a short relaxation interval was also found to be more effective for fouling control with same total combined vibration/relaxation time for vibration relaxation operations in mixed liquor. More membrane fouling was induced by higher concentration of mixed liquor due to more foulant deposited on the membrane surface. Transverse vibration can be more effective for fouling control in mixed liquor than longitudinal vibration due to the secondary flows and vortices generation by transverse vibration. The effect of transverse vibration could be further intensified with a small amount of air sparging due to the turbulence enhancement by the moving bubbles. For the long duration operation, the high concentrations of mixed liquor suspended solids (MLSS) from the feed accumulated in the reactor over a long period, fouled the membrane quickly and also led to fibre breakage under transverse vibration. The carbohydrates and proteins in soluble microbial products (SMP) and extracellular polymeric substances (EPS) were observed to play significant roles on the membrane performance, among which the soluble carbohydrate was dominant in the membrane fouling. The operating duration of the membrane filtration was greatly increased at higher vibration frequencies due to the higher shear stresses induced by the transverse vibration, however the risk of fibre breakage was also increased. An average removal efficiency of over 90% was recorded for both the organics and nutrients in the reactor due to the microorganism biological process, which indicated that transverse vibration could be effectively applied in

submerged membrane bioreactors (SMBRs) with real mixed liquor in industrial applications.

Lastly, a Vibratory-Stirring (VS) membrane module was developed by including a specially designed stencil in the module that held the fibre bundles. The VS membrane module was found to be able to further reduce membrane fouling, which can be attributed to the turbulence generated in the neighbouring region of the stencil resulting in a recirculation flow around the module and scouring of the membrane surface. The energy consumption measurement indicated that the vibration of the VS membrane module induced only very small amount of energy consumption.

Overall, the results from the present study confirmed that at moderate frequencies and amplitudes, hollow fibre membrane fouling in SMBRs could be reduced substantially by vibration due to the dynamic shear enhancement on the membrane surface.

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LIST OF SYMBOLS

A	Vibration amplitude (mm)
ACH	Aluminium Chlorhydrate
b	Longitudinal intercept of Eq. (3.8) (s/L)
BAP	Biomass associated product
BSA	Bovine Serum Albumin
c	Mass of cake deposited per unit volume of filtrate (g/L)
COD	Carbon oxygen demand (mg/L)
COD _f	Feed COD (mg/L)
COD _p	Permeate COD (mg/L)
D	Hollow fibre diameter (mm)
d_e	Equivalent diameter of an annular vessel (mm)
DO	Dissolved oxygen (mg/L)
dTMP/dt	Rate of TMP increase (or fouling rate) (kPa/h)
E	Enhancement factor
EPS	Extracellular polymeric substances
F	Vibration frequency (Hz)
HRT	Hydraulic retention time (h)
IA	Interrogation area
J	Flux ($(L/(m^2 \cdot h))$ or LMH)
J_w	Clean water flux (LMH)
k	Slope of Eq. (3.8) (s/L^2)
L	Hollow fibre length (cm)
L_0	Distance between fixed ends of hollow fibres (cm)
LMH	$L/(m^2 \cdot h)$
MBR	Membrane bioreactor
MF	Microfiltration
MLSS	Mixed liquor suspended solid (g/L)
MLVSS	Mixed liquor volatile suspended solid (g/L)

LIST OF SYMBOLS

NF	Nanofiltration
NOM	Natural organic matter
OLR	Organic loading rate
PAC	Polyaluminium Chloride
PAN	Polyacrylonitrile
PIV	Particle Image Velocimetry
R	Radius of membranes (mm)
R_1	Inner radius of membranes (mm)
R_2	Outer radius of membranes (mm)
R_c	Hydraulic resistance attributed to the cake layer (m^{-1})
R_c'	Specific cake resistance per unit mass (m/g)
R_{ef}	External fouling resistance (m^{-1})
Re_v	Vibrational Reynolds number
R_{if}	Internal fouling resistance (m^{-1})
RO	Reverse osmosis
R_m	Hydraulic resistance of the membrane (m^{-1})
R_p	Polarization layer resistance (m^{-1})
R_t	Total resistance of the membrane (m^{-1})
S	Effective membrane area (m^2)
SMBRs	Submerged membrane bioreactors
SRT	Sludge retention time (h)
t	Filtration time (s)
ΔP , TMP	Trans-membrane pressure (kPa)
u	Fluid velocity parallel to the surface (m/s)
$\bar{u}$	Average velocity of each grid position (x direction) in the contour map (m/s)
$\bar{\bar{u}}$	Average velocity of all grid positions (x direction) in the contour map (m/s)
U'	Velocity deviation in the PIV contour map (m/s)
UAP	Utilisation associated product

LIST OF SYMBOLS

UF	Ultrafiltration
$\bar{v}$	Average velocity of each grid position (y direction) in the contour map (m/s)
$\bar{\bar{v}}$	Average velocity of all grid positions (y direction) in the contour map (m/s)
V	Cumulative volume of permeate (L)
$\bar{V}$	Mean vibrational speed (m/s)
VS	Vibratory-Stirring
VSEP	Vibratory Shear-Enhanced Processing

Greek letters

η	COD removal efficiency
ρ_s	Solid density (g/L)
μ	Fluid dynamic viscosity (Pa·s)
ν	Fluid kinematic viscosity ($\text{m}^2 \cdot \text{s}^{-1}$)
γ	Shear rate (s^{-1})
γ_ω	Surface shear rate (s^{-1})
$\bar{\gamma}_\omega$	Average shear rate (s^{-1})
$\gamma_{\omega \max}$	Maximum shear rate (s^{-1})
ω	Angular velocity (rad/s)
δ_c	Cake thickness (mm)
$\emptyset_c$	Solid volume fraction

RESEARCH OUTPUT

Publications

- Li, T.**, Law, A. W. K. and Fane, A. G. (2014), “Submerged Hollow Fibre Membrane Filtration with Transverse and Longitudinal Vibrations”, Journal of Membrane Science, Vol. 455, pp. 83-91.
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Patent Application

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Chapter 1 Introduction

1.1 Background

Submerged hollow fibre membranes are widely used in water and waste water treatment processes due to their cost effectiveness and relative large packing densities. In particular, it is becoming the preferred configuration in submerged membrane bioreactors (SMBRs) to produce high quality effluent in a reduced reactor size and also minimized sludge production. However, its application is still hindered by problems associated with concentration polarization and membrane fouling.

For fouling mitigation, the use of shear stresses on the membrane surface is recognized as one of the most effective techniques. There are mainly three ways to generate membrane surface shear: (i) conventional crossflow; (ii) air sparging; and (iii) vibration. In the conventional crossflow filtration, shear stress is produced as the feed fluid runs tangentially on the membrane surface. However, the shear stress generated by the crossflow requires high crossflow velocity or pressure gradient, which not only requires greater energy to drive the pumps, but also causes decrease of effective trans-membrane pressure (TMP) along the membrane leading to non-optimal membrane utilization (Jaffrin, 2008).

Air sparging has been commonly adopted in the SMBR for industry applications. In addition to inducing wall shear stresses on the membrane surface (Cui et al., 2003), the rising bubbles also oxygenate the fluid and disrupt the concentration polarization layer around the hollow fibres (Bellara et al., 1996). However, shear stresses induced by bubbling are relatively weak. Also, the flux improvement reaches a limit beyond which further increase in the air flow rate becomes ineffective due to an optimal superficial air velocity in the air sparging process (Xia et al., 2013). Moreover, the energy efficiency

by the air sparging process is quite low due to additional dissipation of energy in the region away from the membrane module.

In addition, vibration can induce dynamic shear stresses on the membrane surfaces for fouling mitigations, which can be done by vibrating/rotating either the membranes or the adjacent fluid. The former is more energy efficient since vibration is focused on the membrane itself and thus nearly 99% of the total energy is converted at the surface of the membranes. With the dynamic shear generated on the membrane surface, problems associated with concentration polarization and membrane fouling can be reduced. However, due to the complexity and incomplete understanding of the process, the vibration of submerged hollow fibre membranes is not widely used at present. For example, the relationships between the vibration characteristics, membrane geometries, and feed properties are not well studied. The membrane performance and the hydrodynamics will be affected by conditions such as different vibration frequencies/amplitudes. An ideal case is to operate the submerged system at certain conditions that requires low energy consumption but maintains high membrane permeability.

1.2 Research Questions

This study examines fouling control of submerged hollow fibre membranes by vibration. Some questions are raised before the objectives are presented.

(1) Is vibration effective for membrane fouling control? How does vibration affect membrane filtration performance? Does membrane geometry affect membrane filtration performance under vibration?

(2) Do the feed properties affect membrane filtration performance under vibration? How does vibration affect the mass transport of the feed?

(3) How does the vibration mode, e.g. transverse vibration/longitudinal vibration and continuous vibration/vibration relaxation, affect membrane filtration performance? What are the hydrodynamics and energy consumption under vibration?

(4) Is vibration effective for real applications? Can vibration effect be further enhanced with air bubbling?

(5) Can vibration effect be further improved with other special structure? What are the hydrodynamics and energy consumption under vibration with the special structure?

1.3 Objectives of the study

The current study focuses on the vibration of submerged hollow fibre membranes. It aims to investigate the applicability of vibration as a fouling control technique in submerged hollow fibre membrane bioreactors (MBRs). Four main objectives are examined as described below.

(1) Study the effect of vibration frequencies/amplitudes and membrane geometries on the membrane filtration performance in both inorganic and organic model feeds under longitudinal vibration, and investigate the hydrodynamics and energy consumption of longitudinal vibration.

(2) Study the effect of transverse vibration in both inorganic and organic model feeds and investigate transverse vibration on the membrane filtration performance, and compare the membrane filtration performance, hydrodynamics and energy consumption between transverse vibration and longitudinal vibration.

(3) Apply low frequency of transverse vibration and small flow rate of air bubbling in real mixed liquor to study the effect of combined vibration and aeration and biosolids characteristics on the membrane filtration performance.

(4) Further develop a Vibratory-Stirring (VS) membrane module for fouling control of submerged hollow fibre membranes, and study the hydrodynamics and energy consumption of the VS membrane module.

1.4 Layout of the thesis

A brief introduction and background to the problem and objectives of this study are given in Chapter 1.

The main hydrodynamic methods including air bubbling and vibration of membranes to control fouling are summarized in Chapter 2. Detailed calculation of shear rate by vibration and applications of membrane vibration are also presented.

The use of longitudinal vibration in an inorganic feed suspension of Bentonite particles was first investigated (Chapter 3). Various combinations of vibration frequencies and amplitudes, and degrees of fibre looseness (previous studies involved only tightly held fibres) were examined. In addition, the frame that held the hollow fibre membranes could generate turbulence in the fluid upon vibration, thus contributed to the reduction in membrane fouling. The turbulence induced by vibrating the holding frame was examined using the Particle Image Velocimetry (PIV) technique by comparing the filtration performance of submerged hollow fibre membranes with and without the vibration of the holding frame. The energy consumption comparison by longitudinal vibration and air bubbling was also conducted.

The use of longitudinal vibration in an organic feed suspension of yeast was also examined (Chapter 4). The yeast particle suspensions were separated into washed yeast suspensions and supernatant, and their contributions to membrane fouling under longitudinal vibration were evaluated. In addition, the effect of fibre looseness in yeast suspensions under longitudinal vibration was also investigated.

The use of transverse vibration was explored in this study as well (Chapter 5). The membrane filtration performances with transverse and longitudinal vibration were compared in both Bentonite and yeast suspensions. The effects of fibre packing density and vibration relaxation were also investigated. Moreover, the energy consumption by transverse and longitudinal vibration was also compared.

The use of transverse vibration in real mixed liquor is presented in Chapter 6. Both short and long duration tests by transverse vibration were explored. A combination study of air bubbling and vibration was conducted as well. The biomass physiological state and sludge characteristics related to the removal efficiency and fouling potential under different vibration frequencies were examined. By comparing the membrane performance in different situations, the optimal operating condition was proposed.

The inclusion of a VS membrane module by including a specially designed stencil in the module that held the fibre bundles was developed and studied (Chapter 7). The effect of the VS membrane module was tested in different feed suspensions including real mixed liquor. The turbulence induced by the vibrating stencil was examined using PIV technique. The energy consumption by the vibrating stencil was also explored.

Finally the major findings in this study are concluded and some recommendations for future work are proposed (Chapter 8).

Chapter 2 Literature Review

In this chapter, a detailed review of existing theories and previous studies is presented. Over the past decades, the shear-enhanced filtration theories have been developed to study the membrane filtration performance in vibration processes. Generally, the membrane performance not only relies on the shear generated by the vibration, but also on the hydrodynamic environment experienced by the membrane inside the reactor. In the following, MBR and membrane fouling are introduced first before the theory of vibration is presented.

2.1 Background of SMBR

The SMBR processes combine the conventional bioreactor and a submerged membrane filtration unit as a direct solid-liquid separation technology. With either microfiltration (MF) or ultrafiltration (UF) at a pore size less than 0.2 μm , SMBR allows the complete physical retention of bacteria flocs and suspended solids within the reactor (Krauth and Staab, 1993; Chiemchaisri et al., 1993 and 1994).

Hollow fibre membranes are now extensively used in SMBR owing to the modest energy requirement, large flexibility, high surface area-to-volume ratio, and low operation cost (Delgado et al., 2008; Çulfaz et al., 2011). The most well know uses of hollow fibre membranes in wastewater treatment are to remove turbidity and pathogens.

SMBR technology has been widely adopted in wastewater treatment because of its advantages including small footprint and reactor requirements, high effluent quality, good disinfection capability, higher volumetric loading and less sludge production (Lesjean et al., 2004). However, membrane fouling is still the main problem that hinders its development (Le-Clech et al., 2006; Drews, 2010).

2.2 Membrane fouling mechanism

Membrane fouling is the deposition of foulants on the membrane surface or inside the membrane pores. It is the result of interactions between the membrane and the feed solution. According to the nature of the foulants, fouling can be classified into scaling (precipitation of insoluble salts), colloidal fouling, organic fouling, and biofouling (formation of a biofilm). Fouling leads to an additional hydraulic resistance (foulant resistance) and therefore a lower permeability of the fouled membrane (Fane et al., 2011) in the form of flux reduction and TMP increase. The fouling of membranes in MBR is complex and determined by the basic factors including the nature of the feed (feed composition, floc properties, biomass activity), the membrane properties (material, pore size, hydrophobicity/hydrophilicity, roughness, etc) and the hydrodynamic environment experienced by the membrane (Guglielmi et al., 2007).

The fouling mechanism can be described by three stages (Zhang et al., 2006): (1) an initial short-term rapid rise in TMP of pore closure or blockage due to the rapid formation of a conditioning film and deposit of floc residues on the membrane surface; (2) a long-term linear or weakly exponential rise in TMP of the increasing fouling layer coverage contributed by pore blocking, biopolymer deposition, biofilm attachment and growth; and (3) a sharp increase in TMP jump caused by the local flux higher than the critical flux.

Membrane fouling can occur both on the outer side, creating a cake layer, and on the inner side, clogging with small particles. The inner fouling, known as the irreversible fouling, can be removed only by using chemical cleaning. Generally, the fouling running along the inner side follows the creation of the cake layer on the outer surface of the membrane. Nevertheless, by regular back flush or intensive air sparging to generate shear stress, it is possible to reduce the outer fouling and reversible fouling (Geng et al., 2007).

From previous references, the individual components in the reactor such as bacteria (Meng et al., 2006), yeast (Negaresh et al., 2007), proteins (Ng et al., 2006), and colloids (Rosenberger et al., 2006) can all lead to membrane fouling. The factors of ion charge and composition (Tang et al., 2007), crossflow (Zhang et al., 2011) or dead end flow, concentration (Le-Clech et al., 2003), membrane hydrophilicity (Kim et al., 2004), membrane properties (Le-Clech et al., 2003), flux (Choi et al., 2005) and hydrodynamic conditions (Jaffrin, 2008) also affect the membrane performance. By operating below the critical flux, it is possible that membrane fouling can be avoided. The concept of critical flux was raised in the middle 1990s (Field et al., 1995). It depicts a flux below which a decline of permeability with time does not occur, and above which fouling can be observed. Two distinct forms of the critical flux concept have also been defined, with no fouling and little fouling occurring at sub-critical operation for the strong and weak forms, respectively.

The critical flux depends on the back transport provided by the crossflow or turbulence generated by the imposed liquid flow and/or bubbling as well as the specific solute–membrane interactions (Le-Clech et al., 2006). Solute size also plays a significant role in determining the regime of back transport whether it is diffusive or inertial lift (Davis, 1992; Belfort et al., 1994; Field et al., 1995; Le-Clech et al., 2006). High local concentrations that promote local aggregation due to concentration polarization can also promote the cohesiveness of the foulant layer.

With a mixed feed environment, the membrane fouling mechanism is even more complicated. The interactions between the macromolecules and particulate components of the feed can result in the unexpected changes in fouling. The kinetics and total adsorbing macromolecules determine the initial fouling formation phase. The progressive closure of pores or deposit on the membrane surface then results in the build-up of the foulant cake. The change of the foulant cake and its irreversibility depends on both the composition and the hydrodynamic environment. The interactions between the particulate and macromolecules need to be considered as well as the

complexities observed in fouling studies of natural organic matter. Macromolecular fouling increases the particulate adhesion, but particles can affect the transmission and infiltration of macromolecules into the membrane pores. More studies of the foulant properties in mixed species systems that can prevent foulant build-up or to disengage the foulant layer are needed (Belfort et al., 1994; Le-Clech et al., 2006).

2.3 Feed biomass characteristics on membrane fouling

2.3.1 Mixed liquor suspended solid (MLSS) concentration

MLSS concentration has a complex interaction with MBR fouling and has been regarded as the main foulant parameter. Many studies have been carried out to study the MLSS concentrations related to membrane fouling. However, controversial findings were reported, both positive (Le-Clech et al., 2003) and negative (Chang and Kim, 2005; Trussell et al., 2007).

Operating MBRs with high MLSS concentrations creates serious problems. The oxygen transfer efficiency, which is a ratio of mass transfer coefficient in the process and in clean water, was reported to decrease exponentially with increase of MLSS concentration (Muller et al., 1995; Krampe and Krauth, 2003; Ozdemir and Yenigun, 2013). Thus, high aeration rates were required to provide adequate oxygen supply. Effective membrane scouring was difficult to achieve due to increased mixed liquor viscosity (Shimizu et al., 1996) and decreased filterability. High MLSS concentrations can have detrimental effects on membrane performance (Chang et al., 2002; Le Clech et al., 2003). Chabaliná et al. (2012) studied the influence of MLSS concentrations on the MBR performance. They found that an increase in MLSS caused an increase in the viscosity induced by the proteins and carbohydrates from the mixed liquor, which resulted in the decrease of the filterability. Muller et al. (1995) found that sludge was hardly produced when the MLSS concentration increased to 40-50 g/L. Insel et al. (2011) simulated the MBR, and their results indicated that MBR operation with a level

of around 12-14 g/L MLSS provided an optimal compromise between reducing the reactor footprint and minimizing of mass transfer limitation for effective nitrogen removal. Their work on the comparison of response of the biomass fractions showed that the autotrophic biomass was much more influenced by the mass transfer limitation conditions with MLSS concentrations higher than 15 g/L. Itonaga et al. (2004) indicated that a maximum MLSS concentration of around 10 g/L led to an efficient operation in MBR without pre-treatment while higher MLSS concentrations could greatly increase the suspension viscosity, and exceedingly high MLSS concentrations (> 15 g/L) would lead to serious membrane fouling. van der Roest et al. (2002) suggested the MLSS concentration to be 10 to 12 g/L in order to both reduce membrane fouling and energy consumption. Rosenberger et al. (2005) carried out detailed research on the influence of MLSS concentration on membrane fouling. They found that with the increase of MLSS concentration, the membrane fouling decreased for smaller MLSS concentration (< 6 g/L) and increased for higher MLSS concentration (> 15 g/L). They suggested a best MLSS concentration of 8 to 12 g/L for the efficient MBR operation.

For low MLSS concentration, however, a major concern is to achieve adequate substrate removal and maintain high effluent quality (Trussell et al., 2007). For the highest chemical oxygen demand (COD) (Ren et al., 2005) and virus (Shang et al., 2005) removal, an optimal MLSS concentration of 6 g/L was suggested.

In the SMBRs, both heterotrophic and autotrophic bacteria coexist. They simultaneously remove the organics and nitrogenous materials, and produce soluble microbial products (SMP) and extracellular polymeric substances (EPS) during the microbial metabolism of growth, decay or in a response to changing environmental conditions (Tsuneda et al., 2003; Saa and Teschke, 2006). The description of SMP and EPS is given in the following sections.

2.3.2 SMP

SMP is defined as the soluble cellular compounds that are released into solution during cell lysis. They diffuse through the cell membrane, and are lost during synthesis or excreted for some purpose (Laspidou and Rittmann, 2002). SMP is therefore complex, and includes polysaccharides, proteins, humic and fulvic acids, nucleic acids, organic acids, amino acids, antibiotics, steroids, exocellular enzymes, siderophores, structural components of cells and products of energy metabolism. It constitutes the majority of soluble organic matter in the effluent (Barker and Stuckey, 1999).

SMP can be classified into substrate-utilization-associated products (UAP) that are associated with substrate metabolism and biomass growth, and biomass-associated products (BAP) that are associated with biomass decay. UAP is from the processing of low molecular weight of compounds under substrate-utilizing conditions, and is found to be produced at a rate proportional to the rate of substrate utilization. BAP is from the conversion of high molecular weight of molecules in endogenous processes, and is found to be produced at a rate proportional to the concentration of biomass (Barker and Stuckey, 1999; Xie et al., 2013).

SMP production can be affected by feed strength, substrate type, organic loading rate (OLR), temperature, sludge retention time (SRT), hydraulic retention time (HRT), biomass concentration, and reactor type (Barker and Stuckey, 1999). Dissolved oxygen (DO) concentration has nearly no effect on the total SMP production. Increasing substrate concentration, temperature or OLR can increase the SMP production (Xie et al., 2013). Increasing SRT can result in high sludge concentrations maintained in the MBR so as to treat industrial wastewater with a high loading rate inside the bioreactor. However, the SMP that is released to the microbiological environment also increases, which can have strong implications to the membrane fouling (Liang et al., 2007; Kimura et al., 2009; Okamura et al., 2009; Xie et al., 2012). Moreover, exceedingly high concentrations of sludge and the associated increase in the viscosity of the mixed

liquor can lead to additional aeration requirements to provide adequate oxygen supply and effective membrane scouring (Shimizu et al., 1996). With small concentrations of sludge, however, a major concern is to achieve adequate substrate removal and maintain high effluent quality. Comparatively, HRT has only a minor impact on the SMP production, but it can affect the effluent quality (Xie et al., 2012).

The presence of SMP has significant implications for the performance of the treatment processes, as well as the quality of the feed water and membrane fouling. SMP has been found to play an important role in the formation of flocs and biofilms, and is the major fouling components in MBR processes (Barker and Stuckey, 1999; Massé et al., 2006, Tay et al., 2007). In particular, the main components of carbohydrates and proteins have been regarded as main membrane foulants, although controversial results have been reported on whether carbohydrates or proteins contribute more toward membrane fouling (Mukai et al., 2000; Rosenberger and Kraume, 2002; Hernandez et al., 2005; Rosenberger et al., 2006). In addition, increase in SMP causes a decrease in the mean particle size of the biosolids, which results in the decrease of the membrane filterability (Chabaliná et al., 2012). It has been suggested that an optimization of the biological treatment process could reduce SMP, rather than increasing the size of the treatment plant which could increase both investment costs as well as operation and maintenance costs (Barker and Stuckey, 1999).

2.3.3 EPS

EPS is a complex mixture of high molecular polymers with complicated structures present outside of cells or in the interior of microbial aggregates that protect them against environmental stress and toxicity (Liao et al., 2004; Lin et al., 2014). EPS matrix has multiple functions including the adhesion to surfaces, aggregation of bacterial cells in flocs and biofilms, stabilization of the biofilm structure, formation of a protective barrier to provide resistance to biocides or other harmful effects, retention of water, sorption of exogenous organic compounds for the accumulation of nutrients

from the environment, and accumulation of enzymatic activities, such as digestion of exogenous macromolecules for nutrient acquisition (Laspidou and Rittmann, 2002; Le-Clech et al., 2006). Bioflocs are formed with interactions among microbial aggregates, filamentous bacterial strains, organic and inorganic particles, which can be held together by EPS (Urbain et al., 1993). EPS allows cooperation and communication among cells in microbial aggregates.

EPS is generally subdivided into two categories: bound EPS and soluble EPS. Bound EPS refers to sheaths, capsular polymers, condensed gel, loosely bound polymers and attached organic material, and soluble EPS refers to soluble macromolecules, colloids and slimes (Laspidou and Rittmann, 2002). Soluble EPS is thus the same as SMP.

EPS plays important roles in the performance of the treatment processes and the quality of the effluent and membrane fouling (Rosenberger and Kraume, 2002). EPS relates to the formation of flocs and biofilms, contributes to the structural, surface charge and settling properties, and is regarded as main membrane fouling components in MBR systems (Barker and Stuckey, 1999; Hernandez Rojas et al., 2005; Massé et al., 2006; Tay et al., 2007; Bala Subramanian et al., 2010). In particular, the main components of carbohydrates and proteins in EPS have been regarded as main membrane foulants (Dvořák et al., 2011; Huang et al., 2012).

The presence of large quantities of EPS may increase the interactions via entanglement, but may also affect hydrophobic interaction, while electrostatic forces are important but less so than the polymer-related forces (Mikkelsen and Keiding, 2002). The concentration of EPS in the mixed liquor influences the structure and porosity of the cake layer on the membrane surface. According to the Carman-Kozeny equation, the specific resistance of sludge cake is inversely proportional to the particle diameter; in other words, membrane fouling increases as floc size decreases. It has been reported that the filterability of the cake layers improves when the EPS concentration increases, due to the fact that sludge with higher extractable EPS concentrations has a tendency to

aggregate the micro-organisms, small particles and colloids to form larger flocs and increase the settleability (Mikkelsen and Keiding, 2002; Chabaliná et al., 2012).

A decrease in EPS can reduce membrane fouling. However, if the sludge concentration is too small and the rate of biomass production exceeds the rate of EPS production, the bioflocculation could then be ineffective resulting in poorly settling sludge (Ng and Hermanowicz, 2005). Ca^{2+} addition can increase the sludge settling and dewatering capacity (Bala Subramanian et al., 2010) since EPS is negatively charged in nature.

2.4 Hydrodynamic methods to reduce membrane fouling

By changing the hydrodynamic condition in the reactor, the membrane fouling can also be reduced. For example, air sparging is now commonly used as a useful strategy to limit membrane fouling. During air sparging, shear stresses generated by the rising air bubbles can sweep away the foulants deposited on the membrane surface. Unfortunately, the energy consumption by air sparging mainly from the energy associated with the coarse bubble aeration can be as high as 70% of the total cost (Gander et al., 2000; Judd, 2006; Drews, 2010), and the flux improvement by air sparging is limited due to an optimal superficial air velocity for the air sparging (Xia et al., 2013). Details of air sparging on membrane fouling control will be presented in Section 2.5.

Hence, new techniques with better efficiency are needed. Among these attempts have been turbulence promoters, Couette motion, pulsations, and vibration (Vigo et al., 1993).

Turbulence is a flow regime characterized by chaotic property changes, with rapid variation of pressure and velocity in space and time. In turbulence flow, unsteady vortices appear on many scales and interact with each other. Drag due to boundary layer skin friction increases. Turbulence in the reactor can reduce membrane fouling, as

it can generate rotational or swirling secondary flows that increase the shear stresses on the membrane, thus enhancing the scouring of the membrane surface (Krstić et al., 2002).

In fluid dynamics, plane Couette flow refers to the laminar flow of a viscous fluid in the space between two parallel plates, one of which is moving relative to the other. The flow is driven by virtue of the viscous drag force acting on the fluid and the applied pressure gradient parallel to the plates. The Couette flow is commonly applied in chemical (Vigo et al., 1985) and biotechnological (Kroner and Nissinen, 1988) as well as medical areas (Beaudoin and Jaffrin, 1989) for fouling control.

Pulsations are also attempted in biotechnological and medical applications (Philp et al., 1994; Jaffrin et al., 1995). Pulsating pressure was used in ultrafiltration in either the feed or the permeate flow by Nikolov et al. (1993). They found that the pulsation improved the trans-membrane flux which was attributed to the almost complete elimination of the possibility for the formation of a gel layer.

The use of vibration in membrane filtration refers to the creation of shear rate at the membrane surface by a moving part, either by vibrating/oscillating/rotating the membrane or the adjacent fluid. During the relative movement of the membranes and the adjacent fluid, shear stress is generated on the membrane surface. As compared to air sparging or vibrating/oscillating/rotating the adjacent fluid, vibration of membranes is more energy efficiency since the energy dissipation is mainly concentrated on the boundary layers (Gomaa and Al Taweel, 1995). In addition, the vibration energy is more focused on the membrane itself, thus nearly 99% of the total energy is converted at the surface of the membranes during vibration of membranes (Culkin and Armando, 1992). Detailed information of vibration on membrane filtration can be found in Section 2.6.

2.5 Membrane fouling control by air bubbling

The moving bubbles can generate secondary flows and wakes, which could disrupt the mass transfer boundary layer and promote local mixing near the membrane surface (Cui et al., 2003). Moreover, the air bubbling can produce shear stress and turbulence fluctuations which are recognized as an important role in membrane fouling control (Yeo et al., 2006). In addition, the interaction between the bubbles and the fibres also affects the membrane performance, which is restricted by the fibre geometry, e.g. the fibre flexibility and packing density. In the following, the air bubbling used for membrane fouling control with increase of air flow rate is first discussed. Next, the flow dynamics by the air bubbling is described subsequently. Finally the fibre geometry that affects the air bubbling effect is also elaborated.

2.5.1 Increase in superficial air velocity

High gas flow rate injection can increase the cross flow velocity, which results in an increase of local mixing near the membrane surface. However, the flux enhancement reaches a plateau over certain superficial air velocity (Chang and Fane, 2011) and the improvement of membrane filtration performance is only significant at high gas flow rate, which requires extensive energy consumption.

Xia et al. (2013) studied the membrane fouling control by air bubbling with a superficial air velocity from 0.1 to 2.2 mm/s 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 (Figure 2.1). They found the fouling reduction to be in 3 stages: a fast fouling reduction stage with the superficial air velocity below 0.65 mm/s (Stage 1), a low mitigation stage from 0.65 to 1.1 mm/s (Stage 2), and a limiting stage with no further membrane fouling reduction beyond 1.1 mm/s (Stage 3). They suggested that a small amount of air to the membrane filtration system could improve the membrane performance to a great extent. Additionally, they also illustrated that the existence of an optimal superficial air

velocity for the air sparging of a membrane system beyond which further increases had no benefit on fouling mitigation.

Figure 2.1 Fouling rates for 0.65 g/L Bentonite solution at 0.3 and 0.6 m locations (Xia et al., 2013)

2.5.2 Flow dynamics by air bubbling

The arising bubbles generate a relative movement between the bubbles and adjacent fluid, thus, shear stress can be produced by the moving motion, which can be used to reduce membrane fouling. Recently great concern is attracted by the shear stresses of air and liquid on the membrane surface in the reactor by the bubbling. Khalili-Garakani et al. (2011) studied the hydrodynamics of air bubbling for fouling control using both experimental approaches and numerical simulations. They determined the wall shear stresses of air and liquid on the membrane surface by computational fluid dynamics, and found that the permeate flux and resistances could be well related to the wall shear stresses.

In addition to the shear stress, there is also an increasing concern that turbulence fluctuations induced by the air bubbling can play a significant role in reducing membrane fouling. Yeo et al. (2007) investigated the membrane filtration performance of submerged hollow fibres with air bubbling. Their results clearly showed the importance of the turbulent shear stresses on the membrane fouling control.

2.5.3 Fibre geometry effect on the fouling control by air bubbling

In SMBR, the membrane fouling control by air bubbling is affected by the fibre geometry, which is also important for MBR design with vibrations. Here, the fibre geometries, such as fibre length, fibre looseness and packing density, in the air bubbling studies that affect the membrane filtration performance are also reviewed.

2.5.3.1 Fibre length

Longer fibres have larger surface area that can increase permeate production. Fibres can be swayed with the motion of the adjacent fluid flow and air bubbles. The effect of fibre length by air bubbling was investigated. Chang and Fane (2001) simulated the effect of fibre length on the flux distribution of submerged hollow fibre modules by air bubbling. They found that longer fibres led to more inhomogeneous flux distribution, thus resulted to larger fluid resistance, higher lumen pressure losses and offset the fibre movement in the reactor.

However, longer fibres have the potential of more lateral movement during vibration, which could help reduce membrane fouling. Wicaksana et al. (2006) examined the membrane fouling of both short and long fibres by air bubbling (Figure 2.2). They found that the longer fibres first induced larger fouling rate and subsequently a slightly lower fouling rate. They attributed the initial larger fouling rate for the greater initial flux variation and greater fibre movement for the longer fibres.

Figure 2.2 The filtration performances with 50 and 70 cm fibre lengths (0.65 mm fibre o.d., 99% tightness, 5 g/L yeast, 1.5 L/min air flowrate, 1 mm diffuser and 30 LMH) (Wicaksana et al., 2006)

2.5.3.2 Fibre looseness

Fibre looseness is referred to fibre flexibility. Fibre flexibility can be expressed in term of tightness and looseness, where the tightness and looseness are defined as (Zenon, 1997; Wicaksana et al., 2006):

$$Tightness = \frac{L_0}{L} \times 100\% \quad (2.1)$$

$$Looseness = 1 - Tightness \quad (2.2)$$

where L_0 is distance between fixed ends of hollow fibres, and L is hollow fibre length. Loose fibres are imposed to have the lateral movement by the induced liquid flow. For MBRs, the looseness of the hollow fibre membranes was recommended to be in the

range of 0.1-5% by Zenon (1997). Wicaksana et al. (2006) studied the fouling control by air bubbling with tight and loose fibres. The effect of fibre looseness including 0%, 1% and 4% (or tightness 100%, 99% and 96%) with 1.5 L/min air flowrate was conducted. The results showed when fibre looseness was increased from 0% to 1%, significant membrane fouling could be reduced. However, when fibre looseness was increased to 4%, only a little membrane fouling could be further reduced. The fibre lateral displacement was then further analyzed and the results showed that higher fibre lateral displacement could be induced by larger fibre looseness but limited by the geometric maximum displacement (Figure 2.3). They suggested that 40% of the bubble-induced benefit was gained by allowing fibre movement.

Figure 2.3 Fibre amplitude vs. fibre tightness (70 cm fibre length, 0.65 mm fibre o.d., 2 L/min air flowrate and 1 mm nozzle size) (Wicaksana et al., 2006)

Yeo et al. (2007) studied the relationship between performance of submerged hollow fibres and bubble-induced phenomena, and quantified the effect of bubble frequency

and fibre looseness on the membrane movement (Figure 2.4). They examined the shear stress for loose fibres, and indicated that fibre looseness increased the shear stress. They also found that fibre velocity depended mainly on fibre looseness at low bubbling frequency, while the effect could be reduced with high bubbling frequency. By comparing the membrane fouling for 0%, 0.5%, 1% and 2% looseness fibres, they suggested an optimal value of small looseness for fouling control by air bubbling.

Figure 2.4 Variation of mean shear stress with air airflow rates for small, medium and large bubbles at various looseness (Yeo et al., 2007)

Bérubé et al. (2006) quantified the shear force at the surface under dual-phase flow for both loose and tight fibres using the electrochemical shear probe. For single-fibre module, they found that there was no substantial difference in the surface shear forces for the loosely and tightly configured single-fibre modules, and they attributed to that the lateral movement induced by the swaying fibre did not contribute to the magnitude of shear forces at the surface of a fibre. However, for the multi-fibre modules, they examined that the surface shear forces for tightly configured multi-fibre modules were

substantially lower than those for loosely configured multi-fibre modules with the exception of infrequent peaks (Figure 2.5), and they suggested that the close proximity of other fibres in a tightly configured multi-fibre module could potentially shield certain areas of a fibre from both the bulk liquid flow and sparged gas bubbles.

Figure 2.5 Typical surface shear force measured under dual-phase flow for loose and tight multi-fiber module configurations (results presented are for a bulk cross-flow velocity of 0.4 m/s) (Bérubé et al., 2006)

Chan et al. (2007) quantified the shear profiles of both tightly and loosely held fibres inside gas sparged reactor. Their results also clearly suggested the benefit of the loosely held fibres.

2.5.3.3 Fibre packing density

With more hollow fibre membranes in the reactor, the permeate flow can be increased with a high packing density. However, high packing density leads to severe flux

competition or the inhomogeneous flow distribution within the fibre bundles, e.g., higher flux for the side fibres and lower flux for the corner fibres (Yeo et al., 2006).

Bérubé et al. (2006) measured the surface shear forces under dual-phase flow for both single- and multi-fibre modules (Figure 2.6). Their results showed that, as compared to single-fibre modules, the peak surface shear force was periodically 45% greater for multi-fibre modules, which was responsible for the significantly higher permeate flux maintained under dual-phase flow for multi-fibre modules.

Figure 2.6 Typical surface shear force measured under dual-phase flow for single- and multi-fibre modules in a loose configuration (results presented are for a bulk cross-flow velocity of 0.3 m/s) (Bérubé et al., 2006)

Chan et al. (2007) quantified the shear profiles of different packing densities of fibres inside gas sparged reactor. Their results illustrated that low and medium fibre packing density bundles could benefit from the more favorable hydrodynamic condition for

fouling reduction and flux enhancement in tightly held fibres. However, they also found that for the loosely held fibres, the high packing density bundles can also benefit from sparged bubbles since the flow path of bubbles rising in loosely held fibres were not confined to a specific region.

Experiments performed by Yeo et al. (2006) with a model bundle of 3×3 fibres revealed that the overall module performance was much worse than that of an individual fibre. It was suggested that the packing density should be lower than 30% in order for the bundle to perform similarly to a single fibre.

2.6 Membrane fouling control by vibration of hollow fibre membranes

2.6.1 Introduction of shear-enhanced filtration

The shear-enhanced filtration by vibration was first explored in 1992 by J. Brad Culkin and Armando (Culkin and Armando, 1992). The initial concept, or the so-called Vibratory Shear-Enhanced Processing (VSEP), was a membrane separation technology platform designed to prevent membrane fouling, or the build-up of solid particles on the surface of the membrane. The original VSEP prototype was a combination of loudspeaker and membrane technology. In this prototype, a stack of circular organic membranes were separated by gaskets and permeate collectors, and mounted on a vertical torsion shaft spun in azimuthal oscillations and rotated rapidly at the base with a resonant frequency of about 60 Hz (Figure 2.7). This produced a shear rate at the membrane-liquid interface of about $150,000 \text{ s}^{-1}$ to treat feed suspensions containing high concentrations of solid. The shear rate at the membrane surface was generated due to the inertia of the fluid which moved at 180° out of phase with the membrane (Figure 2.8). The high shear rate produced was about ten times that obtainable in the typical crossflow membrane systems, and was effective for foulant removal.

Figure 2.7 Schematic diagram of VSEP (New Logic Research, Inc.
<http://www.vsep.com/technology/index.html>)

Figure 2.8 Principles of VSEP (New Logic Research, Inc.
<http://www.vsep.com/technology/index.html>)

The hydrodynamics or shear-enhanced filtrations are now widely developed in MF (Brou et al., 2002; Beier et al., 2006), UF (Belfort et al., 1994; Jaffrin et al., 2004; Shi and Benjamin, 2008), NF (Frappart et al., 2006 and 2008a) as well as in RO (Frappart et al., 2008b; Shi and Benjamin, 2011). And the applications are extensively explored, including the removal of humic substance (Takata et al., 1998), diluted milk (Frappart et al., 2006), natural organic matter (NOM) (Petala and Zouboulis, 2006; Shi and Benjamin, 2008) as well as wastewater treatment (Delgado et al., 2008).

Many modules based on shear-enhanced filtration have now been made available, with further development such as torsional oscillating disks (Huuhilo et al., 2001; Postlethwaite et al., 2004), rotating disks and membranes (Murkes and Carlsson, 1988; Bouzerar et al., 2000; Liu et al., 2012), vibrating flat sheet membranes (Akoum et al., 2002; Bilad et al., 2012), and vibrating hollow fibre membranes (Beier et al., 2006). However, due to the complexities and incomplete understanding involved, the vibration technique is still not widely implemented in industrial applications so far.

During the vibration, shear stress is generated on the membrane surface by the relative motion between the membranes and liquid, thus concentration polarization and cake fouling can be reduced. As compared to torsional or rotating disks which are usually operated at very high frequencies up to 60 Hz which may break the floc and damage the biosolids, vibration of hollow fibre membranes operated at low frequency is more suitable for wastewater treatment.

2.6.2 Longitudinal and transverse vibration

Submerged hollow fibre membranes are now very popular in water and wastewater treatment processes owing to the modest energy requirement, large flexibility, high surface area-to-volume ratio, and low operation cost (Çulfaz et al., 2011). The most well-known uses of hollow fibre membranes in wastewater treatment are to remove turbidity and pathogens. However, the vibration of hollow fibre membranes is not widely used at present due to the complexity of the configurations. Vibrating the membrane module with hollow fibre membranes can generate shear stress on the membrane surface, thus can be regarded as an effective way to reduce concentration polarization and cake fouling.

The vibration of hollow fibre membranes can be done longitudinally (i.e. along the fibre length) or transversely (i.e. perpendicular to the fibre length). Beier et al. (2006) carried out experiments with a longitudinally vibrating hollow fibre membrane module

(Figure 2.9) using baker yeast suspensions. They found that higher critical fluxes could be achieved at higher vibration frequencies and amplitudes, and the critical flux improved 325% at the maximum vibration frequency of 30 Hz and amplitude of 1.175 mm comparing with that at the minimum frequency of 5 Hz and amplitude of 0.2 mm. From the corresponding values of the critical fluxes and average surface shear rates, they suggested that the critical flux increased as a power function with respect to the average membrane surface shear rate. They also found that the longitudinal hollow fibre membranes could be capable of operating for long duration below the critical flux with a very low and constant TMP and at a very low module feed cross-flow velocity.

Figure 2.9 Diagram of vibrating hollow fibre membranes (Beier et al., 2006)

Genkin et al. (2006) evaluated the effect of longitudinal vibration over the range of 0-10 Hz frequency and 20 mm amplitude and also with coagulant addition on the filtration performance of submerged hollow fibre membranes (Figure 2.10). Their results showed that at vibration frequency of 1.7 Hz, the critical flux increased from 17 to 46 LMH with the coagulant addition of 34 mg/L Aluminium Chlorhydrate (ACH). With combined longitudinal and transverse vibration, a five-fold enhancement in

critical flux to 86 LMH was also achieved at 1.7 Hz with the same concentration of ACH addition. They attributed the effect of coagulation to the aggregation of fine particles and evacuation of aggregates away from the membrane surface due to inertial and gravitational forces, and the effect of vanes due to the intensified turbulence arising from both longitudinal and transverse vibration.

Figure 2.10 Photograph of laboratory-scale submerged membrane unit showing the oscillating unit attached to hollow-fibre membrane cartridge. In this instance, the unit contains two fibres with vanes inserted horizontally in a “chess-style” pattern. The “chess style” pattern of the vanes is evident in the enlarged image of the membrane cartridge (top) (Genkin et al., 2006)

The possibility of using transverse vibration for submerged hollow fibre membranes in MBR was raised by Low et al. (2005). They investigated different mechanical motions, including both cross oscillation (Figure 2.11(a)) and lengthwise oscillation (Figure 2.11(b)) in MLSS between 1800 and 2000 mg/L. They ran the cross oscillation at frequency of 0.5 Hz and an angular amplitude of 180° , and the lengthwise oscillation at amplitude of 0.1 m and frequency of 30 Hz. They found that cross oscillation was not effective because of the unequalled shear forces on the membrane bundle, being higher on the outer portion of the bundle and lower in the inner portion; while the lengthwise oscillation provided alternating shear forces that were equal throughout the membrane surface. They concluded that the mechanical vibration helped maintain the MBR

membrane in a relatively “clean” condition and keep the permeate flux close to that of the clean membrane.

Figure 2.11 Schematic diagram of SMBR with (a) cross oscillation, and (b) lengthwise oscillation (Low et al., 2005)

Kola et al. (2012) studied the transverse vibration by either oscillating the liquid with a stationary membrane module or by imposing linearly transverse vibratory motion of the membrane (Figure 2.12). They observed that the transverse vibration can perform effectively for alginate, yeast, Bentonite, as well as anaerobic mixed-feed suspensions at low displacements (< 5 mm) and frequencies (< 21 Hz) because it limited the cake formation by focusing the shear forces more directly on the membrane surface rather than recirculation the bulk fluid. They also suggested that transverse vibration produced more effective shear stress by providing a more disruptive flow regime, which has the potential to induce boundary layer separations and minimize membrane fouling. However, these strategies may have limited benefits in controlling internal membrane pore blocking.

Figure 2.12 Diagram of linearly transverse membrane vibration (Kola et al., 2012)

Recently, Kola et al. (2014) studied the effect of membrane vibration with the anaerobic bioreactor effluent. They found that transverse vibration was more beneficial in terms of filtration performance, and generated more reversible fouling as compared to traditional fouling limitation method such as crossflow velocity and gas sparging under similar bulk solution hydrodynamic conditions. They suggested that transverse hollow fibre membrane vibration was not only effective for increasing the shear near the membrane surface, but also offered additional mass transfer enhancement in terms of generating vortices in the wake of the vibrating surface. They also found that coupling periodic backwash or relaxation to filtration with vibration could further improve the performance in comparison to transverse vibration alone, which may be due to that the fast formation of a thin layer of fouling cake with low resistance would also serve as a secondary membrane to limit the internal fouling.

2.6.3 Shear rate

Since the shear rate plays an important role on the membrane performance, the estimation of the shear rate is essential. The following presents some previous studies on the calculation of the shear rate.

CHAPTER TWO

For a surface vibrating harmonically in a fluid with an amplitude of A , and angular frequency of ω , the vibratory velocity U is given by

$$U = U_0 \cos \omega t \quad (2.3)$$

where U_0 is the maximum velocity amplitude ($U_0 = A\omega$). Taking the y axis the direction of vibration and u the fluid velocity parallel to the surface, the simplified Navier-Stokes equation is

$$\frac{\partial u}{\partial t} = \nu \frac{\partial^2 u}{\partial y^2} \quad (2.4)$$

where ν is the kinetic viscosity. The boundary condition is:

$$u = U_0 \cos \omega t \text{ at } y = 0. \quad (2.5)$$

Gomaa and Rao (2011) used the solution from Schlichting (1979) as below:

$$u = U_0 e^{-\eta} \cos(\omega t - \eta) \quad (2.6)$$

where

$$\eta = y \sqrt{\frac{\omega}{2\nu}} \quad (2.7)$$

Thus, the relative velocity Δu between the surface and the adjacent fluid is then:

$$\Delta u = U_0 \cos \omega t - u \quad (2.8)$$

and the shear rate is given by:

$$\gamma(t) = \frac{\partial(\Delta u)}{\partial y} = U_0 e^{-\eta} \sqrt{\frac{\omega}{\nu}} \sin \left(\omega t - \eta + \frac{3\pi}{4} \right) \quad (2.9)$$

So the surface shear rate can be obtained when $y = 0$, as:

$$\gamma_{\omega}(t) = \frac{A\omega^{1.5}}{\nu^{0.5}} \sin \left(\omega t + \frac{3\pi}{4} \right) \quad (2.10)$$

Thus the maximum shear rate can be stated, when $\omega t = -\pi/4$ or $3\pi/4$, as:

$$\gamma_{\omega \max} = (2\pi F)^{3/2} A \nu^{-1/2} \quad (2.11)$$

The above equations can also be used to calculate the shear stress of vibrating of larger radius of hollow fibre membranes (Zamani et al., 2013).

For two parallel disks, the mean shear rate could be obtained by averaging the absolute value of the shear rate over a period as (Akoum et al., 2002; Gomaa and Rao, 2011):

$$\bar{\gamma}_{\omega} = \frac{2^{\frac{3}{2}}(R_2^3 - R_1^3)}{3\pi R_2(R_2^2 - R_1^2)} \gamma_{\omega \max} \quad (2.12)$$

The maximum of the shear rate could be produced at the edge of the disk when $R = R_2$ as stated in Eq. (2.11). Thus larger shear stress could be generated by vibration of hollow fibre membranes.

2.6.4 Vibration energy consumption

Apart from fouling control, the energy consumption is another key concern to apply the vibration technology in SMBR. Due to the variation of the experimental setup and

vibration mode, the vibration energy consumption was not widely reported. Here the power requirement for running the vibrating module is reviewed from the limited references.

As the membrane elements are the major energy consumer, the power necessary to vibrate the membrane module is mainly to supply the drag force and to resist the friction force during the vibration process in a two-phase or three phase flow.

Vigo et al. (1993) vibrated a UF cylindrical membrane longitudinally at high frequency range of 50 - 1000 Hz and evaluated the vibration energy by force measurements performed with a load cell inserted between the motor and the membrane module. They found that the vibration energy increased exponentially with both increase of vibration frequencies and amplitudes. They also found that the energy increased more rapidly at high frequencies despite little influence on membrane performance. They attributed the fast increase of energy consumption to the friction losses of mechanical system.

Kola et al. (2014) evaluated the energy consumption of transverse vibrating hollow fibre membranes by calculating the unsteady oscillatory force for both an oscillating cylinder in a stationary fluid and a stationary cylinder in an oscillating fluid. They obtained that the energy to transversely vibrate the hollow fibre membrane was lower comparing with that used for MBR aeration alone.

However, the actual energy consumption in the vibration process is higher than the estimation through the vibration force since it is dependent on the efficiency of mechanical connection converting the driving apparatus to vibration process and friction and heat losses. Thus the direct measurement using power meter became a choice for the energy evaluation.

Bilad et al. (2012) measured the energy consumption of the magnetic membrane vibration in up-scale MBR. They found that the power of the vibration engine was

proportional to the critical flux, and also proportional to the applied amplitude. They also found that the energy demand for vibration resulted in the highest in the MBR costs. However, it remained the same when the membrane modules increased from one to six. They suggested that the vibration was a very promising method in MBR.

2.7 Summary

In this chapter, literature relevant to this study is reviewed. First, membrane fouling in MBR and factors affecting MBR fouling were given. Subsequently the main hydrodynamic methods to control fouling including air bubbling and vibration of membranes were also presented.

While submerged hollow fibre membranes have great potential for waste water treatment, the problem of membrane fouling and the applicability of vibration have to be addressed. The performance of the membrane module was affected by the feed properties including the concentrations of MLSS and carbohydrate/protein in the MBR, the physical characteristics of the hollow fibre membranes (such as fibre looseness and fibre packing density), as well as the vibration characteristics (such as vibration frequency/amplitude and longitudinal/transverse vibration). In addition, the hydrodynamic condition within the reactor also played an important role on the membrane filtration performance, while the cost-effective analysis determined the development of the technology. The complex interactions of the various physical processes and the applicability of the technique are not well understood at this point.

In this study, hollow fibre membrane modules were submerged in different feed suspensions including inorganic Bentonite, organic yeast suspensions and real mixed liquor, and vibrated at different modes. The membrane performance, the hydrodynamics and energy consumption were examined in details as described in the following chapters.

Chapter 3 Longitudinal Vibration of Submerged Hollow Fibre Membranes in Inorganic Bentonite Suspensions

3.1 Introduction

In this chapter, the effectiveness of mechanical longitudinal vibration for fouling control of submerged hollow fibre membranes in inorganic Bentonite suspensions was investigated. The scope of investigation included various combinations of vibration frequencies, vibration amplitudes, fibre length, degrees of fibre looseness and fibre spacing. In addition, the effect of vibrating module frame that held the hollow fibre membranes was also evaluated. Moreover, the turbulence inside the membrane reactors by the vibrating frame was conducted by PIV technique. Furthermore, the comparison of membrane filtration performance and energy consumption by longitudinal vibration and air sparging process was carried out.

3.2 Experimental setup

A system was set up in the laboratory to perform both the membrane filtration and flow characterization experiments relevant to submerged hollow fibre membranes with vibration. The system is described in the following.

Part of the work in this chapter has been published in:

- Law, A. W. K., Xia, L., **Li, T.**, Zamani, F. and Fane, A. G., “Dynamic Shear Enhancement for Fouling Control in Hollow Fiber Membrane Filtration”, Singapore International Water Week, July 1-5, 2012, Singapore, Poster Presentation.
- Li, T.**, Law, A. W. K., Cetin, M., Fane, A. G. and Wicaksana, F. (2012), “Fouling Control of Submerged Hollow Fibre Membranes: the Effect of Vibrations and Fibre Looseness”, Procedia Engineering, Vol. 44, pp. 24-26, Euromembrane 2012, September 23 - 27, 2012, London, UK, Oral Presentation.
- 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.
- Law, A. W. K., Jiang, Y., **Li, T.**, Harijanto, A. K. and Fane, A. G., “Energy consumption for membrane fouling mitigation in Membrane Bioreactors (MBRs)”, IWA Regional Conference on Water Reuse and Energy, October 21-24, 2014, Daegu, Korea, Oral Presentation.

3.2.1 Vibration setup

The schematic diagram and photograph of the experimental setup (I) are shown in Figures 3.1 and 3.2, respectively. The test tank was made of Perspex with sizes of 400 mm (L) $\times$ 400 mm (W) $\times$ 1200 mm (H). An effective volume of 140 L was adopted in this study. The holding frame of the membrane module was driven by a brushless DC motor (BXM 6200-A, Oriental Motor Co., Ltd) with a crank moving mechanism. Four screw nuts on the holding frame determined the fibre submergence. The vibration amplitude could be varied from 0 to 12 mm accurately with every 1 mm increase, while the vibration frequency could be set from 0 to 15 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, and the permeate flux with a digital balance (UX 6200H, Shimadzu). In the experiments, small amount of air bubbling (50 mL/min) was maintained in the tank to keep the feed particles suspended in the reactor.

Figure 3.1 Schematic diagram of longitudinal vibration setup (I)

Figure 3.2 Photograph of longitudinal vibration setup (I)

3.2.2 Experimental setup for PIV

The laser imaging technique of PIV had been successfully applied before to measure the local velocities around a hollow fibre array (Yeo et al., 2006 and 2007). In PIV measurement, a laser sheet is projected onto the flow field at successive time intervals, and the subsequent capturing of images details the position of seeding particles that scatters the laser light. A cross-correlation analysis of the changes in the particle position in the sequence of images reveals the Lagrangian velocity distribution. The principles of PIV can be found in earlier references (Law and Wang, 2000; Yeo et al., 2006 and 2007).

In the present study, a Dantec flow map system was used for the PIV measurements. The illumination was from a dual-cavity frequency doubled Q-switched pulsed mini

Nd:YAG laser. The energy level was 150 mJ and the pulse duration was 6 ns. The emitted light sheet was green, at a wavelength of 532 nm. The thickness of the light sheet was approximately 1 mm with a divergence angle of 32°. A Hi-Sense Mk II camera was used to capture the images. The camera had a high-performance progressive scan interlined CCD chip. The chip included 1280 × 1024 light-sensitive cells and an equal number of storage cells. Seeding particles, with a diameter of 20 µm, were used as the particle markers. The concentration of the seeding particles was set at 0.1 g/L, to make sure that a sufficient number of particle markers were present within an interrogation area (IA). The data acquisition was performed at 6 Hz. The final interrogation cell size was 32 × 32 pixels with 50% overlap in IA, giving a matrix of 83 × 63 for a total of 5229 velocity vectors. For every experiment, a total of 300 double frame images were typically taken to establish the velocity vector maps, from which the magnitude of the mean velocity and the turbulence fluctuations could be analyzed.

3.3 Materials and operating procedures

3.3.1 Hollow fibre membranes

Two different sizes of Polyacrylonitrile (PAN) hollow fibres made by Ultrapure Pte Ltd in Singapore with inner/outer diameters of 1mm/1.7 mm and 1 mm/2 mm, respectively, were tested in the experiments. The length of each fibre was 40 cm, and the nominal pore size was 0.1 µm. A total of 13 fibres were included in the membrane modules. They were aligned vertically in parallel, with the distance between two adjacent fibres of 15 mm (Module A). Both ends of the fibres were connected to a 3 cm hard tubing with epoxy, and then mounted on the cross beam of the holding frame (Figure 3.3). Four screw nuts located at the border of the cross beam could be adjusted to change the submergence of the membrane module in the reactor.

Figure 3.3 Hollow fibre membrane module (Module A)

3.3.2 Preparation of feed suspensions

In this study, the Bentonite particles were chosen as the inorganic feed due to the fact that they would form a cake deposit without internal pore fouling and were in the size range capable of shear-induced diffusive back transport (Davis, 1992; Belfort et al., 1994). The Bentonite particles were commercially purchased from Sigma-Aldrich, with the formula of $\text{H}_2\text{Al}_2\text{O}_6\text{Si}$ and the molecular weight of 180.1 g/mol. The average particle diameter was 5.83 μm with a relative density of 2.4 g/cm³. A histogram of the size distribution of the Bentonite was analyzed using the Mastersizer Hydro 2000SM and plotted in Figure 3.4. The Bentonite particles were added to tap water and mixed with a magnetic stirrer at 300 rpm for 30 min. After the complete mixing, they were diluted to make 4 g/L suspensions (pH 6.0-9.0) as the inorganic feed.

Figure 3.4 Size distribution of Bentonite particles

3.3.3 Experimental procedures

Before each experiment, a clean water backwash at 20 mL/min was first performed on the hollow fibre membranes under the condition of 10 Hz vibration for half an hour. The purpose was to eliminate any bubbles trapped inside the hollow fibres. After the backwash, the filtration test was initiated, and the permeate volume was recorded at every 20 second interval by a digital balance. The permeate flux was then calculated as the rate of change of the permeate volume. In all the experiments, the time $t = 0$ was defined as the start of membrane filtration time, while the vibration was activated at the same time with the filtration.

Two types of experiments were conducted in this study, namely the constant flux and constant pressure experiments. They are described in the following.

3.3.3.1 Constant flux

For the constant flux experiments, the permeate flux was typically maintained at 30 ± 0.3 LMH, while the corresponding suction pressure was recorded using a pressure gauge at 1-min interval. Each experiment lasted for about 1 hour. However, if the TMP increased to around 50 kPa, many bubbles began to be generated from the tubing especially around the needle valve. When this occurred, the experiment was terminated and the duration of the particular experiment would then be shortened to be less than 1 hour. To maintain consistency, the average fouling rate of the first 30 min was reported as the experimental fouling rate in this study.

3.3.3.2 Constant pressure

In the constant pressure experiments, the suction pressure was controlled at -24 ± 0.1 kPa, while the permeate fluxes were varied. Before each experiment, the membrane was backwashed in the same manner as in the constant flux experiments. Subsequently, the experiment would begin with the pump flow increased so that the suction pressure reached -24 kPa. Over time, the permeate flux would typically decrease progressively which was determined by the measurements of permeate volume recorded at 20 s intervals using the digital balance. Each constant pressure experiment lasted for about 1 hour. Since the pressure was maintained constant, the interruption due to air bubble generation as in the constant flux experiments did not occur.

3.3.4 Vibrating hollow fibres with and without holding frame

As part of the overall experiments, the effects of holding frame vibration on the filtration performance of the hollow fibre membranes were also examined by comparing two test conditions: (a) vibrating hollow fibres, and (b) stationary hollow fibres. The former condition was used in most experiments. To study the stationary hollow fibres with the vibrating holding frame, the hollow fibres were separately fixed

to another stationary holding frame while the original holding frame was driven by the motor (Figure 3.5). By comparing the two test conditions, the frame effect on the membrane performance could be evaluated.

Figure 3.5 Schematic diagram of fibre holding frame (a) with hollow fibre membranes, and (b) without hollow fibre membranes

3.4 Analysis of results

3.4.1 Membrane filtration

The definition of permeate flux is

$$J = \frac{1}{S} \frac{dV}{dt} \quad (3.1)$$

where S is the effective membrane area and V the cumulative volume of permeate. According to the resistance-in-series model (Choo and Lee, 1996), the relationship between the permeate flux (J) and TMP (ΔP) can be expressed in the following form:

$$J = \Delta P / (\mu R_t) \quad (3.2)$$

$$R_t = R_m + R_p + R_{ef} + R_{if} \quad (3.3)$$

where μ is the dynamic viscosity of the permeate; R_t the total resistance; R_m the intrinsic membrane resistance; R_p the polarization layer resistance caused by the concentration gradient; R_{ef} the external fouling resistance formed by a deposited cake layer from physic-chemical interactions of solids with the membrane surface; and R_{if} the internal fouling resistance due to irreversible adsorption or pore plugging.

For clean water, Eq. (3.2) can be simplified as

$$J_w = \Delta P / (\mu R_m) \quad (3.4)$$

where J_w is the clean water flux.

In the present study, a clean water permeability (Flux/TMP) test was conducted before each experiment for both 1.7 mm and 2 mm fibres. Their permeabilities were typically found to be about 2.04 L/(m²·h·kPa) and 1.73 L/(m²·h·kPa), respectively. Since the clean water viscosity at 25°C (the typical temperature in the experiments) was 0.891×10⁻³ Pa·s, R_m for 1.7 mm and 2 mm fibres can thus be calculated to be 1.76 × 10¹² m⁻¹ and 2.07 × 10¹² m⁻¹, respectively.

For the Bentonite suspensions, the nominal particle size was much larger than the pore size of the hollow fibre, thus it can be assumed that there was no pore plugging. Hence, Eq. (3.2) can be rearranged as

$$J = \frac{\Delta P}{\mu(R_m + R_c)} \quad (3.5)$$

where R_c is the cake resistance ($R_c = R_{ef}$, according to cake filtration law, R_c is only external fouling), which for hollow fibre membranes should also vary with the cake thickness δ_c as (Gomaa et al., 2011a),

$$R_c = R_c' \rho_s \phi_c \delta_c \quad (3.6)$$

where R_c' is the specific cake resistance per unit mass, ρ_s the solid density, and ϕ_c the solid volume fraction. The mass of cake deposited per unit volume of filtrate, c , can then be expressed as

$$c = \frac{S \delta_c \phi_c \rho_s}{V} \quad (3.7)$$

Therefore, for an incompressible cake, integrating Eq. (3.1) with constant ΔP gives (Gomaa et al., 2011a)

$$\frac{t}{V} = \frac{\mu R_c' c}{2S^2 \Delta P} V + \frac{\mu R_m}{S \Delta P} \quad (3.8)$$

Eq. (3.8) quantifies the filtration characteristics when a cake layer is formed.

3.4.2 Estimation of filtration parameters

For each experiment, the permeate volume was recorded continuously, and the permeate flux was computed with Eq. (3.1). By plotting the permeate volume versus time, the longitudinal intercept of Eq. (3.8) can be obtained as

$$b = \frac{\mu R_m}{S \Delta P} \quad (3.9)$$

The membrane resistance R_m can then be determined as

$$R_m = \frac{b}{\mu} S \Delta P \quad (3.10)$$

The slope of Eq. (3.8) can be defined as

$$k = \frac{\mu R_c' c}{2 S^2 \Delta P} \quad (3.11)$$

The cake resistance R_c can be calculated from this slope together with Eqs. (3.6) and (3.7) as:

$$R_c = \frac{2k}{\mu} S \Delta P V \quad (3.12)$$

Examples of the calculation can be found in the later part of results and discussion.

3.4.3 Vibration enhancement factor

Membrane oscillation can potentially lead to an improvement in the fouling mitigation. The enhancement factor, E , in terms of the permeate flux can be used to describe the vibration intensification as follows:

$$E = \frac{(J)_{with\ oscillation}}{(J)_{without\ oscillation}} \Big|_{t=1\ hr} \quad (3.13)$$

The flux values were taken after 1 hour which corresponded to the typical time needed to reach quasi-steady state conditions. This approach has been widely used for

membrane vibration filtration analysis (Akoum et al., 2005; Gomaa and Rao, 2011). In this study, this parameter was also used to evaluate the membrane filtration improvement with vibration.

3.5 Results and discussion

3.5.1 Filtration characteristics

Figure 3.6 shows the measured fouling rate at different constant permeate fluxes from 10 to 30 LMH for both 1.7 mm and 2 mm fibres without vibration in 4 g/L Bentonite suspensions. It was found that the fouling rate increased as the fibre diameter decreased for all the testing fluxes, which may be attributed to the higher axial flux and non-uniform flux distribution induced by the smaller radius of 1.7 mm fibres. For example, at a constant permeate flux of 25 LMH, 1.7 mm fibres induced a fouling rate of 53.4 kPa/h, which was 2.5 times higher than that for 2 mm fibres with a fouling rate of 21.6 kPa/h; while at a constant permeate flux of 15 LMH, higher fouling rate of 8.8 kPa/h was produced by 1.7 mm as compared to 6.8 kPa/h by 2 mm fibres. It should be noted that the similar effect (greater fouling for smaller diameter fibres) was also observed elsewhere in aeration studies (Chang and Fane, 2001; Chang et al., 2006). In addition, larger permeate fluxes led to much higher fouling rates, as illustrated by the fact that the fouling rates at constant permeate flux of 30 LMH were 91.2 and 48.6 kPa/h for 1.7 mm and 2 mm fibres, respectively, which were much higher than at flux of 10 LMH where nearly no fouling was observed for both fibres. This could be attributed to the greater deposition increased cake compression and consolidation at higher fluxes. This phenomenon that higher fluxes caused more severe membrane fouling was widely reported in microfiltration studies (Parameshwaran et al., 2001; Ho and Zydney, 2002; Yang et al., 2011).

Figure 3.6 Fouling rate at different permeate fluxes without vibration

Figure 3.7 shows the measured fouling rates at different vibration frequencies, at a fixed vibration amplitude of 5 mm for 2 mm fibres (note that 0 Hz in the figure represents no vibration) in 4 g/L Bentonite suspensions. The fouling rate typically decreased significantly when vibration was applied. It dropped from 48.6 to 0.8 kPa/h at a permeate flux of 30 LMH, and from 14.6 to 0.2 kPa/h at a permeate flux of 20 LMH, when vibration frequency was increased from 0 Hz to 10 Hz. The reduction of the fouling rate was attributed to the shear stresses by the longitudinal vibration. It was also found that, the fouling rate was more significant when higher permeate flux was applied. The fouling rate increased from 0.2 to 15 kPa/h at 2 Hz vibration, and from 3.4 to 7.4 kPa/h at 5 Hz vibration, when the permeate flux was increased from 10 to 30 LMH. The same trend was also observed for no vibration and 10 Hz vibration. This implied that more serious membrane fouling occurred when larger amount of fluid permeated through the membrane as expected. In addition, almost no fouling was observed at 10 Hz vibration for 2 mm fibres. In other words, vibrating the hollow fibre membrane at 10 Hz increased the critical flux for 2 mm fibres to beyond 30 LMH in this case.

Figure 3.7 Fouling rate versus permeate flux at different vibration frequencies
(vibration amplitude = 5 mm, 2 mm fibre)

Figure 3.8 plots the fouling rate at different vibration frequencies and amplitudes for both 1.7 mm and 2 mm fibres, at constant permeate flux of 30 LMH in 4 g/L Bentonite suspensions. Big ranges of both vibration frequencies and amplitudes were tested to obtain the basic information of vibration on the fouling control. The reduction of fouling rate by vibration was intensified when both vibration frequency and amplitude were increased. The fouling rate decreased from 15 to 7.4 kPa/h when vibration frequency was increased from 2 to 5 Hz at amplitude of 5 mm, and further decreased to 2.4 kPa/h when the amplitude was increased to 8 mm at 5 Hz for 2 mm hollow fibres. Similar results were found for 1.7 mm hollow fibres as well. There was an 85% reduction in the fouling rate when 2 mm hollow fibres were vibrated at 5 mm amplitude and 5 Hz frequency, as compared to no vibration (Figure 3.8 (a)). Similar reduction was obtained for 1.7 mm fibres at 6 mm amplitude and 8 Hz frequency (Figure 3.8 (b)). The fouling rate dropped from 48.6 to 0.2 kPa/h and from 91.2 to 1 kPa/h for 2 mm and 1.7 mm hollow fibres, respectively, when a vibration frequency of 10 Hz and vibration amplitude of 8 mm was applied, which led to more than 95%

reduction in fouling rate for both fibres. When vibration amplitude was further increased to 10 mm at frequency of 12 Hz, nearly no fouling was observed for both fibres.

Figure 3.8 Fouling rate at different vibration frequencies and amplitudes in 4 g/L Bentonite suspensions (constant permeate flux = 30LMH) with (a) 2 mm fibre, and (b) 1.7 mm fibre

The reduction of membrane fouling was attributed to the shear stress induced by the longitudinal vibration. Larger shear stress could be generated on the membrane surface by higher vibration frequencies or amplitudes. These observations that high vibration frequencies and amplitudes led to small membrane fouling were also reported by other studies (Low et al., 2004; Postlethwaite et al., 2004; Beier et al., 2006; Gomaa and Rao, 2011).

In the cake filtration case, the overall resistance was composed of the membrane resistance, which was assumed to remain unchanged, and the cake resistance. For dead-end filtration of incompressible particles, the cake thickness was proportional to the filtered volume. The mechanism of cake filtration differed significantly from the complete blocking mechanism (Hermia, 1982; Field et al., 1995; Corbaton-Baguena et al., 2015). The cake filtration law was applied to determine the relationship of cake resistance and permeate volume under different vibration conditions for the Bentonite suspensions. For constant pressure experiments, the plot of t/V versus V based on cake filtration law at different vibration frequencies from 0 to 10 Hz for both the 1.7 mm and 2 mm fibres in 4 g/L Bentonite suspensions is presented in Figure 3.9. The time needed to obtain the same amount of permeate was longer at lower vibration frequencies, implying that vibration could improve the permeate flux. For example, for 2 mm fibres, 25 min was required to collect 400 mL volume permeate without vibration, only 21 min filtration could collect the same amount of permeate under vibration frequency of 5 Hz, and the time required to collect the same amount of permeate was greatly shortened to 17 min under higher vibration frequency of 10 Hz. In contrast, for 1.7 mm fibres, 33 min, 27 min and 23 min were required to collect the same 400 mL permeate for vibration frequencies of 0 Hz, 6 Hz and 10 Hz, respectively. The phenomenon that vibration enhanced permeate flux was also noted in other studies (Beier et al., 2006; Kola et al., 2012).

Figure 3.9 t/V versus cumulative permeate volume at different vibration frequencies (constant suction pressure = - 24 kPa) with (a) 2 mm fibre, vibration amplitude = 5 mm, and (b) 1.7 mm fibre, vibration amplitude = 6 mm

The membrane resistance was calculated based on Eq. (3.10). As shown in Figure 3.9(a), intercept $b = 2.63 \times 10^3$ s/L and slope $k = 2.98 \times 10^3$ s/L². Thus, the average membrane resistance R_m was 2.26×10^{12} m⁻¹ by Eq. (3.10), and the relationship between R_c (10¹² m⁻¹) and V (L) was $R_c = 5.12 V$ by Eq. (3.12). A similar method was used for 1.7 mm fibres. The average membrane resistances R_m was 1.97×10^{12} m⁻¹ and the relationship between R_c (10¹² m⁻¹) and V (L) was $R_c = 8.33 V$. The average membrane resistance calculated by the cake filtration law analysis was nearly the same as that from the clean water permeability tests, which illustrated the consistency of the test results.

Figure 3.10 plots the cake resistance, R_c , versus cumulative permeate volume for 4 g/L Bentonite suspensions. R_c was calculated using Eq. (3.12). It can be observed that the cake resistance increased gradually with time at different vibration frequencies for both 1.7 mm and 2 mm hollow fibres. Also, the cake resistance of 1.7 mm fibres without vibration was much larger than 2 mm fibres due to the smaller diameter which would lead to greater effective fouling (Chang et al., 2006). For 2 mm fibres at 1.5 L permeate volume, R_c decreased from 7.68×10^{12} m⁻¹ to 2.37×10^{12} m⁻¹ when 5 Hz vibration was applied, and was further decreased to 0.35×10^{12} m⁻¹ when 10 Hz vibration was applied as compared to no vibration. Hence, 70% and 95% reduction in cake resistance were achieved at 6 and 10 Hz vibration, respectively. Comparatively, for 1.7 mm fibres, 60% reduction in cake resistance at 6 Hz vibration and 84% reduction in cake resistance at 10 Hz vibration were obtained, which was also significant but nevertheless less than 2 mm fibres.

In summary, Figures 3.7 - 3.10 show improved performance of the membrane for both constant flux and constant pressure operation under longitudinal vibration, and the improvement was very significant when a certain level of vibration frequency and/or vibration amplitude was reached. This could be attributed to the fact that at higher vibration frequencies, the particles could be easily removed from the membrane surface under conditions of high shear stress produced by the longitudinal vibration.

Figure 3.10 Evaluation of cake resistance R_c versus cumulative permeate volume at different vibration frequencies (constant suction pressure = - 24 kPa) with (a) 2 mm fibre, vibration amplitude = 5 mm, and (b) 1.7 mm fibre, vibration amplitude = 6 mm

3.5.2 Intensification effects of vibration

For all the experiments, the average permeate flux was determined experimentally after 1 hour, which was typically the time needed to reach quasi-steady state (Akoum et al., 2005; Gomaa and Rao, 2011). The membrane vibration resulted in an increase of this quasi-steady state permeate flux, with the enhancement factor depending on the applied vibration frequency and amplitude as well as the TMPs. The degree of reduction in fouling is dependent on the initial flux, i.e., greater reduction at higher initial flux. The enhancement factor was adopted in this study to evaluate the membrane filtration improvement with vibration.

Figure 3.11 depicts the effect of the vibration enhancement factor, calculated based on Eq. (3.13) for both 1.7 mm and 2 mm fibres in 4 g/L Bentonite suspensions. Generally vibration enhancement factor increased as an increase of both vibration frequency and amplitude. Vibration enhancement factor increased from 1.0 to 2.5 when vibration frequency was increased from 2 to 10 Hz at vibration amplitude of 5 mm for 2 mm fibres, and it further increased to 2.6 at vibration frequency of 10 Hz when vibration amplitude was increased to 8 mm. Similar trend was also observed for 1.7 mm fibres. Vibration enhancement factor increased from 1.2 to 2.0 when vibration frequency was increased from 4 to 10 Hz at vibration amplitude of 4 mm, and it further increased to 2.2 at vibration frequency of 10 Hz when vibration amplitude was increased to 8 mm. As compared to 2 mm fibres, the smaller vibration enhancement factor of 1.7 mm fibres was attributed to the initial higher axial fluxes induced by the smaller diameter (Chang and Fane, 2001), while the larger increase of enhancement factor of 1.7 mm fibres was due to higher shear stress of smaller diameter fibres induced by the vibration (Zamani et al, 2013). The enhancement was attributed to the reduction of the deposited cake layer at the membrane surface due to the vibrational shear stresses at the membrane surface.

Figure 3.11 Vibration enhancement factor versus vibration frequency at different vibration amplitudes (constant suction pressure = - 24 kPa) with (a) 2mm fibre, and (b) 1.7 mm fibre

3.5.3 Effect of fibre length

In this study, the fibre length effect in submerged membrane system with longitudinal vibration was examined. Two fibre curtains with the same number of 13 fibres and spacing between fibres of 15 mm but different length of 20 and 40 cm were vibrated longitudinally under different frequencies from 6 to 10 Hz in 4 g/L Bentonite suspensions (Figure 3.12).

Figure 3.12 Fouling rate of different lengths of fibres (constant permeate flux = 30 LMH, vibration amplitude = 8 mm, 1.7 mm fibre)

At vibration frequency of 6 Hz, fouling rate of 95.4 kPa/h was induced by the 20 cm fibres, while lower fouling rate of 26.6 kPa/h was induced by the longer fibres of 40 cm. When vibration frequency was increased to 10 Hz, lower fouling rates of 15.8 and 3.8 kPa/h were induced by the 20 cm and 40 cm fibres, respectively. This observation could be attributed to the additional movement of longer fibres under the effect of vibration, which could reduce fouling on the membrane surface. This fibre movement effect induced by fibre length was dominant so that it overcame the drawbacks induced

by the higher lumen pressure losses (Chang and Fane, 2001). Therefore, a significant improvement of membrane performance was achieved by the longer fibres. The same phenomenon was also found in the movement of submerged hollow fibres by rising air bubbles (Wicaksana et al., 2006).

3.5.4 Effect of fibre looseness

In the industry, the fibres are usually not mounted with 100% tightness (or no looseness) in order to encourage fibre movement (Fane et al., 2002; Wicaksana et al., 2006). Here the fibre looseness effect under longitudinal vibration was investigated. Figure 3.13 shows the quasi-steady state permeate flux for the tight, 1% and 2% looseness fibres in 4 g/L Bentonite suspensions. The quasi-steady state flux increased with an increase of vibration frequency and was higher for the loose fibres. With 1% looseness, it increased 20%, from 17 to 21 LMH, at 4 Hz, and 30% at 10 Hz. However, very little improvement was noted for all the vibration frequencies when the fibre looseness was increased from 1% to 2%.

Figure 3.13 Quasi-steady state flux for tight and loose fibres at different vibration frequencies (constant suction pressure = - 24 kPa, 1.7 mm fibre)

The vibration enhancement effect for tight and loose fibres is further shown in Figure 3.14, and a similar trend is observed. The enhancement factor was higher with a larger vibration frequency. It increased from 1.6 to 2 at 6 Hz and from 2 to 2.5 at 8 Hz with 1% looseness. The factor reached as high as 3 with 1% looseness and 2.2 with the tight fibres at 10 Hz. The results confirmed that the fibre looseness could improve the membrane performance with vibration due to axial vibrational shear stresses and the extra lateral movement induced by the looseness, and only a looseness of 1% would be required to realize the improvement.

Figure 3.14 Vibration enhancement factor for tight and loose fibres at different vibration frequencies (constant suction pressure = -24 kPa, 1.7 mm fibre)

Figure 3.15 shows the fouling rate of tight and loose fibres at 6 to 12 Hz vibration frequencies in 4 g/L Bentonite suspensions. The fouling rate decreased significantly for tight and loose fibres in this frequency range. It dropped from 29.4 to 2 kPa/h from 6 to 12 Hz for the tight fibres, and from 8.9 to 1.4 kPa/h for the 1% looseness fibres, respectively. Again the fouling rate for the 1% and 2% looseness was quite similar, confirming that the fibre looseness can reduce the fouling rate, and 1% looseness was

sufficient to improve the membrane filtration performance. The improvement can be attributed to the additional lateral movement of the loose fibres and the resulting increase in shear stress. Similar effects were also noted in the bubbling studies by Yeo et al. (2007) and Wicaksana et al. (2006). However, it is probable that excessive fibre looseness would lead to fibre breakage due to extreme movement of fibres.

Figure 3.15 Fouling rate for tight and loose fibres at different vibration frequencies (constant permeate flux = 30 LMH, vibration amplitude = 6 mm, 1.7 mm fibre)

3.5.5. Fibre spacing

The membrane spacing can be an important parameter in industrial applications. Greater spacing between the membrane elements can increase the permeate flux and solids handling capability as illustrated by Postlethwaite et al. (2004) who investigated the vibrating MF performance using both *Bacillus* and *Aspergillus* fermentation broths at gap widths of 1.4 and 4.2 mm. They found a pronounced increase in performance when the gap width was increased and they attributed to the packing differences of the cells in the core region between the membrane discs. In this study, the fouling of submerged hollow fibre membranes with two fibre spacings of 2 mm and 15 mm of

single row of membranes with longitudinal vibration in 4 g/L Bentonite suspensions was first tested. Figure 3.16 shows the TMP of hollow fibre membranes with 2 mm and 15 mm spacing at vibration frequencies of 6 Hz and 10 Hz. It is obvious that at the lower frequency of 6 Hz, the TMP of hollow fibres with the spacing of 2 mm increased significantly in a short time, and was much larger than the 15 mm spacing. The TMP for the 2 mm spacing reached as high as 80 kPa, while it was only 27 kPa for the 15 mm spacing. However, when vibration frequency was increased to 10 Hz, the TMP profile for both became nearly the same.

Figure 3.16 TMP of hollow fibre membrane with 2 mm and 15 mm spacing at vibration frequencies of 6 Hz and 10 Hz in 4 g/L Bentonite suspensions (fibre length = 20 cm, vibration amplitude = 8 mm, permeate flux = 30 LMH)

These results indicated that membrane fouling was more severe for closely spaced fibres at lower frequencies during longitudinal vibration; while there was little difference in performance between the closely and sparsely spaced fibres at higher vibration frequencies. This phenomenon might be because at low frequency of vibration, higher filtration resistance was induced by the smaller spacing; while at high

frequency of vibration, the fluid motion induced was able to overcome the greater permeate flux competition between neighboring fibres with the smaller spacing (Sethi and Wiesner, 1997). The phenomenon of permeate flux competition was also observed in the experiments by Yeo et al. (2006) and Fulton and Bérubé (2012). A recent numerical study by Zamani et al. (2013) had shown that there could be an optimal spacing in vibrating system.

3.5.6 Effect of fibre holding frame

Figure 3.17 shows the fouling rate at constant flux with stationary and vibrating fibres and with the vibrating holding frame in 4 g/L Bentonite suspensions. It is obvious that the fouling rate of the stationary fibres was much higher than the vibrating fibres together with the vibration of the holding frame, decreasing from 85.8 to 41.5 kPa/h at 6 Hz, and from 79.6 to 2.2 kPa/h at 10 Hz. With the stationary hollow fibres, the fouling rate was a little lower with the vibrating holding frame than no vibration.

Figure 3.17 Fouling rate for vibrating and stationary fibres with vibrating holding frame at different vibration frequencies (constant permeate flux = 30 LMH, vibration amplitude = 10 mm, 1.7 mm fibre)

In Figure 3.18, a similar trend can also be observed at constant pressure in 4 g/L Bentonite suspensions. The quasi-steady state flux of the vibrating fibres with the vibrating holding frame increased 80% from 17 LMH at 4 Hz to 31 LMH at 10 Hz, while the quasi-steady state flux increased by only small amount of around 1 LMH with the vibrating holding frame for the stationary fibres at all the frequencies conducted. Overall, the results showed that the vibration of the holding frame and the associated turbulence induced did not significantly affect the membrane performance. Thus, it can be concluded that the vibration of fibres to induce shear at the membrane surface is the primary factor that led to the reduction of membrane fouling.

Figure 3.18 Quasi-steady state flux of vibrating and stationary fibres with vibrating holding frame (constant suction pressure = - 24 kPa, vibration amplitude = 8 mm, 1.7 mm fibre)

In the present study, the results were different from those reported by Genkin et al. (2006) where they intentionally used a specially designed neighboring stationary grid to generate turbulence in order to markedly enhance the critical flux. However, present

data allows direct examination of the role of dynamic vibration shear on membrane filtration.

3.5.7 Dynamic shear rate

Previous researchers had shown that the dynamic shear stress on the membrane surface during vibration could reduce the membrane fouling (Jaffrin, 2008; Akoum et al., 2002). For the vibrating disk, Akoum et al. (2002) suggested the relationship between the maximum shear stress and vibration frequency and amplitude to be as shown in Eq. (2.11). For simplicity, Genkin et al. (2006) assumed that the same expression could be used to describe the shear rate at the surface of a vibrating fibre. However, the omission of the consideration of radius of curvature of the fibre can lead to significant errors with small diameter fibres as pointed out by Zamani et al. (2013). In this particular study, however, the fibre diameters at 1.7 mm and 2 mm were relatively large, and thus the errors are expected to be small.

Experiments with the same theoretical constant shear rate ($A \cdot F^{1.5} = 134$) according to Eq. (2.10) and at amplitudes varied from 4 mm to 12 mm were conducted in 4 g/L Bentonite suspensions. The results are shown in Figure 3.19. The fouling rate increased from 10.8 to 18.8 kPa/h when vibration amplitude was increased from 4 mm to 9 mm. It then gradually decreased to 16 kPa/h when vibration amplitude was increased from 9 mm to 12 mm. This shows that membrane filtration at amplitude of 9 mm performed the worst under the same shear rate. The results demonstrated that at higher vibration frequencies, the power ratio of vibration frequency in Eq. (2.10) can be larger than 1.5. It can also be deduced that the vibration frequency could have much more impact than the vibration amplitude for fouling mitigation, which suggests that vibration frequency is more effective to improve membrane performance than vibration amplitude by longitudinal vibration. This is consistent with the study of oscillating flat sheet membrane by Gomaa and Rao (2011).

Figure 3.19 Fouling rate with the same theoretical shear rate (constant permeate flux = 30 LMH, 1.7 mm fibre)

Vigo et al. (1993) suggested that the shear stress was dependent on the shift speed ($4 A \cdot F$) of the membrane surface in a vibrating system. The product $4 A \cdot F$ was a quantity proportional to the so-called vibrational Reynolds number as:

$$Re_v = d_e \bar{V} \rho / \mu \quad (3.14)$$

where d_e was the equivalent diameter of an annular vessel, and $\bar{V} = 4 A \cdot F$. Experiments with the same shift speed were performed in this study at vibration amplitudes ranging from 4 mm to 12 mm (Figure 3.20). The results showed that the fouling rate increased rapidly from 7.4 to 66.7 kPa/h with increase of vibration amplitude at the same shift speed (when $A \cdot F = 48$), i.e., the membrane performance was strongly affected by the decrease of vibration frequency. This influence could be attributed to the much higher maximum shear stress at the membrane surface when the fibre was moving relative to

the fluid (Vigo et al., 1993). The figure also demonstrates that the effect of vibration frequency was more obvious in a vertical vibrating system.

Figure 3.20 Influence of the shift speed ($4A \cdot F$) on fouling rate (constant permeate flux = 30 LMH, 1.7 mm fibre)

3.5.8 PIV measurement of longitudinal vibration

With PIV, the two-dimensional velocity distribution can be obtained in the form of vector maps, while the turbulence characteristics can be computed by evaluating the local vector values. For the vibration experiments in current study, the velocity components of 300 vector maps were obtained and the average velocity components $\bar{u}$ and $\bar{v}$ were calculated.

In this study, PIV measurements were carried out in the area shown in Figure 3.21 just in front of the fibres and plotted the contour map of the velocity deviation U' from the mean velocity at different frequencies in Figure 3.22, where

$$U' = \sqrt{(\bar{u} - \bar{\bar{u}})^2 + (\bar{v} - \bar{\bar{v}})^2} \quad (3.15)$$

Figure 3.21 Location of the image window in the reactor

From Figure 3.22, it can be observed that the value of U' and the generation of turbulence by the holding frame was much more significant at higher vibration frequencies. The induced turbulence can potentially reduce the cake fouling layer on the membrane surface, thus increase the apparent permeability. Gomaa et al. (2011b) investigated the flux enhancement using oscillatory motion and turbulence promoters. They revealed that at higher frequencies ($F > 5$ Hz), the effect of turbulence promoters extended further away from the surface, resulting in a well-mixed flow structure and scouring of the surface between the promoters caused by vortices shedding. The effects of turbulence promoters on a flat sheet membrane by Gomaa et al. (2011b) were similar to the turbulence produced by the holding frame in the present study. However, as discussed in Section 3.5.6, the effect here of the holding frame per se was not significant due to the different structural configurations.

Figure 3.22 Contour of U' at different vibration frequencies (no suction pressure, 2 mm fibre)

3.5.9 Power consumption comparison of longitudinal vibration with bubbling

Since the movement of the membrane module needs the motor to drive, thus it is necessary to evaluate the power consumption and membrane performance by vibration.

As reported by Genkin et al. (2006), the specific power consumption is defined as the power necessary to oscillate a kilogram of mass with a given frequency and amplitude. In current study, the power consumption of vibration of the motor at the different vibration frequencies and amplitudes was measured by a clamp meter and shown in Figure 3.23(a).

As expected, the vibration power consumption increased at higher vibration frequencies and amplitudes. It was also found that increase of vibration frequency resulted in larger increase of energy consumption as compared to increase of vibration amplitude. For example, at frequency of 4 Hz, 7.59 and 9.2 watt were consumed at amplitudes of 4 and 8 mm, respectively; while at frequency of 8 Hz, much higher energy of 11.04 and 16.1 watt were consumed, respectively. This indicated that operation at lower vibration frequencies could save energy consumption. In addition, large vibration amplitude and high vibration frequency could lead to more energy consumption but lower membrane fouling. For example, at amplitude of 8 mm and frequency of 10 Hz vibration, power of 16.6 watt was consumed, which from observations shown in Section 3.5.1 led to 95% fouling reduction. For comparison, with the same setup, the use of aeration in a preliminary experiment was examined and the result showed that 5 L/min bubbling rate led to only 10% reduction in fouling but consumed power of 21 watt (Figure 3.23(b)). Clearly, energy consumption of vibration system was lower than that of aeration, which may be due to the fact that only the boundary fluid layer next to the fibres were mobilized in the vibrating system, while the whole system was activated in the air sparging process. Thus, membrane vibration can have a distinct advantage in term of energy consumption. A similar benefit was also observed by Akoum et al. (2002).

The relationship between the vibration power consumption and membrane fouling rate from Section 3.5.1 for 4 g/L Bentonite suspensions at constant flux of 30 LMH was further plotted in Figure 3.24. Generally larger power consumption by vibration could result in higher fouling rate reduction. In addition, it can be also found that there is a

good relationship between the longitudinal vibration power and the membrane fouling rate that larger power consumption resulted in higher fouling rate reduction.

Figure 3.23 A comparison of operating power consumption between (a) vibration, and (b) aeration

Figure 3.24 The relationship between longitudinal vibration power consumption and membrane fouling rate in 4 g/L Bentonite suspensions (Constant flux = 30 LMH)

3.6 Conclusions

The present study confirms that mechanical longitudinal vibration of hollow fibres can improve the membrane filtration performance of inorganic Bentonite suspensions by reducing the fouling on the membrane surface. The membrane permeability increased with increase of vibration frequency and amplitude, which could be attributed to the thinning cake layer and lowering cake resistance. In the vibration system, longer fibres were preferred due to the fact that greater fibre movement induced by larger length could overcome the drawbacks induced of higher lumen pressure loss in larger element. The introduction of membrane looseness of 1% was found to be able to significantly reduce the membrane fouling and improve the membrane permeate flux. The vibration of submerged hollow fibres with and without the vibrating holding frame suggested that the turbulence generated by the vibrating holding frame played a minor role in enhancing the membrane performance in this study. A low frequency of vibration

would be favorable since more energy could be reduced with decrease of vibration frequency as compared to decrease of vibration amplitude. Finally, it was found that the consumption of energy for vibration technique is significantly less than aeration although vibration producing a much less fouling rate, which can be due to the fact that only the boundary fluid layers around the fibres are mobilized and thus the energy dissipation is much reduced.

Chapter 4 Longitudinal Vibration of Submerged Hollow Fibre Membranes in Organic Yeast Suspensions

4.1 Introduction

This chapter investigates the effectiveness of membrane filtration with the mechanical longitudinal vibration of submerged hollow fibre membranes in the organic yeast suspensions.

4.2 Vibration setup

The experimental setup used here was the same as stated in Chapter 3.

4.3 Materials and operating procedures

4.3.1 Hollow fibre membranes

The same PAN hollow fibres with the inner/outer diameter of 1mm/1.7 mm as described in Chapter 3 were used. The fibre curtain (Module A) with displacement of 15 mm and length of 40 cm (Figure 3.3) was vertically mounted on the quadrate standard steel holding frame submerged in the tank (Setup I), and was driven up and down by a brushless DC motor with a crank moving mechanism.

4.3.2 Preparation of feed suspensions

Dry baker's yeast (Levure Sèche de Boulanger, France), which is commercially available from a supermarket, was mixed with tap water to represent the organic feed

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suspensions. The motive for choosing the yeast suspensions was the size range in the shear-induced diffusive back transport (Davis, 1992; Belfort et al., 1994), the widespread use in the biotechnology industry and food chemistry, the easy availability and large number of studies conducted using yeast with microfiltration (Sur and Cui, 2001; Chandler and Zydney, 2006; Genkin et al., 2006; Wicaksana et al., 2006). The yeast (so-called unwashed yeast) used in the experiments had an average particle diameter of 4.95 μm and a relative density of 1.2 g/cm^3 . Each time, 560 g dry baker's yeast was first mixed with 10 times the mass of water using a magnetic stirred at 600 rpm for half an hour. After the yeast was completely suspended in water, the suspension was poured into the reactor and further diluted with tap water to 4 g/L as the organic filtration feed. The same concentration of 4 g/L was adopted so that the membrane performance under vibration can be compared with that in Bentonite suspensions. The yeast suspensions were changed every day to keep the yeast cells alive. Yeast suspensions can also be separated into washed yeast and supernatant by the washing procedures (Wicaksana, 2006).

4.3.2.1 Water content in the yeast particles

Dry baker's yeast were measured with 50 g and dried in the oven at 60°C until the weight did not decrease anymore. The dried weight was 49.20 g. Thus, the water content in this instant yeast was 1.6%.

4.3.2.2 Washed yeast

Washed yeast was used to prepare the feed suspensions in some experiments as a comparison to the unwashed yeast but without the supernatant. The washing procedures were adopted from an earlier reference of Negaresh et al. (2007) who removed the cell debris and soluble macromolecules (such as EPS) which had been reported before as potential foulants (Le-Clech et al., 2006). Around 5 g of the unwashed yeast was placed in a 50 mL centrifuge tube, and then mixed with 10 times volume of milli-Q water. The

suspension was then placed in a centrifuge (Thermo Scientific, Legend Mach 1.6R) at 2000 rpm for 15 min. After centrifugation, the supernatant was discarded. The same procedure was repeated three times by adding an extra 10 times volume of milli-Q water each time. Afterward, the washed yeast was dried in an oven at 80 °C. This was repeated until there was no change of the weight of the dried yeast. The results are shown in Table 4.1. The averaged wash removal efficiency was found to be 19.7%. This value was used for computation in the washed yeast experiments.

Table 4.1 Summary of washing removal efficiency of the instant yeast

Number	Net weight of the centrifuge tube (g)	Weight with the washed yeast	Wash removal efficiency (%)
1	9.94	13.86	20.3
2	9.95	13.99	17.9
3	10.01	13.87	21.5
4	9.96	13.95	18.9

4.3.2.3 Supernatant

After the yeast washing, the supernatant was retained and made into a 1 g/L feed solution. This feed was also used in some experiments to compare with the unwashed yeast suspensions.

4.3.2.4 Particle size distribution of unwashed yeast, washed yeast, and supernatant

The particle size distributions of the unwashed yeast, washed yeast and supernatant were analyzed using the Mastersizer Hydro 2000SM. The particle size distribution analysis was summarized in Table 4.2. A histogram of the size distribution is shown in Figure 4.1. The mean diameters of unwashed yeast, washed yeast and supernatant were 4.95, 4.63, and 4.38 μm , respectively. The washed yeast has a smaller average particle size and a narrower particle size distribution as compared to the unwashed yeast suspensions after the washing procedures.

Table 4.2 Summary of size distribution analysis of unwashed yeast suspensions, washed yeast suspensions, and supernatant (μm).

Types	D (10%)	D (50%)	D (90%)
Unwashed yeast	2.66	4.95	10.94
Washed yeast	3.28	4.63	6.50
Supernatant	2.59	4.38	7.67

Figure 4.1 Particle size distribution of unwashed yeast, washed yeast and supernatant

4.3.3 Experimental procedures

The same experiment procedures as described in Chapter 3 were adopted. Both constant pressure and constant flux operations were applied as well. For all the yeast experiments including unwashed yeast, wash yeast and supernatant, after each experiment, the membranes were flushed with 1% enzyme solution (Sigma-Aldrich) for 15 min, and then followed by 20 mL/min milli-Q water backwash for half an hour. After the cleaning procedures, the permeability of the membranes was measured. If the

permeability recovered to above 95% of the original value, the membranes were then reused, otherwise they were replaced with new ones.

4.4 Results and discussion

4.4.1 Membrane filtration

Membrane filtration tests at constant flux of 30 LMH with longitudinal vibration were conducted in 4 g/L unwashed yeast suspensions, 4 g/L yeast suspensions and 1 g/L supernatant for 1 hour. Due to the big volume of the reactor, a 4 g/L concentration of supernatant was difficult to attain, thus a small concentration of 1 g/L was instead. The TMP profiles are compared in Figure 4.2. At vibration amplitude of 8 mm and frequency of 10 Hz, there was 23.4 kPa increase in TMP of the unwashed yeast suspensions over the 60 min duration, whereas for the washed yeast suspensions, the increase in TMP was at slower rate at 3.5 kPa over 60 min duration. In contrast, for the supernatant, a significant increase of 26 kPa was observed even at a lower concentration of 1 g/L for the same vibration conditions. The fouling was minor in the washed yeast suspensions as compared to unwashed yeast suspensions, which was due to the removal of cell debris and macromolecules in the supernatant. The differences of the TMP rise values confirmed quantitatively that the presence of cell debris and macromolecules in the supernatant contributed dominantly to membrane fouling in the microfiltration of yeast materials (Kuberkar and Davis, 1999). The cell debris and macromolecules in yeast suspensions are the important EPS components. EPS has been recognized as a main contributor to membrane fouling (Negaresh et al., 2007; Hughes and Field, 2006; Beier and Jonsson, 2009). It can be adsorbed and deposited on the membrane surface thus increases the hydraulic resistance to flow (Belfort et al., 1994). The current experimental findings were consistent with Sur and Cui (2005) and Wicaksana (2006), who reported that the removal of EPS in yeast elevated the permeate flux at constant pressure.

Figure 4.2 TMP of unwashed yeast, washed yeast and supernatant (concentration of unwashed and washed yeast = 4 g/L, concentration of supernatant = 1 g/L, constant permeate flux 30 LMH, 1.7 mm fibre, vibration amplitude 8 mm, vibration frequency 10 Hz)

4.4.2 Effect of vibration frequency and amplitude in unwashed yeast suspensions

Figure 4.3 displays the fouling rate at different vibration frequencies of 6, 8 and 10 Hz and amplitudes of 6, 8, and 10 mm for 1.7 mm fibres, at constant permeate flux of 30 LMH in 4 g/L unwashed yeast suspensions. The similar range of vibration frequencies and amplitudes were used so that the vibration effect in the yeast suspensions can be compared with that in Bentonite suspensions. It was found that the membrane filtration by vibration was enhanced when both vibration frequency and amplitude were increased. The TMP without vibration increased rapidly from 16 to 80 kPa in a very short time which showed that yeast caused severe membrane fouling. The fouling rate of yeast suspensions decreased from 95 to 55.2 kPa/h when vibration amplitude was increased from 6 to 8 mm at vibration frequency of 6 Hz, and further dropped to 43.5

kPa/h when the frequency was increased to 8 Hz at amplitude of 8 mm. Comparing to no vibration, 68% reduction in fouling rate was observed at amplitude of 8 mm and frequency of 10 Hz. Similar fouling reduction was also found with vibration amplitude of 10 mm and frequency of 8 Hz. The fouling rate was comparatively lower at 7 kPa/h when vibration frequency was further increased to 10 Hz at amplitude of 10 mm.

Figure 4.3 Fouling rate at different vibration frequencies and amplitudes in 4 g/L unwashed yeast suspensions (constant permeate flux = 30 LMH)

As compared to Bentonite suspensions (Figure 3.8 (b)), the yeast suspensions induced more significant membrane fouling. The Bentonite and yeast suspensions had average particle sizes of 5.83 and 4.95 μm , respectively. Thus, the shear-induced back transport was dominant (Davis, 1992; Belfort et al., 1994). According to Eckstein et al. (1977), the shear-induced diffusion coefficient is proportional to the square of the particle size, thus the smaller size of yeast induced much lower diffusivity. In addition, higher specific cake resistance was also induced by the smaller size of yeast due to the hydrodynamic selection of smaller particles and cake reorganization (Belfort et al.,

1994; Chellam and Wiesner, 1997). Moreover, the cell debris and macromolecules in the yeast components could be adsorbed and deposited on the membrane surface, which led to increase of filtration resistance and decrease of mass transport. Therefore, higher membrane fouling was observed during the yeast filtration.

4.4.3 Intensification effect of vibration

The cake filtration law was also applied to determine the relationship between cake resistance and permeate volume under different vibration conditions for the unwashed yeast suspensions. The experiments were conducted at constant suction pressure of -24 kPa by adjusting the pump flowrate together with the needle valve. Different vibration frequencies of 0 to 10 Hz were applied at amplitude of 6 mm. Figure 4.4 shows plot of t/V versus V of unwashed yeast under different vibration frequencies at constant pressure filtration. The time required to collect the same amount of permeate was greatly shortened when higher vibration frequencies were applied, indicating that vibration could improve the membrane filtration permeability. For example, 69 min was required to collect 400 mL volume permeate without vibration, only 45 min filtration could collect the same amount of permeate under vibration frequency of 6 Hz, and the time required to collect the same amount of permeate was greatly shortened to 29 min at higher vibration frequency of 10 Hz. Comparing with the performance by Bentonite using the same hollow fibre membranes under same vibration frequency and amplitude (Figure 3.9(b)), longer time was required to collect similar amount of permeate in the yeast filtration, which illustrated more severe membrane fouling in the yeast suspensions.

From the best fit curve in Figure 4.4, the slope k for no vibration is 14138 s/L^2 , thus the relationship between R_c (10^{12} m^{-1}) and V (L) was $R_c = 20.7 V$ by Eq. (3.12). And it was changed to $R_c = 9.87 V$ for 6 Hz, and $R_c = 2.41 V$ for 10 Hz. This indicated that vibration could enhance the membrane filtration performance since the cake resistance was reduced.

Figure 4.4 Evolution of t/V versus cumulative permeate volume at different vibration frequencies with cake filtration law identification (constant suction pressure = - 24 kPa) with 1.7 mm fibre, vibration amplitude = 6mm

Figure 4.5 shows the cake resistance versus cumulative permeate volume under different vibration frequencies for 4 g/L unwashed yeast suspensions according to the cake filtration law. It was observed that the cake resistance decreased significantly with increase of vibration frequency. At collected volume of 0.3 L, R_c decreased from $6.22 \times 10^{12} \text{ m}^{-1}$ to $2.97 \times 10^{12} \text{ m}^{-1}$ when vibration frequency of 6 Hz was applied as compared to no vibration, and was further reduced to $0.72 \times 10^{12} \text{ m}^{-1}$ when a higher vibration frequency of 10 Hz was applied. Thus it decreased 50% at vibration frequency of 6 Hz and 80% at frequency of 10 Hz as compared to no vibration. The reduction of the cake resistance with the less severe membrane fouling (Figure 4.3) can be attributed to the shear rate on the membrane surface with longitudinal vibration. Comparing with the cake resistance induced by Bentonite (Figure 3.10(b)) under the same vibration condition, the yeast caused more severe membrane fouling, which may be due to the smaller particle size of yeast and the cell debris and macromolecules in

the yeast components. The smaller shear forces and larger specific cake resistance could be produced by the smaller size of yeast (Belfort et al., 1994; Chellam and Wiesner, 1997; Zhang and Song, 2000), thus reduced the shear-induced back transport, while the cell debris and macromolecules in the yeast components could be adsorbed and deposited on the membrane surface resulting in the increase of the hydraulic resistance and decrease of the thermodynamic driving force (Belfort et al., 1994; Hughes and Field, 2006).

Figure 4.5 Evaluation of cake resistance R_c versus cumulative permeate volume at different vibration frequencies (constant suction pressure = - 24 kPa) with 1.7 mm fibre, vibration amplitude = 6 mm

4.4.4 Effect of vibration in washed yeast suspensions

In this study, the membrane performance with vibration of washed yeast suspensions as a comparison to the unwashed yeast suspensions was also evaluated. The hollow fibre membrane curtain was vibrated at different frequencies from 6 to 10 Hz at amplitude of

8 mm in 4 g/L washed yeast suspensions at constant flux of 30 LMH. Figure 4.6 shows the fouling rate of the washed yeast suspensions at different vibration frequencies. The fouling rate decreased from 5.8 kPa/h at 6 Hz to 5 kPa/h at 10 Hz. A reduction in fouling rate was obtained due to a higher shear rate at higher vibration frequency. The washed yeast suspensions induced less membrane fouling as compared to unwashed yeast suspensions (Figure 4.3) which indicated that membrane filtration performance could be improved by removing the cell debris from the yeast components. Comparing with the same mass concentration of inorganic Bentonite suspensions (Figure 3.8(b)) under the same vibration conditions, however, there was more severe membrane fouling by the washed yeast suspensions, which could be due to the smaller particle size of washed yeast (Table 4.2). The smaller particle size of washed yeast induced smaller diffusivity and larger specific cake resistance, thus more significant membrane fouling was observed for the washed yeast filtration.

Figure 4.6 Fouling rate of washed yeast at different vibration frequencies (vibration amplitude = 8 mm, constant permeate flux = 30 LMH)

4.4.5 Effect of membrane looseness

The effect of fibre looseness by longitudinal vibration in inorganic Bentonite suspensions was studied in Chapter 3. Here, the effect of fibre looseness was also investigated in the presence of longitudinal vibration in organic yeast suspensions. Hollow fibre membranes with tight, 1% and 2% looseness were submerged in 4 g/L unwashed yeast suspensions, and vibrated at amplitude of 8 mm and frequencies from 6 to 10 Hz at constant permeate flux of 30 LMH. Figure 4.7 shows the dTMP/dt profile of tight, 1% and 2% looseness fibres in 4 g/L unwashed yeast suspensions. The fouling rate was 55.2 kPa/h for tight fibres at frequency of 6 Hz, it decreased to 39.1 kPa/h at 1% looseness, and further dropped to 19 kPa/h at 2% looseness. At frequency of 10 Hz, the fouling rate was 35.8 kPa/h for the tight fibres, 20.3 kPa/h for 1% looseness fibres, and 17.4 kPa/h for 2% looseness fibres, respectively. This indicated that the membrane performance was improved with small degree of fibre looseness. The improvement was attributed to additional lateral movement induced by the looseness of fibres in the vibration system. Same phenomenon was also reported in the bubbling study by Wicaksana et al. (2006). Other researchers attributed the enhanced effect of the looseness to the reduced inter-fibre clogging as compared to the tight module at high feed concentrations (Fane et al., 2002). This small degree of looseness was important because it would save energy as the intensity of vibration can be reduced to achieve the same effect (Fane et al., 2002). However, more looseness was not introduced in the present study, as excessive looseness could cause fibre damage (Wicaksana et al., 2006; Yeo et al., 2007). Comparing with the fibre looseness effect in the Bentonite suspensions (Figure 3.15), the looseness effect in the yeast suspensions was less probably due to the fact that the yeast had a smaller particle size, which resulted in larger specific cake resistance and smaller shear stress (Belfort et al., 1994; Chellam and Wiesner, 1997; Zhang and Song, 2000).

Figure 4.7 Fouling rate for tight and loose fibres at different vibration frequencies
(constant permeate flux = 30 LMH, vibration amplitude = 8 mm, 1.7 mm fibre)

4.4.6 Fouling rate of same number particles of Bentonite and unwashed yeast

There were more washed yeast particles in the reactor as the density of yeast was far lower than Bentonite particles and the particle diameter was smaller as well. It was necessary to conduct experiments with the same number particles of yeast and Bentonite to further confirm the observations. To achieve this, the experiments were carried out with the same theoretical number particles of Bentonite and yeast by assuming that both Bentonite and yeast particles were spherical. A group of 25 fibres with length of 18 cm were submerged and vibrated longitudinally in 4 g/L Bentonite and 1.2 g/L yeast suspensions (Figure 4.8). A large vibration amplitude of 28 mm and a low vibration frequency of 2 Hz were adopted due to the fact that low frequency of vibration can be easier to be implemented in real applications with lower energy consumption. It was found that TMP increased by 14.4 and 9.3 kPa at constant flux test for yeast and Bentonite suspensions, respectively. Therefore, the results also suggested that greater membrane fouling induced by the yeast suspensions might be attributed to

the smaller nominal particle size (Table 4.2) as well as the cell debris and the macromolecules in the yeast suspensions. The small particles induced smaller shear forces and larger specific cake resistance (Belfort et al., 1994; Chellam and Wiesner, 1997; Zhang and Song, 2000), while the cell debris and macromolecules were adsorbed and deposited on the membrane surface, which increased the hydraulic resistance and reduced the thermodynamic driving force (Belfort et al., 1994).

Figure 4.8 TMP of feed suspensions with the same number of particles of Bentonite and unwashed yeast suspensions by longitudinal vibration (concentration of Bentonite suspensions = 4 g/L, concentration of unwashed yeast suspensions = 1.2 g/L, constant permeate flux = 25 LMH, vibration amplitude = 28 mm, vibration frequency = 2 Hz).

4.5 Conclusions

Some conclusions can be drawn as follows:

Experiments among the unwashed and washed yeast suspensions and supernatant showed that the supernatant induced the greatest fouling rate which was attributed to

that the cell debris and macromolecules in the yeast components were the main membrane fouling contributors and produced severe membrane fouling.

The vibration was found to reduce membrane fouling in the organic yeast suspensions. The fouling rate decreased with increase of vibration frequencies and amplitudes for both unwashed yeast and washed yeast suspensions due to the shear stress by the vibration. A small degree of fibre looseness improved the membrane filtration performance in the organic yeast suspensions due to extra lateral movement induced by the fibre looseness.

More profound membrane fouling was observed in yeast suspensions as compared to Bentonite suspensions, which could be attributed to the smaller back-transport and higher specific cake resistance induced by the smaller particles of yeast.

Chapter 5 Experimental Study of Transverse and Longitudinal Vibration of Submerged Hollow Fibre Membrane Filtration

5.1 Introduction

As discussed in Chapters 3 and 4, the performance of submerged hollow fibre membranes under longitudinal vibration can provide significant improvement. However, transverse vibration can produce vortices which could be more advantageous for membrane fouling control. The comparison of longitudinal and transverse vibration has not been systematically studied yet. Hence, it is necessary to compare the membrane filtration under the two vibration modes with the same vibration condition (same frequency and amplitude).

The productivity of submerged hollow fibre membranes is related to both membrane filtration flux and fibre packing density. A hollow fibre membrane module can be densely or sparsely packed. For the densely packed fibres, there is a flux competition which conversely reduces the permeate flow. For the sparsely packed fibres, there is an inefficient space use which also reduces the permeate productivity. A higher membrane packing density would increase productivity, as long as the flux on a per unit area basis is not affected. However, the hydrodynamics within the fibre bundle under transverse

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Law, A. W. K., **Li, T.** and Fane, A. G. (2013), "Vibration-Stirring (VS) Membrane Module System for Submerged Hollow Fibre Membrane Filtration", Provisional Patent Application No.: US 61/901,609.

Li, T., Law, A. W. K. and Fane, A. G. (2014), "Submerged Hollow Fibre Membrane Filtration with Transverse and Longitudinal Vibrations", Journal of Membrane Science, Vol. 455, pp. 83-91.

Li, T., Harijanto, A., Jiang Y. and Law, A. W. K., "a Novel Transverse Vibration on Fouling Control of Submerged Membrane Bioreactor", NAMS 2014, May 31-June 4, 2014, Houston, Texas, USA, Oral Presentation.

Law, A. W. K., Jiang, Y., **Li, T.**, Harijanto, A. K. and Fane, A. G., "Energy consumption for membrane fouling mitigation in Membrane Bioreactors (MBRs)", IWA Regional Conference on Water Reuse and Energy, October 21-24, 2014, Daegu, Korea, Oral Presentation.

vibration is quite complicated, which could also affect membrane filtration performance. Thus, it is necessary to evaluate the fibre packing density under vibration.

The objective of this chapter is therefore to address the effectiveness of mechanical transverse vibration towards membrane fouling of submerged hollow fibre membranes in both the inorganic Bentonite and organic yeast suspensions. The present study also provides a direct quantitative comparison between the transverse and longitudinal vibration modes. In addition, the vibratory parameters for optimal fouling mitigation in submerged hollow fibre membranes were also further investigated. Various combinations of feed characteristics, fibre looseness, and fibre packing density, as well as vibration relaxation and energy consumption were examined in a series of comprehensive laboratory experiments.

5.2 Vibration setup

The schematic diagram and photograph of the vibration setup are shown in Figures 5.1 and 5.2, respectively. The setup included the vibration mechanism and the permeate measurement equipment. The test tank was made of Perspex with sizes of 600 mm (L) $\times$ 500 mm (W) $\times$ 600 mm (H). During the experiments, a small background of air bubbling (50 mL/min) was maintained in the tank to keep the feed particles suspended in the reactor. Longitudinal or transverse vibration was achieved 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 length of the rod connecting to the motor determined the submergence of the hollow fibres. The vibration amplitude could be manually adjusted from 0 to 28 mm at 4 mm intervals, while the vibration frequency could be varied from 0 to 10 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 5.1 Schematic diagram of transverse vibration setup (II)

Figure 5.2 Photograph of transverse vibration setup (II)

5.3 Materials and operating procedures

5.3.1 Hollow fibre membranes

The same PAN hollow fibre membranes with the inner/outer diameter of 1mm/1.7 mm as described in Chapter 3 are used. In most of the experiments conducted in this chapter, the membrane module was a 5×5 hollow fibre bundle (Module B) with a displacement of 5 mm (Figure 5.3). The hollow fibre membranes were aligned in parallel with both ends fixed to the water chamber using Araldite epoxy. The membrane module was then mounted to the C shape holding frame and connected to the motor with a metal rod.

Figure 5.3 5×5 hollow fibre membrane module (Module B)

5.3.2 Preparation of feed suspensions

Two kinds of feed suspensions were used: the inorganic Bentonite (Sigma-Aldrich) and organic dry yeast (Levure Sèche de Boulanger, France) mixed with tap water. They represented inorganic and organic feeds, respectively. Their characteristics are described in the following.

5.3.2.1 Bentonite suspensions

The Bentonite suspensions used here is the same as that described in Chapter 3.

5.3.2.2 Yeast suspensions

The yeast suspensions used here is the same as that described in Chapter 4.

5.3.3 Experimental procedures

The experimental procedures were the same as that described in Chapter 4. In this study, the constant flux condition was adopted both to elucidate fouling mechanisms and monitor the fouling progress as the rate of TMP rise (Field et al., 1995). The corresponding TMP was recorded using a pressure gauge at 1-min interval.

5.4 Results and discussion

5.4.1 Vibration frequencies and amplitudes

The variations of fouling rates at different vibration frequencies and amplitudes were first studied. A 5×5 hollow fibre membrane bundle with spacing of 5 mm (Module B) was submerged in 4 g/L Bentonite suspensions, and vibrated transversely at different vibration frequencies from 2 to 3 Hz (with every 0.17 Hz, or 10 rpm increase) and at vibration amplitude of 8 mm (Figure 5.4). Constant flux of 25 LMH was maintained and the change in TMP profile was recorded. When the frequency was increased from 2.33 to 2.5 Hz, significant reduction in the fouling rate was obtained. However, only marginal improvement was observed when the frequency was further increased to 2.67 Hz. This indicated that the critical vibration frequency was 2.5 Hz at vibration amplitude of 8 mm and constant permeate flux of 25 LMH for 4 g/L Bentonite suspensions. The reduction of the TMP was due to the shear stress on the membrane surface induced by the transverse vibration.

Figure 5.4 TMP profile at different transverse vibration frequencies

Similar experiments were carried out at amplitudes from 4 to 40 mm and vibration frequencies of 0.5 to 5 Hz at constant permeate fluxes of 25 and 30 LMH. The results of corresponding critical frequency at given amplitude to achieve the same permeate flux was plotted in Figure 5.5 on a log scale. It was found that an increase in vibration (either amplitude or frequency) was necessary to keep a larger permeate flux of 30 LMH than 25 LMH. Another observation was that increasing either vibration amplitude or frequency could improve the membrane performance. In addition, a relationship of the critical vibration frequency (F) and vibration amplitude (A) at both fluxes of 25 and 30 LMH was obtained from Figure 5.5 as below:

$$A \cdot F^{1.35} = \text{constant (dependent on flux)} \quad (5.1)$$

Previous researchers had illustrated that the dynamic shear stress on the membrane surface during vibration could reduce the membrane fouling (Beier et al., 2006). For

the vibrating disk, Akoum et al. (2002) suggested the relationship between the maximum shear rate and vibration frequency and amplitude as shown in Eq. (2.11).

Figure 5.5 Critical vibration frequencies and amplitudes to maintain permeate flux of 25 and 30 LMH

By conducting the experiments with the same theoretical shear stress ($A \cdot F^{1.5} = \text{constant}$) in 4 g/L Bentonite suspensions in Section 3.5.7, the studies had illustrated that the power ratio of the vibration frequency to the shear rate is larger than 1.5 in the longitudinal vibration. From Eq. (5.1), the power factor of the vibration frequency is lower than 1.5, which suggests vibration amplitude has greater impact in the transverse vibration than in the longitudinal vibration. With the transverse vibration, besides the generation of shear stresses, secondary flow could also be induced by the motion of the whole fibre bundle. Comparatively, only shear stresses on the membrane surface could be produced by longitudinal vibration. The larger vibration amplitude in transverse

vibration might well induce stronger secondary flows thus improving the membrane filtration performance.

5.4.2 Membrane filtration in yeast suspension

The effect of longitudinal vibration on membrane filtration of unwashed yeast, washed yeast suspensions and supernatant were studied in Chapter 4. Here, the effect of transverse vibration was investigated. Membrane filtration tests of a 5×5 membrane module with length of 18 cm and spacing of 5 mm (Module B) at constant flux of 25 LMH with transverse vibration were conducted in 4 g/L unwashed yeast suspensions, 4 g/L washed yeast suspensions and 1 g/L supernatant for 400 min. The TMP profiles are compared in Figure 5.6. A large vibration amplitude of 16 mm and a low vibration frequency of 2 Hz was adopted due to the fact that low frequency of vibration could reduce energy consumption. It was found that the TMP of the unwashed yeast suspensions increased by 72.7 kPa over the 400 min duration, whereas the washed yeast suspensions increased at slower rate of 35.7 kPa per 400 min. In contrast, the TMP of the supernatant increased at a higher rate of 77.9 kPa to the water vapour pressure even at a lower concentration of 1 g/L for the same vibration conditions. The differences of the TMP rise values confirmed quantitatively that the presence of cell debris and macromolecules in the supernatant contributed dominantly to membrane fouling in the microfiltration of yeast materials (Kuberkar and Davis 1999). The cell debris and macromolecules in yeast suspensions are the important EPS components (Negaresh et al., 2007; Hughes and Field, 2006; Beier and Jonsson, 2009). EPS has been recognized as a main contributor to membrane fouling. The current experimental findings were consistent with Sur and Cui (2005) and Wicaksana (2006) who reported that the removal of EPS in the yeast components elevated the permeate flux at constant pressure.

Figure 5.6 TMP of unwashed yeast, washed yeast suspensions and supernatant (concentration of unwashed and washed yeast suspensions = 4 g/L, concentration of supernatant = 1 g/L, constant permeate flux = 25 LMH, fibre length = 18 cm, transverse vibration, vibration amplitude = 16 mm, vibration frequency = 2 Hz)

5.4.3 Comparison of longitudinal and transverse vibration

In the present study, the experimental setup of the longitudinal and transverse vibration was identical except the orientation of the fibres. Hence, a direct comparison of the measurements can reveal the relative effectiveness of the two modes of vibration. Experiments using the same 5×5 membrane module (Module B) were performed for both the inorganic Bentonite and organic yeast suspensions at constant flux filtration of 25 LMH. Figure 5.7 shows the average fouling rates at a low frequency of 1 Hz. At amplitude of 28 mm and 4 g/L Bentonite suspensions, the fouling rates were measured to be 21.8 and 4.2 kPa/h by the longitudinal vibration and transverse vibration, respectively. They increased to 24.2 and 15.5 kPa/h in 4 g/L yeast suspensions, respectively. Clearly, the fouling rates for the transverse vibration were much lower

than that of the longitudinal vibration for all the tests performed in the present study. Hence, the present study confirms that the transverse vibration is more effective than longitudinal vibration for membrane fouling control. It should be noted that the holding frame did not have much effect on the results (Section 3.5.6).

Figure 5.7 Comparison of fouling rate of longitudinal and transverse vibration (5×5 fibre bundles, tight fibres, fibre length = 18 cm, vibration frequency = 1 Hz, constant permeate flux = 25 LMH) in (a) 4 g/L Bentonite suspensions, and (b) 4 g/L yeast suspension

The improvement due to the transverse vibration can be attributed to the separating boundary layers induced by the transversely moving fibres, which is effective in reducing membrane fouling. In addition, with the periodic movement by transverse vibration, a streaming secondary flow pattern can be produced, which generates vortices that further increase the shear rate in the vicinity of the membrane surface. At the same time, it should be noted that the risk of fibre breakage is obviously higher with the transverse vibration at higher vibration frequencies and amplitudes due to more severe lateral movement and stresses as compared to the longitudinal vibration. The potential of damage to the fibres induced by the fibre movement was also pointed out in earlier studies (Wicaksana et al., 2006; Yeo et al., 2007). Further investigation in the damage potential is therefore required before prototype implementation.

The fouling improvements by both longitudinal and transverse vibration in 4 g/L yeast suspensions were weaker than that in 4 g/L Bentonite suspensions. The yeast particle density was lower than Bentonite particles, so there were a relatively larger number of yeast particles than Bentonite particles for the same mass concentration. Here transverse vibration experiments were carried out in the reactor with the same theoretical number of particles for the two feed suspensions (4 g/L Bentonite and 1.2 g/L yeast) by assuming that these particles were spherical for comparison. The same membrane module was also used in the experiments. It can be observed that the yeast suspensions induced more severe fouling than the Bentonite suspensions even at the same number of particle concentration (Figure 5.8). With the transverse vibration, the TMP of the yeast and Bentonite suspensions increased by 12.4 and 0.3 kPa, respectively, in the constant flux tests. Therefore, these results also suggested that the more severe membrane fouling induced by the yeast suspensions can be attributed to the smaller nominal particle size (Table 4.2) and cell debris and macromolecules in the yeast components. In the shear-induced back transport, the small yeast particles had smaller diffusivity and larger specific cake resistance (Belfort et al., 1994; Chellam and Wiesner, 1997; Zhang and Song, 2000), thus they induced worse membrane filtration performance than the Bentonite particles. In addition, cell debris and macromolecules

from the yeast components might deposit and form a cohesive layer on the membrane surface resulting in a reduction of the membrane filtration performance.

Figure 5.8 TMP of feed suspensions with the same number of particles of Bentonite and unwashed yeast suspensions (concentration of Bentonite suspensions = 4 g/L, concentration of unwashed yeast suspensions = 1.2 g/L, constant permeate flux = 25 LMH, vibration amplitude = 28 mm, vibration frequency = 2 Hz) with transverse vibration

5.4.4 Effect of fibre looseness in the transverse vibration

In Chapters 3 and 4 with longitudinal vibration, the small degree of fibre looseness was found to reduce membrane fouling. Here the effect of fibre looseness for fouling control was also examined in the transverse vibration operation. The same membrane module was used as above, with tight, 1% and 2% looseness of fibres mounted on the holding frame and vibrated transversely in the reactor. The experiments were carried

out in the Bentonite and yeast suspensions. Figure 5.9 presents the measured fouling rates of both tight and loose fibres. The figures clearly show that the membrane performance was better with the loose fibres. At 20 mm vibration amplitude in 4 g/L Bentonite suspensions, the fouling rate reduced from 36.4 kPa/h with tight fibres to 28.8 kPa/h with 1% looseness, and further to 28.4 kPa/h with 2% looseness. The fouling rate also reduced from 19.8 to 16.2 kPa/h in 4 g/L yeast suspensions with 1% looseness. Bérubé et al. (2006) reported no substantial differences in the surface shear forces between the loose or tight fibres in two-phase flow conditions. While Yeo et al. (2007) reported that fibre looseness increased the shear stress in air sparging process. Here, it can be assumed that fibre looseness would induce additional lateral fibre movement by vibration that may help shake loose the foulants on the membrane surface and thus further reduce membrane fouling.

The membrane performances of longitudinal and transverse vibration were compared by using the same 5×5 membrane module with a length of 16 cm and 1% looseness fibres at constant flux of 25 LMH and vibration frequencies of 1 - 3 Hz (Figure 5.10). As expected, the performance of the transverse loose fibres was much better than that of the longitudinal loose fibres, implying that there was more significant lateral movement in transverse vibration. The lateral displacement of fibres induced by the two different vibration (as controlled by the vibration mechanism and the set parameter on vibration amplitude) was also measured using a high speed camera (the photos are not included here). It was confirmed that the lateral displacement induced by the transverse vibration was much larger than that during longitudinal vibration (which was also limited by the looseness) (Yeo et al. 2007). Typically the displacement induced by the transverse vibration could easily reach its maximum, which was 7% of the fibre length for 1% looseness fibres (Wicaksana et al., 2006). However, there was only around 2-4% of the fibre length of displacement induced by longitudinal vibration (Section 3.5.4) for the same 1% looseness fibres.

Figure 5.9 Fouling rate of tight and loose fibres of Bentonite and unwashed yeast suspensions with transverse vibration (5×5 fibre bundles, fibre length = 18 cm, vibration frequency = 1 Hz) with (a) 4 g/L Bentonite suspensions, constant flux = 30 LMH, and (b) 4 g/L yeast suspensions, constant flux = 25 LMH

Figure 5.10 Fouling rate of longitudinal and transverse loose fibres in 4 g/L unwashed yeast suspensions (5×5 fibre bundles, fibre length = 16 cm, constant permeate flux = 25 LMH, vibration amplitude = 16 mm)

5.4.5 Fibre packing density

With more hollow fibre membranes in the reactor, the permeate flow can be increased with a high packing density. However, there is more non-uniform flux distribution and flux competition with the smaller fibre spacing (Yeo et al., 2006). The flow velocity within the fibre bundle also increases during vibration.

In this study, four fibre bundles (5×5 , 6×6 , 7×7 , and 8×8) with 1% looseness were uniformly mounted on a $20 \text{ mm} \times 20 \text{ mm}$ area of a $40 \text{ mm} \times 40 \text{ mm}$ plate to make packing densities of 12%, 17%, 24% and 31% (Figure 5.11). They were vibrated transversely at different vibration amplitudes in both 4 g/L Bentonite and yeast suspensions (Figure 5.12). With the smaller vibration amplitude of 20 mm, the fouling rate increased from 7.4 to 95.2 kPa/h when the packing density increased from 5×5 to 8×8 in the Bentonite suspensions (Figure 5.12 (a)). However, the increase decreased

when a greater vibration amplitude of 28 mm was applied. The results illustrated that at lower vibration amplitudes, there was strong permeate flux competition for highly densely packed fibres; however, at higher vibration amplitudes, the flux competition was less severe.

Figure 5.11 Layout of fibre bundles (mm) (a) 5 × 5, (b) 6 × 6, (c) 7 × 7, and (d) 8 × 8

Figure 5.12 Fouling rate of different packing densities of hollow fibre membrane bundles (transverse vibration, 1% looseness, fibre length = 18 cm) with (a) 4 g/L Bentonite suspensions, vibration frequency = 1.2 Hz, constant flux = 30 LMH, and (b) 4 g/L unwashed yeast suspensions, vibration frequency = 2 Hz, constant flux = 25 LMH

A similar trend was observed in 4 g/L yeast suspensions vibrating at 2 Hz (Figure 5.12 (b)). At vibration amplitude of 24 mm, the fouling rate increased from 18.1 to 34.8 kPa/h when the packing density increased from 6×6 to 7×7 , but dropped back to 18.1 kPa/h when the packing density increased further to 8×8 . The reason for the pressure drop can be attributed to the fact that the gap of the adjacent fibres for the 8×8 bundle was as small as 1.2 mm. With such a small gap, a synergetic sweeping and scouring effect of adjacent fibres (i.e. the bundle now acting as a whole unit) under the larger transverse vibration frequency of 2 Hz could overcome the flux competition restraint induced by the narrower fibre spacing, thus enhancing the mass transfer and producing less membrane fouling. In addition, larger fibre bundle could induce higher secondary flows under larger amplitude of transverse vibration which could further reduce membrane fouling. Buetehorn et al. (2012) studied the submerged hollow fibre movement by air sparging. They found that more frequent fibre collisions induced by high packing densities promoted cake removal, but at the same time reduced the lateral surface shear due to the hindered fibre motion. However, a recent numerical study by Zamani et al. (2013) pointed out that an increase in shear rate was obtained when the fibre distance was decreased to an optimal value in a small region. This enhanced shear rate can also reduce membrane fouling. Overall, the results also indicated that the secondary flows induced by the higher packing densities of fibres were more significant and in fact dominant at higher vibration amplitudes.

5.4.6 Vibration relaxation

In previous work, without vibration, intermittent operation of membrane filtration in MBRs, or so-called relaxation, was found to lead to a slower flux decline due to the enhanced removal of foulants accumulated on the membrane surface with the back transport of foulants under the release of suction pressure (Hong et al., 2002). Vibration relaxation was found to be effective if the membrane was not badly fouled (Low et al., 2009). However, the optimized time interval and energy conservation of vibration relaxation have not been fully evaluated to date. Here, vibration relaxation (in

comparison with continuous vibration) was explored to reduce the energy consumption and costs.

In this study, the vibration relaxation of the 5×5 membrane module with 1% looseness was carried out by setting the motor to work intermittently in a half on/off switching mode. A PLC system (M-90, Unitronics) was used to control the motor to rotate and stop periodically at an equal time interval. Here the time $t = 0$ was defined as the start of membrane filtration time, while vibration was also activated at the same time with the filtration for the experiments with vibration relaxation or continuous vibration. The time intervals of 1 min and 5 min were tested in 4 g/L Bentonite suspensions, and 10 s, 20 s, 30 s and 1 min in 4 g/L yeast suspensions. The results of the total filtration resistance are shown in Figure 5.13 by applying Eq. (3.2).

It can be seen that there was a slow increase in the membrane filtration resistance with continuous vibration, and a huge jump without vibration. For 4 g/L Bentonite suspensions (Figure 5.13(a)), with the relaxation interval of 1 min, the total filtration resistance of the hollow fibre membranes doubled in the first 3 h, while with a relaxation interval of 5 min, the total filtration resistance increased further.

For 4 g/L yeast suspensions (Figure 5.13(b)), with the relaxation interval of 10 s, the total filtration resistance of the hollow fibre membranes increased 90% in 150 min, while there was only 50% increase with continuous vibration correspondingly. In contrast, the time to double the resistance reduced to 30 min for the relaxation interval of 60 s. This implied that the membrane fouling can be further reduced with the shorter time interval of the vibration relaxation. The total filtration resistance of hollow fibres with 10 s relaxation interval was much lower than 30 s, and only slightly higher than continuous vibration. Vibration relaxation can therefore help the membrane recover the flux and reduce the energy consumption. It should be noted that the total filtration resistance stayed very high with the longer time intervals of 30 s and 1 min in the yeast suspensions, and was nearly the same as no vibration, which indicated that the long

time intervals of vibration relaxation were ineffective. These results are consistent with those reported by Bilad et al. (2012) but substantially more extensive.

Figure 5.13 Total filtration resistance of hollow fibre membranes with vibration relaxations and different time intervals (1% looseness fibres, 5×5 fibre bundles, fibre length = 18 cm, permeate flux = 25 LMH, transverse vibration, vibration amplitude = 16 mm) in (a) 4 g/L Bentonite suspensions, vibration frequency = 1 Hz, and (b) 4 g/L unwashed yeast suspensions, vibration frequency = 2 Hz

5.4.7 PIV measurement of transverse vibration

The PIV measurement of transverse vibration was adopted using the setup described in Section 3.2.2. A polyethylene dark rod with diameter of 1 cm and length of 25 cm (it was chosen as long as possible to minimize end effect at the middle of the rod) was horizontally orientated in the tank and vibrated up and down. The laser sheet was intersected perpendicularly to the middle of the vibrating rod, and the pictures were captured by the CCD camera. For a transverse oscillating fibre membrane, the continuous streaming flow exists and the hydrodynamics of such a system was studied in this study experimentally using PIV method. Figure 5.14 shows the continuous streaming flows away from the vibrating fibre. The vortices, which can help to mix up the concentrated fluid near the membrane surface with less concentrated fluid away from the membrane surface, can be observed. The continuous streaming and secondary flows (in contrast with periodic streaming and secondary flows) can help to wash off the rejected particles from the membrane surface and reduce membrane fouling.

Figure 5.14 The streaming flows away from the vibrating surface and the induced vortices by PIV measurement

5.4.8 Power consumption comparison of transverse vibration with longitudinal vibration

In current study, the power consumptions of both transverse and longitudinal vibration of the fibres and the holding frame by the motor at different vibration frequencies and amplitudes were measured by a clamp meter and shown in Figure 5.15. Generally for both transverse and longitudinal vibration, the vibration power consumption increased with increase of vibration frequencies and amplitudes. For example, for 1 Hz transverse vibration, at amplitude of 20 and 28 mm, power of 6.61 and 8.93 watt were consumed, which from observations shown in Section 5.4.4 led to 36.4 and 9.6 kPa/h fouling rate, respectively. In addition, the power consumption of transverse vibration was slightly lower than longitudinal vibration, e.g., at amplitude of 28 mm and frequency of 2 Hz, 11.2 and 15.6 watt were consumed by transverse and longitudinal vibration, respectively. However, transverse vibration induced smaller fouling rate than longitudinal vibration (Figure 5.7) which was due to the secondary flows and vortices generation by transverse vibration.

The relationship between the transverse vibration power consumption and membrane fouling rate for 4 g/L Bentonite suspensions at constant flux of 30 LMH was further plotted in Figure 5.16. Generally larger power consumption by transverse vibration could lead to higher fouling rate reduction. In addition, it can also be observed that there is a good relationship between the transverse vibration power and the membrane fouling rate. Comparing with the relationship between the longitudinal vibration consumption and fouling rate (Figure 3.23), less power consumption was consumed by transverse vibration for the same fouling rate reduction, which indicated that transverse vibration was more efficient and effective for fouling control than longitudinal vibration.

Figure 5.15 A comparison of operating power consumption between (a) transverse vibration and (b) longitudinal vibration

Figure 5.16 The relationship between transverse vibration power consumption and membrane fouling rate in 4 g/L Bentonite suspensions (Constant flux = 30 LMH)

5.5 Conclusions

In the present study, the transverse and longitudinal vibration of submerged hollow fibre membranes for fouling control were investigated in both inorganic Bentonite and organic yeast suspensions. A direct comparison of fouling performance between the two vibration orientations was performed. The results confirmed that transverse vibration was more effective than longitudinal vibration in terms of fouling reduction even at low vibration frequency of 1 Hz, which may be due to the shear stress and secondary flows around the cylindrical membrane fibres by transverse vibration. This improvement was however less obvious in yeast suspensions due to the dominant membrane foulants of cell debris and macromolecules in the yeast components and smaller particle size of yeast. A small degree of fibre looseness was found to further reduce the membrane fouling and enhance the membrane performance with transverse vibration in both feed suspensions due to the extra lateral fibre movement. The effect of packing density of the membrane bundle by vibration was also examined. It was found

that lesser membrane fouling was induced by high packing density of fibres with transverse vibration at higher vibration amplitudes, which implied that the secondary flow generated by the larger fibre bundle under transverse vibration was able to overcome the permeate flux competition induced by the smaller fibre spacing. A short relaxation time interval of the vibration relaxation was found to be more effective for fouling control and energy reduction under the half on/off operating mode. PIV measurement illustrated that vortices could be generated by transverse vibration. Finally, the energy consumption measurement indicated that transverse vibration was more efficient and effective for fouling control than longitudinal vibration.

Chapter 6 Vibration of Submerged Hollow Fibre Membranes in Mixed Liquor

6.1 Introduction

Recent work demonstrated that membrane vibration can be an effective alternative for fouling control in inorganic Bentonite and organic yeast suspensions (Beier et al., 2006; Kola et al., 2012), as well as anaerobic mixed liquor (Kola et al., 2014). However, the above studies were mainly carried out in short filtration durations. Since MBR is a more complex system and the fouling pattern differed with short and long operating time, it is therefore of interest to apply membrane vibration in mixed liquor with long operating time to verify its applicability. In addition, air is essential in an aerobic MBR to oxygenate the biomass, and the small oxygenated aeration can also be used to enhance the hydrodynamics in the reactor as well. Such information of the combination of vibration and limited aeration for oxygenation with long operating time has not been reported in the literature so far.

This chapter addresses the effectiveness of mechanical vibration of submerged hollow fibre membranes at different vibration frequencies in mixed liquor with both short and long operating duration in laboratory reactors. Short duration operational experiments were first performed to examine the effects of vibration relaxation and feed concentrations under the action of the vibrating hollow fibre membranes. A comparison study between longitudinal and transverse vibrations, and vibration and aeration in mixed liquor was also conducted in short duration tests. Subsequently, experiments with long operating duration were conducted to investigate the effects of vibration

Part of the work in this chapter has been presented in:

- Li, T.**, Law, A. W. K., and Fane, A. G., “Novel Transverse Vibrations on Fouling Alleviation of Submerged Hollow Fibre Membranes”, 2013 Qingdao International Conference on Desalination and Water Reuse, June 25-28, 2013, Qingdao, China, Oral Presentation.
- Li, T.**, Jiang, Y., Harijanto, A. and Law, A. W. K., “Submerged Membrane Bioreactor under Low Frequency Transverse Vibrations and Different Solids Retention Times (SRTs), NAMS 2014, May 31-June 4, 2014, Houston, Texas, USA, Poster Presentation.

frequency taking into consideration the impact of microbial parameter on the membrane filtration performance. Since membrane fouling had been reported to be significantly influenced by the physical-chemical and biological properties of the MBR, including MLSS, mixed liquor volatile suspended solids (MLVSS), as well as SMP and EPS (Huang et al., 2011; Okamura et al., 2010; Bugge et al., 2013), the determination of the relative influence of these parameters in relation to the microbiology and membrane operating conditions constitutes another major objective of the present study. Due to the complex environment inside the MBR, the biomass physiological state and sludge characteristics related to the removal efficiency and fouling potential were also investigated under different operating conditions.

6.2 Vibration setups

In this study, two vibration setups were used. The first was the Setup II as described in Chapter 5 which was also used for the trial tests. The second was the Setup III for the long operating time, with a larger size hollow fibre membrane module. The schematic diagram and photograph of the vibration setup III are shown in Figures 6.1 and 6.2, respectively. It consisted of the reactors, the vibration mechanism and the permeate measurement equipment. The reactors, made of Persplex, included the feed tank with a dimension of 600 mm (L) $\times$ 600 mm (W) $\times$ 800 mm (H), and the reactor tank with a dimension of 600 mm (L) $\times$ 300 mm (W) $\times$ 800 mm (H). The reactor tank was half filled with 80 L mixed liquor, while around 150 L influent was fed to the feed tank every day. A mixer with impeller was placed onto the feed tank, and rotated to keep the biosolids suspended at all time. A feed pump was activated automatically to circulate the mixed liquor from the feed tank to the reactor tank when the water level in the reactor tank dropped below the target water level. Thus, the constant volume of 80 L mixed liquor was maintained in the reactor tank at all time.

A DC motor was located on top of the reactor tank to drive the submerged membrane module in the reactor tank up and down in a sinusoidal manner with the crank moving

mechanism. 5 pairs of air stones (each air stone with a distance of 6.5 cm in a pair, and each adjacent pair with a distance of 13 cm) were placed at the bottom of the reactor tank to supply the air bubbling for the biomass growth. Each pair was connected to an air flow meter (Dwyer) to monitor the air flow rate in the whole reactor. The permeate effluent from the membrane module was pumped out by a digital permeate peristaltic pump (Cole-Parmer Instrument Company), and the pressure was monitored by the digital pressure sensor. In the present setup, a data logging system with SCADA automation software and PLC control system was used to set the motor and the permeate peristaltic pump to work either continuously or intermittently. The system also controlled the permeate peristaltic pump and liquid flow meter to maintain constant permeate flux and record the TMP values at the same time.

Figure 6.1 Schematic diagram of vibratory SMBR (Setup III)

Figure 6.2 Photograph of vibratory SBR (Setup III)

6.3 Materials and operating procedures

6.3.1 Hollow fibre membranes

The same PAN hollow fibres with the inner/outer diameter of 1mm/1.7 mm and 1 mm/2mm as described in Chapter 3 were used. Two hollow fibre membrane modules were used: Modules B and C. Module B was the same 5×5 fibre bundle with a length of 18 cm as described in Chapter 5. Module C had a larger size as described below.

Module C can hold up to 200 PAN hollow fibres with inner/ outer diameters of 1 mm/2 mm and nominal pore size of $0.1 \mu\text{m}$ (Figure 6.3). The fibres were aligned in parallel with both ends fixed to the membrane module using Araldite epoxy. The total membrane area was therefore equal to 0.5 m^2 (for a fibre length of 40 cm). The fibres

were arranged in 5 rows with 40 fibres each. The row spacing was 20 mm; and the fibre spacing within a row was 6.5 mm. The hollow fibre membranes were mounted with 1% looseness in the module as fibre looseness could increase the membrane filtration performance during the transverse vibration (Sections 5.4.4). The hollow fibre membranes were submerged horizontally in the reactor, so that a transverse vibration of the membrane was induced with the up and down movement. The length of the driving rod connecting to the motor determined the submergence of the hollow fibres.

Figure 6.3 Membrane module (Module C)

6.3.2 Preparation of feed

The mixed liquor was collected from Ulu Pandan Water Reclamation Plant (UPWRP) in Singapore. Two different kinds of mixed liquor were used in this study. The first kind was from the aeration tank of UPWRP, with MLSS concentrations of 4 ± 1 g/L. The second kind was from the membrane tank of UPWRP, with MLSS concentrations of 8 ± 1 g/L. They represented the typical sludge produced in water reclamation plant across Singapore. The particle size distribution was analyzed using the Mastersizer Hydro 2000SM. The mixed liquor had a much larger nominal particle size, with D (50%) of $52.51 \mu\text{m}$ as compared to Bentonite and yeast suspensions. A histogram of the size distribution among them is shown in Figure 6.4.

Figure 6.4 Particle size distribution of Bentonite, yeast and mixed liquor

6.3.3 Experimental procedures

Before each experiment, clean water backwash at 20 and 200 mL/min were first performed on Modules B and C, respectively, for 20 min. Subsequently, the filtration test was initiated. After the test in the mixed liquor was completed, the hollow fibre membrane modules were taken out from the reactor and flushed with tap water first, then soaked with 0.2% sodium hypochlorite and 0.2% citric acid each for 2 hours followed by the clean water backwash procedures. The permeability of the membranes was measured after the chemical cleaning. If the permeability recovered to above 95% of the original value, the membranes were reused, otherwise they were replaced with new ones.

6.3.4 Measurements

The concentrations of MLSS, and MLVSS were quantified according to the Standard Methods (APHA, 1995). The nitrogen concentration, represented by $\text{NO}_3\text{-N}$, was

measured by the Ion Chromatography (IC) (Dionex). COD was determined using HACH USEPA reactor digestion method (HACH 2125915/2415815). COD removal efficiency, η , can be calculated by the equation below:

$$\eta = \frac{COD_f - COD_p}{COD_f} \quad (6.1)$$

where COD_f and COD_p represent feed and permeate COD, respectively.

As discussed before, SMP and EPS have been found to exert significant influence on the membrane filtration performance. Carbohydrates and proteins are main SMP and EPS components, and their concentrations in the present experiments were measured to quantify the biological effects under membrane vibration. Samples of the harvested mixed liquor from the reactor and the feed mixed liquor from the UPWRP were both centrifuged at 4000 rpm for 10 min in order to separate the supernatant and sludge. The supernatant after the filtration of the 0.45 μm membranes was considered as SMP, while the sludge was re-suspended by the same volume amount of Milli-Q water for the analysis of EPS using the heat treatment (Morgan et al., 1990). The proteins and carbohydrates were determined by the modified Lowry method (Frølund et al., 1995) using Bovine Serum Albumin (BSA) as standard, and by the phenol-sulphuric acid method (Dubois et al., 1956) using glucose as standard, respectively.

6.4 Results and discussion

6.4.1 Short time operational experiments

Before the long duration tests, trial tests of membrane filtration with short duration in mixed liquor were performed to obtain the basic information on the filtration of biological suspensions using submerged hollow fibre membranes with mechanical vibration.

6.4.1.1 Effect of vibration frequency

Experiments with hollow fibre membrane filtration for short duration in mixed liquor were performed to obtain the basic information on the filtration of biological suspensions with mechanical vibration. Module B in Setup II was operated at constant permeate flux of 25 ± 1 LMH, and vibrated transversely at amplitude of 16 mm and two frequencies of 1 and 2 Hz in the reactor with the 8 ± 1 g/L mixed liquor from UPWRP mentioned earlier. The results were compared with that without vibration (Figure 6.5). It can be observed that there was a huge TMP jump without vibration, indicating immediate severe fouling of the membrane. At 1 Hz continuous vibration, TMP remained constant in the first 4 hour filtration, and then increased slowly from 15 to 22 kPa after 9 hour. At 2 Hz continuous vibration, there was only 1 kPa increase of TMP for the whole 9 hour filtration. This indicated that the transverse vibration was very effective for membrane fouling control, which was due to the direct shear enhancement by transverse vibrations.

Figure 6.5 TMP of hollow fibre membranes at different vibration frequencies

Comparing with the membrane filtration performance using the same membrane Module B in Bentonite and yeast suspensions with same vibration frequency in Section 5.4.6, membrane fouling in the real mixed liquor was less severe, which may be probably attributed to the larger particle size of the mixed liquor in the present experiments (In short time filtration, biofouling from mixed liquor was not significant). As compared to Bentonite and yeast, the mixed liquor had much larger particle sizes of over 50 μm . With such large particle size, the lateral migration of mixed liquor particles due to inertial lift was dominant (Chellam and Wiesner, 1992; Davis 1992). The inertial lift velocity increased with the cube of the particle size (Davis, 1992; Belfort et al., 1994), thus, the larger size of mixed liquor could induce much higher inertial lift velocity under transverse vibration.

6.4.1.2 Vibration relaxation

Vibration relaxation had been applied in inorganic Bentonite and organic yeast suspensions to reduce the energy consumption and cost in Section 5.4.6. Vibration relaxation helps the membrane recover the flux due to fouling momentarily. Here, the vibration relaxation effect was investigated in mixed liquor. The 5×5 fibre bundle (Module B) was operated at constant permeate flux of 25 LMH and vibrated transversely at amplitude of 16 mm and the frequency of 1 Hz in the mixed liquor collected from both the aeration tank and membrane tank of UPWRP Singapore. The TMP profiles are shown in Figure 6.6. It can be observed that there was a huge jump in TMP without vibration, and a very slow increase of TMP with vibration for both feeds. In the 4 g/L mixed liquor (Figure 6.6 (a)), the TMP increased significantly to 70 kPa within a short filtration time of 125 min without vibration. With vibration interval of 30 s and relaxation interval of 60 s at frequency of 1 Hz, the TMP increased to 53.7 kPa after 510 min, while with vibration and relaxation interval of 1 min, the TMP increased to 24.4 kPa at the same duration, which indicated that longer vibration time was effective for fouling control. However, the increase in TMP was higher to 45.8 kPa,

when the vibration and relaxation interval was increased to 5 min, which may be due to the longer relaxation time.

Figure 6.6 TMP of hollow fibre membranes in (a) 4 g/L mixed liquor and (b) 8 g/L mixed liquor

In the 8 g/L mixed liquor (Figure 6.6 (b)), similar observations were noted. The TMP jumped significantly to above 70 kPa in 115 min without vibration, which was slightly lower than the 4 g/L mixed liquor. At 1 Hz continuous vibration, the TMP increased to only 22.6 kPa after 9 hour, which was the best performance among all the experiments. This indicated that vibration could effectively reduce membrane fouling. With a vibration and relaxation interval of 1 min, the TMP increased to 26.4 kPa after 510 min, and it further increased to 27.7 kPa with a longer relaxation time of 2 min for the same test duration, which indicated that the longer relaxation time was ineffective. The TMP further increased to 39.6 kPa after 510 min with 2 min vibration and 4 min relaxation in one cycle. The TMP of the 5 min vibration and 5 min relation in one cycle increased to 50.4 kPa after 510 min, which was also much higher than that with the 1 min vibration and 1 min relaxation in one cycle. This illustrated that longer relaxation time interval was not effective when the same total combined vibration/relaxation time was applied.

The above findings implied that shear stress generated by vibration with short relaxation time interval could still mitigate the membrane fouling in a near continuous manner. Comparing with the TMP profile of the 4 g/L mixed liquor, the fouling rate of the 8 g/L mixed liquor was slightly higher, which may be due to the presence of more foulants at higher concentration of mixed liquor. Comparing with the membrane filtration in Bentonite and yeast suspensions (Figure 5.7), the mixed liquor induced less severe membrane fouling, which may be attributed to the fact that the mixed liquor had larger particle sizes of over 50 μm . With such a large particle size, the lateral migration of mixed liquor particles due to inertial lift was dominant (Chellam and Wiesner, 1992; Davis 1992; Belfort et al., 1994). The inertial lift velocity and shear stress was much higher with the larger particle size, thus the larger particle size of mixed liquor could induce much higher inertial lift velocity under transverse vibration. The most important, the system can be maintained at constant flux operation at low frequency of 1 Hz and short relaxation time, which suggested that vibration can be very useful in real applications.

6.4.1.3 Longitudinal and transverse vibration in mixed liquor

In Chapter 5 the membrane filtration performances with transverse and longitudinal vibration were compared in Bentonite and yeast suspensions. Here, the membrane filtration performance with transverse and longitudinal vibration in mixed liquor was also examined. The 5×5 fibre bundle (Module B) was run at constant permeate flux of 25 LMH, and vibrated both transversely and longitudinally at amplitude of 16 mm and frequency of 1 Hz in the mixed liquor collected from the membrane tank of UPWRP Singapore. Two vibration relaxation cycles were operated: (a) 1-min vibration 2-min relaxation and (b) 2-min vibration 4-min relaxation. The TMP profiles are shown in Figure 6.7.

Figure 6.7 Comparison of TMP of longitudinal and transverse vibration in 8 g/L mixed liquor (5×5 fibre bundles, tight fibres, fibre length = 18 cm, vibration frequency = 1 Hz, constant permeate flux = 25 LMH)

For the vibration interval of 1 min and relaxation interval of 2 min in 8 g/L mixed liquor, the TMP increased to 58.6 kPa with the longitudinal vibration during the 9 hour

filtration, while it only increased to 29.3 kPa with the transverse vibration. This suggested that transverse vibration is more effective in reducing membrane fouling than longitudinal vibration. The better performance was attributed to the secondary flows generation induced by transverse vibration, which could effectively reduce membrane fouling. Similar trend was also observed at vibration interval of 2 min and relaxation interval of 4 min, but the performance was slightly worse than former although both have the same amount of total combined vibration and relaxation time, which indicated again short interval of relaxation was more effective for the same total combined vibration and relaxation time.

6.4.1.4 Comparison between vibration and air sparging process

Experiments with larger membrane module were performed for short time operation to determine the synergetic effect of combined vibration and aeration. Larger membrane module with larger membrane surface area can increase the permeate productivity with the same operating flux. Earlier, the membrane filtration in the Bentonite and yeast suspensions and mixed liquor with transverse vibration were studied with smaller module in Section 5.4.3 and Section 6.4.1.3, respectively. Here, larger membrane module (Module C) was tested at different transverse vibration frequencies and air flow rates. The larger membrane module had 200 hollow fibre membranes (Figure 6.3). It was submerged in the 4 g/L mixed liquor, and vibrated at different frequencies of 0.5, 0.67 and 0.83 Hz and air flow rates of 1 L/min and 3 L/min in Setup III for over 15 hours (Figure 6.8).

At low vibration frequency of 0.5 Hz, the TMP first remained constant in the initial 2.5 hours, followed by slow increase to 27 kPa in the next 3.5 hours, and then jumped quickly to around 100 kPa in a very short time. At higher vibration frequencies of 0.67 and 0.83 Hz, the TMP maintained constant without severe membrane fouling for over 20 hours, which indicated that transverse vibration was very effective for membrane fouling control in mixed liquor. As compared to the smaller diameter membrane

module, the larger diameter membrane module not only increased the productivity, but also induced less severe membrane fouling under transverse vibration in the mixed liquor. The larger diameter of fibres induced smaller lateral flux and lesser non-uniformity in the flux distribution (Chang and Fane, 2001). In addition, it produced larger Reynolds number under transverse vibration which resulted in the enhancement of secondary flows (Geraldes et al., 2002) and reduction of membrane fouling. This was consistent with the study in Section 3.5.1 that the larger diameter of hollow fibre membranes induced less membrane fouling rate under longitudinal vibration in Bentonite suspensions by using same 1mm/1.7mm and 1mm/2mm hollow fibre membranes.

Figure 6.8 TMP of membrane filtration at different vibration frequencies in 4 g/L mixed liquor (constant permeate flux = 25 LMH, vibration amplitude = 30 mm)

With an air flow rate of 3 L/min, the TMP increased by 14.1 kPa for 2 hour filtration. However, with a combination of 0.5 Hz vibration and 1 L/min air sparging, there was nearly no membrane fouling for 20 hour filtration. This indicated that the combination of vibration and low aeration was very effective for fouling control in SMBR. A

possible explanation to the high effectiveness for fouling control may be attributed to the turbulence enhancement by the air bubbles under transverse vibrations.

6.4.2 Long duration tests

As stated in Section 6.4.1.3, membrane filtration with transverse vibration was more effective than the longitudinal vibration in mixed liquor. Here, membrane filtration with transverse vibration was performed in mixed liquor for long duration operation with the larger membrane Module C. The mixed liquor was collected from UPWRP as described in Section 6.3.2. In the unforeseen days when mixed liquor was not allowed to be collected (e.g. raining days, weekends and Public Holidays), synthetic wastewater was used instead. The synthetic wastewater included: 468.75 mg/L glucose ($C_6H_{12}O_6$), 191.06 mg/L NH_4Cl , 28.06 mg/L K_2HPO_4 , 5 mg/L $MgCl_2 \cdot 6H_2O$, 6.45 mg/L $CaCl_2 \cdot 2H_2O$, 4.5 mg/L $FeCl_3$, 1.91 mg/L $CoCl_2 \cdot 6H_2O$, 1.23 mg/L $Na_2MoO_4 \cdot 2H_2O$, 0.39 mg/L $CuSO_4 \cdot 5H_2O$, 0.16 mg/L $MnSO_4 \cdot H_2O$, 0.44 mg/L $ZnSO_4 \cdot 7H_2O$, 0.5 mg/L H_3BO_3 , 0.1 mg/L KI. Glucose was added as the carbon source which was common in synthetic wastewater (Chao and Keinath, 1979; Carucci et al., 1997; Chae et al., 2006). During the filtration, the characteristics of the biosolids and the permeate water quality were monitored to further explore the membrane fouling mechanism and membrane filtration performance.

For the long duration tests, the reactor was operated at the same temperature of 25°C as before. The pH was between 6.7 and 7.1. In order to compare the performance in a direct manner, the permeate flux was also maintained at 25 LMH which was the same as before. Thus, a permeate flow rate of 210 mL/min was generated from the total 200 hollow fibre membranes during the filtration. Each day, around 8-13 L of sludge was discharged from the reactor tank and refilled with the same amount of tap water. The transient TMP from the membrane filtration was monitored. If the TMP exceeded 60 kPa which was indicative of excessive fouling, the experiment was stopped and the membrane module was taken out for chemical cleaning. For all the experiments, the

peristaltic pump was operated at half-on-half-off mode (one hour filtration and one hour relaxation in sequence). The motor was also controlled with the same sequence as the peristaltic pump, so as to reduce the energy consumption by the vibration during permeation relaxation time.

In order to provide oxygen to the biomass as well as to suspend the mixed liquor, a total air flow rate of 10 L/min (each pair of air flow meter was controlled to be 2 L/min) or an equivalent superficial air velocity of 1 mm/s was used, which was lower than the typical superficial air velocity of 3-6 mm/s (Tavares et al., 1995; Brinke-Seiferth et al., 1999; Villaverde et al., 2000; Al Taweel et al., 2013) due to the fact that the vibration of the membrane module also mixed the biosolids inside the reactor to some extent.

The long duration experiments with the transverse vibration of submerged hollow fibre membranes were operated at vibration amplitude of 30 mm and two different vibration frequencies of 0.67 Hz and 1 Hz. A low vibration frequency was adopted due to the fact that only small amount of energy consumption was required and the potential for fibre breakage was also reduced at low vibration frequency. A total of 5 tests were carried out. In the first 3 tests, the lower vibration frequency of 0.67 Hz was used, while in the other 2 tests, the larger vibration frequency of 1 Hz was used. Table 6.1 shows the basic operational information as well as the SMBR performance for the five tests.

The TMP profiles of the membrane filtration of all the five tests are illustrated in Figure 6.9 (note that the TMP values during relaxation were not presented). Generally, membrane fouling increased rapidly when TMP was higher than 35 kPa. At the end of each test, TMP rose significantly above 70 kPa due to severe membrane fouling, with high concentrations of SMP and EPS accumulated on the membrane surface that increased the filtration resistance significantly. Details of the five tests were described below separately.

Table 6.1 Vibration SMBR characteristics in the five tests with the long operating time

Parameters	Test 1	Test 2	Test 3	Test 4	Test 5
Ratios of mixed liquor/synthetic wastewater	6:5	8:3	5:3	1:6	16:27
*MLSS concentration (g/L)	17.4±4.7	17.2±6.4	18.1±4.1	5.8±6.4	12.5±4.4
*MLVSS concentration (g/L)	9.9±6.0	13.0±4.8	13.8±3.0	4.8±4.6	10.0±3.5
*Carbohydrate concentration in SMP (mg/L)	26.7±21.0	12.3±8.2	13.2±5.3	18.6±9.2	11.6±17.2
*Protein concentration in SMP (mg/L)	39.7±13.1	26.7±13.1	29.4±11.0	30.4±11.6	20.2±6.8
*Carbohydrate concentration in EPS (mg/L)	151.4±73.0	178.1±63.1	200.9±34.5	106.8±78.0	185.6±69.5
*Protein concentration in EPS (mg/L)	645.8±141.0	589.4±128.5	575.7±118.9	581.8±130.6	593.3±118.0
Average COD removal (%)	92.0	93.5	87.4	96.5	93.9
Average NO ₃ -N removal (%)	99.4	98.5	99.8	91.4	96.1

*Mean value ± standard deviation.

Figure 6.9 TMP of hollow fibre membranes at different vibration frequencies in the five tests with the long operating time

In the first three tests, the TMP profiles developed differently despite the fact that the same transverse vibration frequency of 0.67 Hz was utilized. In Test 1, with the relatively high concentration of MLSS in the reactor, the TMP gradually increased to 30 kPa after the first week, then jumped quickly to 57.1 kPa in the next three days. It was noted that very high concentrations of SMP and EPS up to 132.0 and 986.0 mg/L, respectively, were examined in the reactor after the first week filtration, which might be adsorbed on membrane surface and induce severe membrane fouling (Rosenberger and Kraume, 2002)

The membrane filtration period in Test 2 was nearly the same as Test 1 due to similar concentrations of MLSS in the reactor. At Day 5 in Test 2, the TMP reached a temporary peak of 25.1 kPa, which was attributed to the very high MLSS concentration of up to 23.5 g/L in the reactor. The high MLSS concentration induced large viscosity of the biosolids and reduced membrane filterability (Chabaliná et al., 2012). From Day 9 to Day 11, SMP and EPS concentrations of 85.0 and 1038.9 mg/L were examined in the reactor, which resulted in a quick TMP jump from 19 to over 60 kPa.

Despite the same vibration frequency of 0.67 Hz in Test 3, the membrane filtration duration was, however, shorter than Tests 1 and 2, which might be due to the slightly higher MLSS concentrations. In Test 3, high MLSS concentration of 20.5 g/L was recorded in the reactor for 5 days filtration. The high MLSS concentration also damaged and broke the transversely vibrating hollow fibre membranes. This constitutes a serious concern with the use of the membrane vibration approach towards fouling mitigation, i.e., the fatigue of the membrane material upon repetitive cyclic stresses. The membrane breakage typically occurred at the holding ends of the fibres. It is anticipated that more fibre breakage occurred by transverse vibration than longitudinal vibration. The higher MLSS concentrations usually resulted in an increased viscosity (Chabaliná et al., 2012). Hence, the stronger interaction forces between the fibres and the fluid induced larger drag forces with accentuated stresses at the end of the fibres, which accelerated the fibre breakage. The high MLSS concentrations in the reactor

were also highly undesirable in terms of membrane fouling. For example, Trussell et al. (2005) reported that a rapid loss of membrane permeability occurred at high solid concentrations above approximately 20 g/L. Itonaga et al. (2004) also suggested that the high MLSS concentrations could cause severe membrane fouling due to the significant increase of the suspension viscosity. In the current study, the experiment was stopped when significant membrane fouling occurred in such high solid concentrations.

In Test 4, a higher transverse vibration frequency of 1 Hz was utilized. Unfortunately, fibre breakage was also accelerated, and it occurred shortly after the first week of filtration when the MLSS concentration in the reactor reached to 21.2 g/L. At higher transverse vibration frequencies, the number of cyclic periods of repetitive stresses with time also increased. In addition, it should be noted that during the first week filtration, only limited membrane fouling was observed despite the high SMP concentrations of 73.4 mg/L in the reactor. At the same time, a high EPS concentration of 1083.7 mg/L was examined in the reactor, which could turn the biosolids into larger flocs and increase the settleability thus resulting in smaller membrane fouling (Mikkelsen and Keiding, 2002; Chabaliná et al., 2012). The fibre breakage was then repaired and continued. In the following 20 days, the TMP increased slowly from 18 and 60 kPa. The filtration period lasted longer than Tests 1-3, which can be attributed to the fact that the higher shear stresses and secondary flows induced by larger frequency of transverse vibration could mitigate membrane fouling effectively. In this test, relatively high concentrations of SMP and EPS with small concentrations of biosolids were recorded. This might be attributed to the high ratios of synthetic wastewater utilized, which resulted in the fast metabolism of the microorganism.

Comparing with Tests 2 and 3, higher concentration of soluble carbohydrate and lower concentration of bound carbohydrate were examined in Test 4, which might be due to the release of carbohydrate from the biological flocs to the soluble system under the higher vibration frequencies. Liu and Tay (2002) studied the role of hydrodynamic

shear force in the formation of biofilm and granular sludge. They pointed out that high shear force could induce both aerobic granules and biofilms to secrete more carbohydrates resulting in a balanced microbial structure and stability of aerobic biofilms and granules. Rosenberger and Kraume (2002) found that the carbohydrate concentration in SMP correlated well with the membrane fouling rate for eight different SBR sludges in a batch cross-flow membrane cell. They pointed out that soluble carbohydrate was the primary cause of increased membrane fouling rate (Rosenberger et al., 2006). Cicek et al. (1998) also found a good relationship between the soluble carbohydrate concentrations and membrane permeability. Viero et al. (2007 and 2008) reported that lower levels of carbohydrate led to faster filtration. On the other hand, Mukai et al. (2000) and Hernandez et al. (2005) suggested that the soluble protein was the key factor affecting the membrane filtration performance. Ji and Zhou (2006) studied a submerged hollow fibre MBR with air bubbles. They found that proteins were more prone to be adsorbed on the membrane surface than carbohydrates, which increased the membrane hydrophobicity and caused irreversible membrane fouling. Trussell et al. (2007) studied the influence of mixed liquor properties and aeration intensity on membrane fouling in an SBR at high suspended solids concentrations. They found that the highest soluble protein concentration was obtained at the highest aeration intensity, and they attributed to the fact that the additional shear force provided by the increased aeration intensity led to the protein release from the biological flocs to the soluble environment. Trussell et al. (2006) reported that the total SMP concentration determined the membrane fouling rate due to the exposure to the increased soluble organic content, no matter whether it was carbohydrate or protein in the SMP. In an analogous manner, higher shear stresses with the transverse vibrations at higher frequencies and amplitudes could also cause the release of carbohydrate from biological flocs. Comparing with these studies, present results showed that both SMP and EPS contributed significantly to the membrane fouling, while the soluble carbohydrate effect was the most dominant.

In Test 5, the membrane filtration lasted for a longer duration without chemical cleaning. Although the higher transverse vibration frequency of 1 Hz was utilized, there was no fibre breakage probably due to the smaller concentrations of MLSS in the reactor. With the larger surface shear stresses generated by the transverse vibration with the higher frequency, the TMP increased slowly implying that the fouling control was effective. At Day 17, there was a temporary TMP jump due to the high SMP and EPS concentrations of 33.9 and 1109.2 mg/L in the reactor. The high concentrations of carbohydrate and protein were due to sufficient nutrients and moderate biomass concentrations, which were consistent with the results from Xie et al. (2013), who demonstrated that an increase in substrate concentration would result in an increase of SMP production. Again, this observation pointed to the evidence that the higher concentrations of SMP and EPS intensified the membrane fouling. As compared to Test 2, the membrane filtration in Test 5 lasted 4 times longer despite similar SMP and EPS concentrations in the reactor. Ji and Zhou (2006) reported the decline in flocs size with the increase in aeration. Similarly, smaller sizes of flocs may also be anticipated at higher vibration frequencies of a large membrane bundle although the quantification of size distribution was not carried out in the present study. The smaller flocs can easily block the membrane pores and cause serious membrane fouling (Tay et al., 2007; Pan et al., 2010). However, long durations of membrane filtration were observed in both Tests 4 and 5. The enhancement was directly attributed to the fact that the higher shear stresses on the membrane surface at larger frequency could greatly reduce the membrane fouling and improve the membrane filtration permeability. Thus, it can be confirmed that transverse vibration could be regarded as an effective alternative for fouling control in SMBRs with the real mixed liquor. As compared to Test 4, the membrane filtration duration in Test 5 was much longer although the same vibration frequency of 1 Hz was utilized and much higher concentrations of MLSS were observed in the reactor, which again, was due to the much lower soluble carbohydrate concentrations.

In all five tests, high removal efficiencies of both the organics and nutrients were generally observed. In Test 3, a relatively small COD removal efficiency was examined, which may be due to an exceeding high MLSS concentration in the reactor, and a relatively low nutrient concentration from the feed resulting in the slow growth rate and inefficiency in converting the nutrients to biosolids. In Test 4, a small $\text{NO}_3\text{-N}$ removal efficiency was recorded, which was contrarily attributed to the very small MLSS concentrations in the reactor and very high nutrient concentrations from the feed leading to a low microorganism digestion rate.

Finally, it should be pointed out again that a low air flow rate (10 L/min) was used in the 80 L reactor in present study, which was much lower than what was used in many previous studies for conventional MBRs (Ng and Hermanowicz, 2005; Kimura et al., 2008; Menniti and Morgenroth, 2010). Thus, smaller energy consumption was incurred for the air bubbling in this case. Since the additional transverse vibration only required very small amount of energy consumption due to low vibration frequencies of 0.67 and 1 Hz (Section 5.4.8), the combined vibration and aeration approach for fouling control was still energy efficient. Therefore, with the synergetic effect of aeration and transverse vibration, membrane filtration can be enhanced and fouling mitigated with the lower energy consumption than the conventional approaches of air sparging alone. The proposed combination of aeration and vibration has not been explored in the literature so far, and is being reported here for the first time. Note that the biomass could not survive without respiration, thus the air bubbling for oxygenation is essential in aerobic vibratory MBRs.

6.5 Conclusions

The performance of SMBR by transverse vibration in aerobic bioreactors was investigated experimentally in present study. Experiments of membrane filtration in mixed liquor by transverse vibrations with both short and long operating time were carried out. As compared to continuous vibration, vibration relaxation was less

favorable for membrane fouling reduction. However, a short relaxation time interval was more effective for fouling control with same total combined vibration/relaxation time for vibration relaxation operations. High concentrations of mixed liquor induced more severe membrane fouling due to more foulants deposited on the membrane surface. As compared to longitudinal vibration, transverse vibration was more favorable for fouling control in mixed liquor due to the secondary flows and vortices generation. The fouling reduction by transverse vibration was more significant with a small amount of air sparging due to the turbulence enhancement by the moving bubbles. The experiments with long operating time also showed that the use of transverse vibration in SMBR could effectively reduce membrane fouling and the needs for chemical cleaning. Higher frequencies of transverse vibration induced larger shear stresses on the membrane surface, therefore, enhanced the membrane performance and prolonged the membrane filtration time. However, the probability of membrane fibre breakage also increased at the same time, due to the larger drag force on the fibres by transverse vibrations. The analysis of the biosolids properties in the reactor indicated that the concentrations of carbohydrate and protein in both the SMP and EPS greatly affected the membrane filtration performance. Among the various components in SMP and EPS, the soluble carbohydrate was found to be the main membrane fouling contributor. The high removal efficiencies of organics and nutrient were examined in the reactor due to the microorganism biological process, and small membrane fouling was recorded in the present experiments with the low frequency of transverse vibration, which suggested the vibration SMBR to be a practical and beneficial technology.

Chapter 7 VS Membrane Module for the Fouling Control of Submerged Hollow Fibre Membranes

7.1 Introduction

The vertical vibration of stencil, or grid if the void ratio is high, had been found to induce turbulence (Nielsen, 1993; Cheng and Law, 2001). The study on the turbulence induced was mainly focused on the sediment transportation in either solid/water (Nielsen, 1993; Lyn, 1995) or gas/water interface (Brumeley and Jirka, 1987; Herlina and Jirka, 2008). The stencil-generated turbulence is particularly suitable for studies in environmental engineering as it produces an ideal environment for the investigations of physical and chemicals processes of pollutants over long time spans. (Brunk et al., 1996).

Nielsen (1993) studied the turbulence effects on the settling of suspended particles by grid turbulence, and found that the settling velocity decreased by relatively weak turbulence but increased by strong turbulence. Cheng and Law (2001) measured the turbulence generated by an oscillating grid by PIV. They found that the flow structure in the region near the grid was closely related to the grid geometry, and the fluctuations immediately over the bar position were more significantly intensified from those over the grid openings. They also implied that shear flows existed near the grid and the homogeneity of the turbulence could only be achieved at a distance from the grid greater than about three mesh sizes.

For MBRs, the turbulence induced by fluctuating velocities was found to alleviate membrane fouling (Sen et al., 2010; Jiang et al., 2013; Wibisono et al., 2014). Since the

Part of the work in this chapter has been included in:

Law, A. W. K., **Li, T.** and Fane, A. G. (2013), “Vibration-Stirring (VS) Membrane Module System for Submerged Hollow Fibre Membrane Filtration”, Provisional Patent Application No.: US 61/901,609.

stencil oscillation could generate turbulence, thus it also has the potential for fouling reduction. However, it is not used in submerged membrane reactor yet so far.

This chapter aims to develop the stencil turbulence in the submerged membrane reactor and develop a special VS membrane module for fouling reduction for submerged hollow fibre membranes. The feeds included the organic yeast suspensions and the real mixed liquor.

7.2 Experimental setup

The experimental Setup II as described in Chapter 5 was adopted in this study. A specially designed VS membrane module was used. Figures 7.1 and 7.2 show the schematic diagram and photograph of the VS membrane module setup, respectively. Details of the VS membrane module will be described in the following sections.

Figure 7.1 Schematic diagram of VS membrane module setup

Figure 7.2 Photograph of VS membrane module setup

7.3 Materials and operating procedures

7.3.1 Hollow fibre membrane module

The hollow fibre membranes were the same as that used in Chapter 5, with inner/outer diameters of 1 mm/1.7 mm and the nominal pore size of 0.1 μm . The hollow fibre membranes were fabricated to the 5×5 fibre bundle pattern with a length of 18 cm and displacement of 5 mm (Module B), with both ends fixed to the water chamber using Araldite epoxy. The membrane module was then mounted to the C shape holding frame, and connected to the motor with a metal rod.

A specially designed stencil was attached to the C shape holding frame and parallel to the hollow fibre membranes so that it can be vibrated together with the membranes when driven by the motor. The stencil had a dimension of 290 mm $\times$ 170 mm, with a total of 209 square holes. The holes dimensions were 1 cm $\times$ 1 cm with 1.5 cm centre

spacing. The stencil was 5 cm distance from the centre of the membrane fibres, so as to generate the optimal effect towards membrane fouling.

7.3.2 Preparation of feed suspensions

In this study, three kinds of feed suspensions, organic yeast suspensions, and two kinds of mixed liquor collected from UPWRP, were used to test the membrane filtration performance with the VS stencil. The yeast suspensions and mixed liquor were the same as that used in Chapters 4 and 6, respectively.

7.3.3 Experimental procedures

The experimental procedures were the same as that described in Chapter 6. After filtration in yeast suspensions, the hollow fibre membranes were soaked with 1% enzyme detergent solution for 15 min, rinsed with Milli-Q water, followed by a Milli-Q water backwash at 20 mL/min for 20 min. Similarly, after filtration in mixed liquor, the hollow fibre membranes were soaked with 0.2% sodium hypochlorite and 0.2% citric acid each for 2 hours, and followed by the same Milli-Q water backwash procedures. The measurements of water permeability after washing suggested that the membranes could be re-used as their permeability can be restored.

7.4 Results and discussion

7.4.1 Membrane filtration performance with continuous vibration of VS membrane module

Figure 7.3 shows the TMP profiles of the submerged hollow fibre membranes with continuous vibration with and without the stencil in 4 g/L yeast suspensions. The TMP of the submerged hollow fibre membranes increased from 23.8 kPa to 89 kPa after 110 min without vibration. With transverse vibration, the membrane filtration duration

increased to 170 min to reach the same TMP, which indicated that the transverse vibration could reduce membrane fouling due to the shear stress and secondary flows generated by transverse vibration. With additional vibration of the stencil, the TMP increased to only 79 kPa after 325 min. This illustrated that with the vibrating stencil, membrane fouling could be further reduced in the yeast suspensions, which might be due to the velocity fluctuations induced by the vibrating stencil in the neighboring region near the stencil.

Figure 7.3 TMP of hollow fibre membranes with and without oscillating stencil in 4 g/L yeast suspensions (Continuous vibration, vibration amplitude = 16 mm, vibration frequency = 2 Hz, constant permeate flux = 25 LMH)

Figure 7.4 compares the TMP profiles of the submerged hollow fibre membranes with continuous vibration with and without the stencil in the 4 g/L mixed liquor. The TMP of the submerged hollow fibre membranes increased from 15 to 38.7 kPa after 80 min filtration without vibration, and there was 5.3 kPa increase in TMP for the 375 min filtration at transverse vibration frequency of 1 Hz. Comparatively, there was only 2.9

kPa increase in TMP to 17.9 kPa after 375 min filtration with the vibrating stencil. In other words, the TMP remained nearly constant for 6 hours in the mixed liquor. This illustrated that the stencil vibration can be very effective towards fouling control. Comparing with the membrane filtration performance in yeast suspensions, the mixed liquor induced less severe membrane fouling, which was attributed to the larger particle size of mixed liquor.

Figure 7.4 TMP of hollow fibre membranes with and without oscillating stencil in mixed liquor from UPWRP Singapore (Continuous vibration, vibration amplitude = 16 mm, vibration frequency = 1 Hz, constant permeate flux = 25 LMH, 4 g/L mixed liquor)

Figure 7.5 also compares the TMP profiles of the submerged hollow fibre membranes with continuous vibration with and without the stencil with a higher concentration of 8 g/L mixed liquor. The TMP of the submerged hollow fibre membranes increased from 15 to 40 kPa after 90 min filtration without vibration, and it increased to 22.6 kPa after 540 min filtration with the transverse vibration. With the vibrating stencil, there was only a very limited TMP increase to only 16.9 kPa after 540 min filtration, which

further confirmed the effectiveness of the stencil vibration. Comparing with 4 g/L mixed liquor, a slightly higher TMP was examined in 8 g/L mixed liquor, which was attributed to more foulants from larger concentrations of feed.

Figure 7.5 TMP of hollow fibre membranes with and without oscillating stencil in mixed liquor from UPWRP Singapore (Continuous vibration, vibration amplitude = 16 mm, vibration frequency = 1 Hz, constant permeate flux = 25 LMH, 8 g/L mixed liquor)

Generally, two kinds of flows, namely, jets and wakes, can be identified with the stencil oscillation. The jets are formed through the stencil openings, while the wakes are created below and above the solid cover. Whether the jets or wakes are dominant depends on the stencil geometry. For a stencil with a high solidity such as a plate with small holes, jets are important in generating the turbulence away from the stencil. In comparison, for a stencil with a low solidity, the turbulence is formed primarily by the interaction of the wakes (Cheng and Law, 2001). In the present study, the stencil had a high solidity of 57.6%, thus jets were the dominant mechanism that generated the turbulence during vibration.

7.4.2 Membrane filtration performance with vibration relaxation of VS membrane module

Figure 7.6 gives a comparison of TMP profiles of the submerged hollow fibre membranes with vibration relaxation with and without the stencil in 4 g/L yeast suspensions. The vibration and relaxation time was both 1 min. The TMP of the submerged hollow fibre membranes increased from 23.8 to 89 kPa after 110 min filtration without vibration, and it increased to 59.8 kPa after 65 min filtration with the transverse vibration. With the vibrating stencil, the TMP increased to 79.1 kPa after 195 min filtration. The small improvement in the yeast suspension might be due to the fact that a cohesive layer was formed on the membrane surface by the cell debris and macromolecules in the yeast component. With the presence of such cohesive layer, the effect of the additional turbulence by the stencil was limited.

Figure 7.6 TMP of hollow fibre membranes with and without oscillating stencil in 4 g/L yeast suspensions (Vibration relaxation, 1 min vibration 1 min relaxation, vibration amplitude = 16 mm, vibration frequency = 2 Hz, constant permeate flux = 25 LMH)

Figure 7.7 illustrates the TMP profiles of the submerged hollow fibre membranes with vibration relaxation with and without the stencil in the 4 g/L mixed liquor. The vibration and relaxation time was both 1 min. The TMP of the submerged hollow fibre membranes increased from 15 to 38.7 kPa after 80 min membrane filtration without vibration. With transverse vibration, the TMP increased to only 26.2 kPa after 555 min. Comparatively, the TMP maintained nearly constant and increased only to around 17.8 kPa after 525 min filtration with the vibrating stencil. This indicated that the vibrating stencil could reduce the membrane fouling in real mixed liquor with vibration relaxations. Comparing with the membrane filtration performance in the yeast suspensions (Figure 7.6), the stencil was more effective in the mixed liquor, which may be due to the larger particle size of the mixed liquor. The larger particle size of mixed liquor induced larger inertial lift velocity under transverse vibration thus caused less severe membrane fouling (Davis, 1992; Belfort et al., 1994).

Figure 7.7 TMP of hollow fibre membranes with and without oscillating stencil in mixed liquor from UPWRP Singapore (Vibration relaxation, 1 min vibration 1 min relaxation, vibration amplitude = 16 mm, vibration frequency = 1 Hz, constant permeate flux = 25 LMH, 4 g/L mixed liquor)

Figure 7.8 illustrates the TMP profiles of the submerged hollow fibre membranes with vibration relaxation with and without the stencil in the higher concentration of 8 g/L mixed liquor. The vibration and relaxation time was both again 1 min. The TMP of the hollow fibre membranes increased from 15 to 40 kPa after 90 min filtration without vibration, and it increased to 28.1 kPa after 540 min with the transverse vibration. Similarly, with the vibrating stencil, the TMP increased to only 21.5 kPa after 540 min filtration. This indicated that additional improvement was obtained with the installation of the stencil even with vibration relaxation in the higher concentration of mixed liquor. Comparing with continuous vibration, vibration relaxation induced more severe membrane fouling, which indicated that vibration was effective for fouling control.

Figure 7.8 TMP of hollow fibre membranes with and without oscillating stencil in mixed liquor from UPWRP Singapore (Vibration relaxation, 1 min vibration, 1 min relaxation, vibration amplitude = 16 mm, vibration frequency = 1 Hz, constant permeate flux = 25 LMH, 8 g/L mixed liquor)

In summary, the TMP were all smaller for the hollow fibre membrane filtration with the vibrating stencil. This suggested that the installation of the stencil was effective to

improve the submerged hollow fibre membrane performance. In addition, the feed suspensions was well mixed by the vibrating stencil and no extra stirring apparatus was needed. Moreover, the TMP in the mixed liquor stayed nearly constant after around 9 hour of membrane filtration at low vibration frequency of 1 Hz with the stencil, which suggested the potential usefulness of the VS membrane module in the real applications. The improvement of the stencil vibration was attributed to the generated turbulence and associated velocity fluctuations.

7.4.3 Hydrodynamic study of VS stencil

In this study, PIV measurements described in Section 3.2.2 were carried out to study the flow velocity distribution near the stencil region during the vibration. The two-dimensional velocity distribution of an area of $16\text{ cm} \times 12\text{ cm}$ near the stencil was obtained in the form of vector maps to evaluate the turbulence characteristics. The instantaneous velocities of the vector maps were obtained, and the average velocities $\bar{u}$ and $\bar{v}$ were calculated.

The stencil was vibrated at amplitude of 4 mm, and different frequencies of 1, 5 and 10 Hz. Each time, 300 double frame images were taken. The vector maps of the velocity deviation U' from the mean velocity are plotted in Figure 7.9, and the scale maps of the mean velocity are plotted in Figure 7.10.

From the figures, it can be observed that the value of U' and the generation of turbulence by the vibrating stencil was much more significant at higher vibration frequencies. The velocity fluctuations in the neighboring region of the stencil increased at higher vibration frequencies. The induced fluctuations can reduce the cake fouling layer on the membrane surface and improve membrane filtration performance. Figure 7.10 showed that at higher vibration frequencies, the turbulence of the vibrating stencil can be further extended to the farther away region, which could lead to a well-mixed flow structure and scouring of the membrane surface.

Figure 7.9 Velocity map of vibrating stencil

Figure 7.10 Scale map of velocity of vibrating stencil (cm/s)

7.4.4 Power consumption of VS stencil

The power consumption of the stencil and its holder with and without hollow fibre membranes with vibration frequency from 1 to 3 Hz and amplitude of 16 mm was measured by the clamp meter (Figure 7.11). With increase of vibration frequency, the power consumption increased. With increase of the motor load (either holder or fibres or stencil), the power consumption also increased. For example, at frequency of 2 Hz, power of 6.40 watt was consumed by the holder, and 7.08 watt was consumed when additional fibres were connected, while 7.14 watt was consumed when the stencil was connected to the holder, moreover, around 6.40 watt was consumed when all the three parts were vibrated. This indicated that less than 1 watt was consumed by either vibration of the fibres or the stencil at frequency of 2 Hz and amplitude of 16 mm. This also illustrated that the motor power consumption by the motor was mainly dependent on the efficiency of mechanical connection converting the driving apparatus to the vibration movement and friction and heat losses, while vibration of the fibres or the stencil only required very small amount of energy.

Figure 7.11 Power consumption of the stencil and holder with and without fibres
(Vibration amplitude = 16 mm)

7.5 Conclusions

The specially designed VS membrane module was found to be effective to reduce membrane fouling and enhance membrane filtration performance. The VS membrane module could also stir and mix the feed suspensions in the reactor, and thus no extra stirring apparatus was required. The PIV measurements of the vibrating stencil confirmed the velocity fluctuations induced by the vibrating stencil in the neighboring region near the stencil. The energy consumption measurement indicated that vibration of the stencil or the fibres only required very small amount of energy, which suggested that the VS membrane module to be effective for membrane fouling control.

Chapter 8 Conclusions and Recommendations

8.1 Conclusions

The present study focuses on the effect of mechanical vibration on the submerged hollow fibre membrane filtration performance. Based on the results of this study, the following conclusions were drawn and summarized in this chapter.

8.1.1 Longitudinal vibration of submerged hollow fibre membranes in model feed

The mechanical longitudinal vibration of submerged hollow fibre membranes can reduce membrane fouling and improve membrane filtration performance in both inorganic Bentonite and organic yeast suspensions. The fouling rate decreased with increase of vibration frequency and amplitude, which was due to the shear stresses produced by the vibration on the membrane surface. Longitudinal vibration was more effective for fouling control in Bentonite suspensions as compared to yeast suspensions due to the enhanced back-transport of larger Bentonite particle size at higher shear rates. Longer fibres performed better under vibration which was attributed to the significant fibre movement induced by the longer fibre length. A small degree of fibre looseness was preferred as fouling could be further reduced for both Bentonite and yeast suspensions. The effect of fibre spacing illustrated that the greater permeate flux competition between neighboring fibres with the smaller spacing could be overcome by the fluid motion induced by the high frequency of vibration. The vibration of hollow fibre membranes with and without the vibrating holding frame indicated that the turbulence generated by the vibrating holding frame played a minor role in enhancing the membrane filtration performance in the present study, while the vibration of hollow fibre membranes was dominant to reduce membrane fouling. As compared to air sparging, vibration required less energy and also induced less fouling, which was due to the fact that only the boundary fluid layer around the fibres was mobilized in the vibration processes and less energy was dissipated.

8.1.2 Transverse vibration of submerged hollow fibre membranes in model feed

The transverse vibration of submerged hollow fibre membranes for fouling control was examined in both inorganic Bentonite and organic yeast suspensions. Transverse vibration was found to be more effective towards membrane fouling as compared to longitudinal vibration even at a low vibration frequency of 1 Hz, due to the shear stress and secondary flows around the cylindrical membrane fibres. This improvement was however less obvious in yeast suspensions due to the dominant membrane foulants of cell debris and macromolecules in the yeast components and smaller particle size of yeast. A small degree of fibre looseness was found to further reduce the membrane fouling and enhance the membrane filtration performance with transverse vibration in both feeds due to the additional lateral fibre movement. Decreased membrane fouling was induced by high packing density of fibres with transverse vibration at higher vibration amplitudes, which implied that larger fibre bundle could induce higher secondary flows which could reduce membrane fouling. Vibration relaxation was also studied, and a short relaxation interval of the vibration/relaxation was found to be favorable for the half on/off operating mode. PIV measurement indicated that vortices could be generated by transverse vibration. Finally, the energy consumption measurement indicated that transverse vibration was more efficient and effective for fouling control than longitudinal vibration.

8.1.3 Transverse vibration in real mixed liquor

The transverse vibration of submerged hollow fibre membranes as a fouling control method was applied in real mixed liquor. Membrane filtration in mixed liquor by transverse vibration with both short and long operating time were performed in the present study. Continuous vibration was more favorable for fouling control due to the continuous shear rate on the membrane surface as compared to vibration relaxation. However, a short relaxation time interval was more effective for fouling control with same total combined vibration/relaxation time for vibration relaxation operations. High

concentration of mixed liquor induced more membrane fouling due to more foulant deposited on the membrane surface for short time operation. Transverse vibration was found to be more effective for fouling control in mixed liquor than longitudinal vibration due to secondary flows and vortices generation by transverse vibration. The effect of transverse vibration could be further intensified with a small amount of air sparging due to the turbulence enhancement by the moving bubbles. The long duration experiments showed that the low frequency of transverse vibration could effectively reduce membrane fouling. Higher frequencies of transverse vibration induced larger shear stresses on the membrane surface and increased the membrane filtration performance. However, the probability of membrane fibre breakage also increased at the same time, due to the larger drag force on the fibres during vibrations. The analysis of the biosolids properties in the reactor indicated that the concentrations of carbohydrate and protein in both the SMP and EPS greatly affected the membrane filtration performance under transverse vibration. Among the various components in SMP and EPS, the soluble carbohydrate was found to be the main membrane fouling contributor. The overall high removal efficiencies of organics and nutrient were examined in the reactor due to the microorganism biological process, and limited membrane fouling was recorded in the present experiments with the low frequency of transverse vibration, which indicated the vibration SMBR to be a practical and beneficial technology.

8.1.4 VS membrane module for the fouling control of submerged hollow fibre membranes

The VS membrane module was developed for fouling control in the present study. It was found that the VS membrane module could effectively reduce membrane fouling in yeast suspensions and mixed liquor. The VS membrane module could stir and mix the feed suspensions in the reactor, and thus could replace the stirring apparatus. PIV measurement indicated that vibration of VS membrane module led to higher velocity fluctuations in the neighboring regions of the fibres, thus reduced membrane fouling.

Finally, the energy consumption analysis indicated that vibration of the stencil or the fibres only required very small amount of energy consumption, thus, the VS module was very effective for fouling control.

8.2 Recommendations

The vibration of submerged hollow fibre membranes has been investigated in details in the present study. Higher vibration frequencies induced greater shear stresses on the membrane surface. However, the probability of membrane fibre breakage was also increased at the same time, due to the larger drag force on the fibres during vibration. Thus, it is necessary to conduct further studies to optimize the operating conditions among the influent, effluent quality and membrane breakage in the future.

For aerobic MBRs, the transverse vibration could not be used solely without air bubbling, since the biomass also relies on oxygenation to grow. Therefore, a synthetic usage of transverse vibration and air bubbling is essential. However, the air bubbling is no longer essential in an anaerobic environment. Thus, the sole use of transverse membrane vibration could be an effective method for anaerobic membrane bioreactors (AnMBRs) and should be further studied in the future.

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