Effect of turbulence on hollow fiber membrane filtration in multiphase reactors

Pourbozorg, Masoud

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**Effect of turbulence on hollow fiber membrane
filtration in multiphase reactors**

Masoud Pourbozorg

School of Civil and Environmental Engineering

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Effect of turbulence on hollow fiber membrane filtration in multiphase reactors

Masoud Pourbozorg

School of Civil and Environmental Engineering

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Summary

The understanding of hydrodynamics and turbulence in multiphase reactors is essential for the design, operation, control of the system and scale up purposes. The understanding is particularly important for membrane processes, since it is known that the turbulence can significantly influence the membrane fouling performance. At the same time, many underlying mechanisms and operating parameters have not been scrutinized in detail. This is mainly due to the complexities in doing so. In particular, the effect of turbulence on the membrane fouling behavior is rarely reported. It is hoped that the present study can significantly add to the physical understanding of this phenomenon.

In the present study, a unique experimental setup of vibrating perforated plates was designed and utilized for membrane fouling quantification with turbulence. The turbulence generated using this setup was determined using Particle Image Velocimetry, in terms of velocity fluctuations, correlation coefficient, energy spectrum, turbulence kinetic energy and integral length scale. The hydrodynamic characterisation indicated that the turbulence generated by the vibrating perforated plate was analogous to oscillating grid turbulence with zero mean flows and shear stresses. The integral length scale increased linearly with the distance from the turbulence generator plate and with the solidity. The turbulence kinetic energy also varied significantly with the solidity. The magnitude of velocity fluctuations was higher near the perforated plate. Increasing the solidity increased the velocity fluctuations, and also created a more homogenous and isotropic turbulence.

With the experimental setup, the effect of turbulence on hollow fiber membrane filtration was investigated in terms of membrane fouling control. It was found that increasing the turbulence kinetic energy and eddy length scale generally reduced the fouling rate. However, the fouling reduction with integral length scale was limited to

an optimal value. The statistical analysis indicated that the fouling rate is cross dependent on both factors. The effect of hollow fiber bundle characteristics was also examined. An optimum fiber spacing was observed which yielded the most efficient filtration in turbulence, which can be attributed to the synergetic effect of filtration extraction and penetrating interactions between the turbulence eddies and hollow fiber membranes. A fiber looseness of 2% improved the performance to a maximum degree. Given the quantitative analysis of the statistical dependence, the energy demand evaluation between the energy consumption with turbulence and the improved productivity with reduced membrane fouling was also carried out.

The comparison of two sets of equivalent experiments with turbulence and membrane vibration indicated that the two actions produced similar effects on the fouling control of submerged hollow fiber membrane filtration. This confirmed that the oscillating shears produced by the relative motion between the fluid and the membrane surface is the dominant mechanism for the fouling mitigation for both.

The experiments on the impact of jets on the fouling control of hollow fiber membrane filtration showed that the fouling rate was lower with a higher jet velocity due to higher shear rate that led to a higher critical flux. It was also found that the critical flux increased with turbulence kinetic energy. On the other hand, the critical flux was again limited to a maximum with the increase in eddy length scale. The statistical analysis of combining the perforated plate turbulence and constant jet indicated that all three factors, i.e. turbulence kinetic energy, eddy length scale and discharge jet velocity, and their interactions had significant impact on the fouling performance of hollow fiber membrane filtration.

Finally, the development of a novel dynamic pressure sensing approach was examined to quantify the hydrodynamic characteristics of both two-phase (air-water) and three-phase (mixed liquor-air) reactors. Statistical as well as fractal analysis were used to identify the flow structure. The results from the analysis of the standard

deviation of the pressure fluctuation signals implied that the two-phase system had a transition point within the range of air flow rate tested. However, a similar transition point in the three-phase system was not identified. The presence of solid particles was also confirmed to have a significant impact on the flow hydrodynamics.

List of Publications

Journal:

1. **Pourbozorg, M.**, T. Li and A. W. K. Law (2016). "Effect of turbulence on fouling control of submerged hollow fibre membrane filtration." *Water Research* 99: 101-111.
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List of Symbols

A	Area
C_D	Correlation integral
c_p	Concentration of solids in permeate
c_w	Concentration of solids on membrane surface
D	Diffusion coefficient
D_C	Correlation dimension
d_p	Particle diameter
f	Vibration frequency
H	Hurst exponent
h	Distance
J	Permeate flux
K	Turbulence kinetic energy
k	Mass transfer coefficient
L_e	Integral length scale
L_L	Longitudinal length scale
L_T	Transverse length scale
l_0	Dominant eddy length scale
l	Characteristic length scale
l_m	Membrane length
M	Mesh size

N	Total number of pressure signals
p	Pressure
Q	Permeate volumetric flow rate
R	Autocorrelation
R_c	Cake resistance
R_f	Fouling resistance
R_m	Membrane hydraulic resistance
r	Distance between two points in a flow
r_p	Particle radius
S	Vibration stroke
S_c	Surface area of solid cake
S_r	Solidity
t	Time
u	Velocity
u_i	Velocity in i -direction
$\overline{u_i}$	Mean velocity in i -direction
u_i'	Fluctuating velocity in i -direction
u_c	Characteristic velocity scale
u_{rms}	Turbulence intensity in horizontal direction
u_0	Characteristic velocity of dominant eddy
V	Permeate volume

V_j	Jet discharge velocity
v_{rms}	Turbulence intensity in vertical direction
x	Horizontal distance
y	Individual pressure signal

Greek symbols

γ_w	Shear rate on membrane surface
δ_c	Boundary layer thickness
ε_c	Cake void fraction
ξ_i	Strange attractor
η	Mean
λ	Lyapunov exponent
λ_T	Taylor microscale
μ	Viscosity
π	Permeability
ρ	Density
τ	Time delay
τ_c	Characteristic time scale
τ_{ij}	Reynolds stress tensor
Φ_v	Volume fraction

List of Abbreviations

BC	Bubble Column
CAS	Conventional activated sludge
CCF	Cross-correlation function
CFD	Computational Fluid Dynamics
CP	Concentration polarization
DAQ	Data acquisition system
FFT	Fast Fourier Transform
FS	Fiber spacing
HE	Hurst exponent
HF	Hollow Fiber
HRT	Hydraulic retention time
IA	Interrogation Area
LDA	Laser Doppler Anemometry
LE	Lyapunov exponent
LLE	Largest Lyapunov exponent
MBR	Membrane bioreactor
MF	Microfiltration
NF	Nanofiltration
PAN	Polyacrylonitrile
PFS	Pressure fluctuation signals
PIV	Particle Image Velocimetry
PVC	Polyvinyl Chloride

RO	Reverse Osmosis
RSS	Reynolds Shear Stress
SRT	Solid retention time
STD	Standard deviation
TKE	Turbulence kinetic energy
TMP	Transmembrane Pressure
UF	Ultrafiltration
VSEP	Vibratory Shear Enhanced Processing

Chapter 1 Introduction

1.1 Motivation

Any reactor that consists of materials with different phases (i.e. gas, solid or liquid) or materials with different chemical properties, is a multiphase reactor. Multiphase reactors are widely used in different industries, including petroleum and oil refinery, chemical products, organic goods, and water and wastewater treatment. As a result of the broad usage, the economic value generated by the use of the multiphase reactors in the USA exceeded \$500 billion in 1999 as reported by Dudukovic et al. (1999). Since then, the widespread application of this technology continues to increase in time and therefore the amount of value generated worldwide is even more significant now (Duduković and Mills 2015). A type of multiphase reactor which has gained significant importance recently is called the membrane reactor utilizing membranes in two or three-phase separation operations (Basile and Charcosset 2016).

The advancement in the use of membranes in the water market is of particular importance. Firstly, a significant share of the global market is currently being invested in their research and development. Additionally, technologies which utilize membranes such as membrane bioreactors (MBR), reverse osmosis (RO), ultrafiltration (UF), microfiltration (MF) are intensely competing with one another and also other treatment methods to dominate the market (Frost and Sullivan 2012). MBRs offer a wide range of advantages over the conventional methods, e.g. conventional activated sludge (CAS) (Stephenson et al. 2000), including the following:

- (a) Small footprint due to the replacement of sedimentation tanks and other post-treatment steps
- (b) Low sludge production

- (c) Better effluent quality due to an operation at higher biomass concentration
- (d) Better controllability of solid retention time (SRT) and hydraulic retention time (HRT)
- (e) Enhanced nitrogen removal
- (f) Improving biodegradation efficiency

The use of MBRs has been increasing in the past decades. With their significance in the water services market, it is essential to have a full understanding of the underlying principles of the membrane filtration process for the design, operation, system control and scale up purposes. In addition, the necessity of understanding the hydrodynamics in membrane filtration is pertinent to enhance their performance, and many attempts have been made in the literature to quantify the underlying hydrodynamic characteristics of these reactors.

A major challenge in optimizing membrane reactor processes is the lack of sufficient understanding of physical and hydrodynamics of these reactors. It has been shown in the literature that crossflow, aeration and turbulence promotion are effective preventive procedures for fouling reduction in membrane processes (Tijing et al. 2015). However, the question related to cost reduction still stands. In this regards, this study aims to address the following questions: is turbulence on its own capable of reducing fouling? What are the physical consideration of using turbulence in membrane reactors? What are the most important parameters in turbulence induced membrane reactor?

1.2 Objectives

The main objectives of the present study are summarized in the following:

- Study the physical effect of major turbulence characteristics, i.e. turbulence kinetic energy and eddy length scale, on the membrane filtration process, and examine the hydrodynamic characteristics of the reactor and energy demand considerations of utilizing turbulence for fouling mitigation.
- Study the statistical dependence of turbulence parameters and hollow fiber membrane performance, and investigate the impact of fiber bundle characteristics on the membrane filtration in a turbulent ambient.
- Study the role of turbulence generated in a membrane filtration reactor using different techniques, including vibrating perforated plates and jets and monitor the fouling of membranes with various operating conditions e.g. difference jet velocities.
- Investigate turbulence characterization inside multiphase reactors using pressure sensing approach.

1.3 Scope of the study

The effect of turbulence in a membrane reactor is very complicated, and the literature has treated this issue mostly in a qualitative manner because of these complexities. The complexities arise from multiple areas, including the presence of mean flow in a turbulent ambient as well as the presence of solid particles and their interaction with turbulence. In the present study, a setup was designed to induce a turbulent ambient with zero mean flows by vibrating a perforated plate. In this manner, the impact of turbulence parameters such as turbulence kinetic energy and eddy length scale, can

be studied without the complications from the mean flow. In addition, hollow fiber membrane modules were submerged in both inorganic and organic feed suspensions of Bentonite and yeast, respectively and the impact of turbulence generated on the membrane performance was monitored at different turbulence levels. The interdependence among the membrane performance, hydrodynamics and energy consumption were examined in details as described in the following chapters.

1.4 Thesis outline

In this chapter, the basic concepts of membrane filtration are reviewed. An overview of the important concepts in membrane filtration is presented in Chapter 2. The next chapter (Chapter 3) is a review of literature relevant to the content of this study. There are two major sources of complexity in this study. The first arises from the multiphase nature of the reactor due to presence of solid and liquid phases. The second is the presence of turbulence itself. To establish a fundamental understanding of the physics in this problem, the turbulence generated by a perforated plate is quantified in terms of its characteristics in Chapter 4. After gaining insights on the hydrodynamics of turbulence, the effect of turbulence on hollow fiber membrane filtration is examined in Chapter 5. The statistical dependence of the fouling rate of hollow fiber membranes on the turbulence parameters as well as the energy demand analysis in this system is described in Chapter 6. The novel experimental approach of constant jets for the fouling control of submerged hollow fiber membranes is studied in Chapter 7. In Chapter 8, the quantification of turbulence parameters by an intrusive method of pressure sensing is explored as a robust method for hydrodynamic identification in a multiphase reactor. The thesis conclusion and recommendations for future studies are provided in the final chapter.

Chapter 2 Theory

2.1 Membrane fouling

Although MBRs and membranes in general have considerable advantages over traditional methods, they face major challenges in terms of capital and operational costs (Verrecht et al. 2010). One major drawback and concern related to membranes that has considerable energy cost implications, is the rapid fouling of the membrane. Fouling is commonly known to be caused by the deposition of foulants on the membrane surface which would lead to an increase in the membrane's hydraulic resistance. This problem has an overwhelming impact on diverse aspects of membrane operation, including the long-term stability and operational cost due to the increasing energy demand for maintenance as well as the cost of replacing fouled membranes. Depending on the type of particle-membrane interaction, fouling can happen as a result of an internal or external blockage. Regardless of fouling mechanics, the overall effect is to cause a decline in permeability and change the rejection of solutes. This is due to partial or entire blockage of membrane holes by solid particles. Since fouling alleviation techniques impose a significant cost in industrial units, many research studies and engineering efforts are dedicated to understand all the possible aspects and to develop strategies for control (Guo et al. 2012). It had been discussed that fouling prevention can be achieved by implementing hydrodynamic shear stresses on the membrane's surface (Jaffrin 2008).

Hydrodynamic shear stresses are induced by the relative motion between the membrane surface and the surrounding fluid (Wicaksana et al. 2006, Jaffrin 2008). The presence of high shear rates will lead to the suppression of concentration polarization (CP), cake build-up, and as a result reduce fouling in membrane systems. In recent years, the leading practices in generating shear stresses are air sparging, crossflow and vibration. These approaches have been used either individually or in conjunction with other methods. For instance, turbulence promoters are sometimes

coupled with crossflows to improve the mass transfer while also to mitigate fouling (Popović and Tekić 2011). They typically induce turbulence on the surface of membranes.

The most commonly used technique in the industry at the moment is air sparging. Air sparging's effect is a joint process of turbulence and scouring of the membrane's surface (Brindle et al. 2000). The production of air bubbles results in the generation of shear stresses and also additional flows and fiber motion in submerged hollow fiber reactors. The additional flows remove particles from the surface, while the fiber motion results in better performance of loose fibers through the reduced requirement in suction pressures (Cui et al. 2003). Air bubbles also contribute to positive changes in mass transfer (Ashley et al. 1992). Despite the broad application of this technique, alternative methods are being investigated, mainly because of extremely high costs due to high power consumption, which can reach as high as 70% of the total operational cost in some cases (Gander et al. 2000).

The high cost of air sparging can be attributed to the loss of air bubbles due to limited control over the bubble distribution, and also the fact that continuous air does not cause continuous performance improvement. The presence of high concentration of solid particles also affects the efficiency of aeration. Additionally, the shear rate in filtration systems is not strong enough to support a high permeate flux (Cui et al. 2003, Genkin et al. 2006).

A higher shear rate relative to air sparging can be achieved in conventional crossflow filtration. This can be done by increasing the crossflow velocity which is driven tangentially to the membrane surface. In return, the higher crossflow velocity leads to the larger pressure gradient along the membranes and as a result, a greater energy supply will be demanded. Therefore, higher capital and operational costs will be required for purchasing and running a higher-flowrate pump. Besides, the greater variation in pressure gradient would leave a less effective transmembrane pressure

(TMP) distribution along the membrane surface that leads to less efficient membrane usage (Jaffrin 2008).

To increase the shear rate on the membrane surface, a moving part is typically utilized in dynamic or shear-enhanced filtration. Rotating cylindrical membranes, rotating disk systems and vibrating membranes are practices which are frequently used to create shear enhanced systems. In a rotating configuration, the cylindrical membranes are embedded in a fixed cylindrical housing with rotational capability. On the other hand, when using rotating disks, the circular membranes are fixed on the disks to produce shear. However, the cost of these processes is high due to the complexity and the limited membrane area, which limits the application of such systems in the industry (Al Akoum et al. 2002).

The approach of vibrating membranes is a different technique from aeration and crossflows. Depending on the types of membranes, the modes of vibration can differ. This approach may be most effective for hollow fiber membranes since the flexibility of fibers is more significant compared to flat sheet membranes. Longitudinal, transverse and torsional vibration can be utilized to boost the efficiency in a hollow fiber module. This technique is attractive for membrane systems where aeration cannot be used to reduce the fouling such as anaerobic membrane bioreactors. If proven effective in saving energy, it can also be an interesting alternative to expensive air sparging. However, the commercial application of this technique is still under scrutiny (Li et al. 2014).

The presence of hydrodynamic shear stress is essential to the membrane performance improvement. The various means of generating shear stress have been mentioned above, however, they are not limited to the aforementioned techniques. Since it has been observed that the use of turbulence promoters would increase the performance by improving mass transfer and reducing fouling (Gomaa et al. 2011), it is crucial to explore the possibility of other means to do so. There are multiple approaches to

promote turbulence, therefore, it is possible to engineer a turbulent ambient with optimum characteristics (Coppola and Gomez 2009). This would leave us with a great need to understand the physics of turbulence in the membrane filtration processes.

2.1.1 Principals of membrane filtration

Membrane filtration is employed when the separation of solids or solutes from liquid in a physical process is required. The driving force in this process is typically pressure, hence, they are called pressure-driven membrane processes. The size of solid particles versus the size of membrane's pores is the core indicator of whether they can be separated or not. If the size of particles is larger than the pore size of membranes, then the particles are retained and the separation is successful. Therefore, in a porous membrane, pore size is the key indicator of its applicability for the intended separation. Based on this crucial factor, membranes are typically classified as one of the following (Günder 2000).

1. Microfiltration (MF)
2. Ultrafiltration (UF)
3. Nanofiltration (NF)
4. Reverse osmosis (RO)

For some processes such as water or wastewater treatment, the volume of collected permeate is the most important. Therefore, in order to measure this volume, permeate flux (J) is used. Permeate flux measurement is a simple way to assess the hydrodynamic performance of a membrane system. It can be calculated using Equation (2.1) under steady state conditions (Günder 2000). If the process is not steady state, only an average flux value can be stated.

$$J = \frac{Q}{A} \tag{2.1}$$

In this equation, A is the membrane surface area and Q is the permeate volumetric flow rate which is related to the permeate volume (V) and filtration time (t) (

$$Q = \frac{V}{t} = \frac{dV}{dt}).$$

2.1.2 Fouling mechanism

Membrane fouling due to the deposition of foulants on the membrane surface or membrane pores has an adverse effect on the membrane filtration capability. A decline in permeate flux or an increase in TMP is a common undesirable outcome of fouling (Hong et al. 2002). It has been discussed in the literature that fouling can be either reversible or irreversible (Fane et al. 2009). The reversibility of fouling depends on the severity of foulant deposition which can be identified by removal techniques. If the membrane's performance can be reversed to its initial value by removing foulants through physical means, then, fouling is reversible. This indicates that the foulants and membrane have weak interactions. On the other hand, fouling is irreversible when the interactions between foulants and membrane are much stronger (i.e. chemical bonds), where a comprehensive chemical cleaning is required to recover membrane performance.

The interaction between the foulants and the membrane pores is described by four models which are highly dependent on membrane's pore size (Bolton et al. 2006). These models are:

1. Standard blocking: membrane pores are considered to be cylindrical shape and particles accumulate within the pores
2. Intermediate blocking: particles partially block the pores
3. Complete blocking: membrane pores get completely sealed by deposited particles and permeate cannot go through them

4. Cake formation: particles form a layer on top of the membrane surface instead of blocking pores individually, mainly because the size of particles is too large to cause other forms of blocking.

Fouling behaviour is usually explained by the Darcy's law. In this model, which is sometimes called resistance-in-series model as can be seen in Equation (2.2), the permeate flux (J_w) has a direct relationship to the transmembrane pressure (TMP), i.e. the pressure drop across the membrane (ΔP). It is also inversely related to the feed's viscosity and the hydraulic resistance of the filtration system.

$$J_w = \frac{\Delta P}{\mu R_m} \quad (2.2)$$

where R_m is hydraulic resistance of the clean membrane and μ is the feed viscosity (Fane et al. 2009). Equation (2.2) is not adequate to explain the changes in the hydraulic resistance with fouling. This means that to explain the flux reduction or TMP rise in membrane processes with this model, another term (or terms) needs to be added to the resistance term. Both the fouling resistance (R_f) and resistance due to cake formation or concentration polarization (R_c) have been suggested by researchers. Equation (2.2) then takes the following form:

$$J_w = \frac{\Delta P}{\mu(R_m + R_f + R_c)} \quad (2.3)$$

This model has been widely studied and it has been recognized for its accuracy (Yeh et al. 1997).

2.1.3 Concentration polarization

There is another physical phenomenon which is considered to be a major issue in membrane filtration, and it is called concentration polarization (CP). CP is related to the difference between the concentration of solids in the feed solution and the membrane surface. It is due to the propensity of solid particles to accumulate at the interface of the membrane and solution. If the separation is not completely effective, the concentration of particles in permeate (c_p) would be larger than zero. Regardless of the separation being completely effective, the concentration has a major gradient near the membrane surface with a boundary layer thickness of (δ_c). This is because at the membrane surface, the concentration (c_w) is at its highest. While convection is the driving force for separation imposed by TMP, particles near the membrane's surface tend to transport back to the bulk by diffusion. When there is a complete rejection of solid particles ($c_p = 0$), these forces are balanced. Equation (2.4) is the governing equation in the concentration boundary layer (Bowen and Jenner 1995, Mulder 2012).

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

Figure 2.1 Schematic diagram of concentration polarisation

Boundary conditions: $\begin{cases} c = c_w & \text{at } x = 0 \\ c = c_b & \text{at } x = \delta_c \end{cases}$

where x is the direction normal to the membrane surface and D is the diffusion coefficient (Figure 2.1). Solving Equation (2.4) with the abovementioned boundary conditions would give:

$$\frac{c_w}{c_b} = e^{\frac{J}{k}} \quad (2.5)$$

where $k = \frac{D}{\delta_c}$ is the mass transfer coefficient.

It is obvious that an increase in mass transfer coefficient would be advantageous in reducing the negative effect of CP since it would lead to a smaller c_w . Because k is inversely related to δ_c and it is well known that δ_c is directly related to the hydrodynamic properties of the system (Belfort and Nagata 1985, Gekas and Hallström 1990), it is crucial to understand the role that fouling preventive techniques such as crossflow or turbulence can play in modifying the hydrodynamic properties.

2.2 Operational modes

There are two modes of operations known for membrane filtration processes, namely, constant flux and constant pressure (Defrance and Jaffrin 1999). These processes are also characterized as being either dead-end or crossflow. It was mentioned previously that the product of viscosity and hydraulic resistance i.e. total resistance, has a major importance in membrane filtration. The inverse of total resistance is another parameter which is widely used to characterize the performance. The permeability of the membrane is defined as the ratio of flux to TMP:

$$\pi = \frac{J}{\Delta P} \quad (2.6)$$

The increase in total resistance or decrease in permeability as a result of fouling can be attributed to different causes. Feed properties, membrane properties, and the hydrodynamic characteristics of membrane environment are considered to be the main categories involved in this process (Zhang et al. 2006).

2.2.1 Constant flux

The most widely used mode of operation in the industry is constant flux. Constant flux operation is favoured compared to constant pressure, because it is possible to achieve the desired permeate volume constantly throughout the lifetime of the operation. The adverse effects of fouling and increase in hydraulic resistance are reflected in TMP. The result of membrane fouling in constant flux is an increase in TMP. To overcome the rise of TMP and maintain the constant flux, the rate of pump's delivery i.e. overall driving force, needs to be increased. This increase can only be obtained up to the maximum capacity of the pump which corresponds to the maximum TMP. After that, TMP can no longer be increased and the flux will decline consequently. Since TMP rise is linked with an increase in the driving force, this process is self-accelerating. The first step typically utilized to recover permeability (i.e. reduce the total resistance), is permeate backwashing which is a physical cleaning process. Permeability can only be slightly recovered since the accumulated cake layer would be removed partially. The rate of the particle deposition and cake layer formation is constant in constant flux filtration, however in practice, the cake layer thickness may significantly vary along the membrane. In regions with smaller cake thickness, local permeate flux increases and therefore, local particle deposition rises (Chang and Fane 2000, Bacchin 2004, Zhang et al. 2006).

2.2.2 Constant pressure

Constant pressure is less complicated than constant flux since the driving force does not change in this mode. In constant pressure mode, the consequence of membrane fouling is a decline in flux. Since it is desirable to control the amount of permeate filtered out by membranes in a definite time frame, constant pressure is generally not preferred as an operational mode in the industry. This operational mode is described by self-regulation of the rise in resistance (a reduction in permeability). Thus, the overall driving force would remain unaffected even though the local permeate flux is weakened by the local cake growth. The difference between the constant pressure and constant flux modes can be seen in Figure 2.2.

Figure 2.2 Schematic of TMP and flux profile: (a) constant pressure operation, and (b) constant flux operation

2.2.3 Dead-end filtration

The most basic form of membrane filtration in a pressure driven process is the dead-end filtration or batch filtration (Li and Li 2015). The fouling tendency of membranes is much higher in the dead-end filtration mode. This is due to the fact that the entire amount of feed permeates passes through the membrane pores perpendicular to it,

and the solutes are rejected and accumulated on the membrane surface (Figure 2.3 (a)). Therefore, the number of cleaning periods is higher, and cleaning is frequently done since the permeability reduces due to the formation of a cake layer. It should be noted that the low permeability limits the dead-end filtration processes with the concentration of solids in the feed. The main contributors to the driving force for solute removal in this mode are gravitation or diffusion.

2.2.4 Crossflow filtration

In a crossflow filtration, a tangential flow is present near the membrane surface which creates shear stresses. The use of crossflow filtration mode is more popular than dead-end filtration, because by adjusting the crossflow velocity it is possible to maintain the flux or TMP at a desirable value. The differences between the crossflow and dead-end filtration can be seen in Figure (2.3). The crossflow can be generated by pumping, stirring, bubbling or a combination of these.

Figure 2.3 Differences between two modes of operation: (a) Dead-end filtration, (b) Crossflow filtration

2.3 Submerged membrane modules

Two types of membrane configuration have been largely used in the treatment industry; submerged or immersed membranes and side-stream membranes. In a submerged system, the desired operations including the biological treatment, separation, etc. are performed in a single reactor. If the reactor is aerobic, air is used for both providing oxygen to the micro-organisms and membrane scouring to reduce the fouling rate. However, for anaerobic bioreactors, fouling reduction remains a significant issue to address. In side-stream reactors, biological treatment and membrane separation are conducted in two compartments. The dominant fouling reduction technique in this type of reactors is crossflow. Since the membrane separation is integrated with the biological treatment, submerged membrane units are low-cost modules without housing (Stephenson et al. 2000).

Membrane modules are commonly made of flat sheet or hollow fiber membranes. Modules are formed in different ways (e.g. cassette, cartridge, and spiral wound) by varying the assembly arrangement of membranes. The investigations conducted in the framework of this study are related to submerged membrane reactors. For this reason, only submerged flat sheet and hollow fiber membrane modules are discussed in the following.

2.3.1 Flat sheet membranes

Flat sheet membranes are used in cassette and spiral wound modules. They form cassette modules in a complicated plate and frame package. In every plate, two membranes are connected to permeate spacers which promote turbulence in the feed stream. The characteristics of multi-phase flow are significantly affected by the distance between plates which is directly related to the size of the feed channel. A small distance between the plates magnifies the tendency of particulate plugging in

flat sheet modules which is an important shortcoming of these configurations. Flat sheet membrane modules generally have a lower packing density than that of hollow fiber units. In addition, the difficulty in cleaning is another notable shortcoming of flat sheet modules. The complex assembly of the membranes plates limits the mechanical stability which constrains permeate backwashing. To overcome this issue and to efficiently remove the cake layer, a larger number of relaxation periods defined as periods of steady aeration without filtration are implemented.

2.3.2 Hollow fiber membranes

Hollow fiber (HF) membranes used in cartridge modules are placed in cylindrical housings which may contain several hundreds to thousands of HFs. HF membranes have smaller diameters (commonly less than 2 mm) compared to tubular, with several layers: a supporting tissue, a porous support layer, and an active separation layer. Tensile strength and flexibility are made possible due to the presence of the supporting tissue. The porous support layer, on the other hand, provides break strength and an active separation layer that serves as a barrier for components to be rejected. The use of HF membranes has been increasing in the market due to their distinctive advantages over other configurations. The higher packing density achieved by increasing the number of fibers in HF modules allows them to have a higher surface area to volume ratio. The fibers are either fixed at one end or at both ends. The length of the fibers fixed at both ends is longer to allow the fibers to move to a certain extent. The use of fibers which are fixed at one end (instead of two ends) adds to the flexibility of them. The higher surface of membranes will result in higher fluxes and filtrate volumes which are highly desirable. Compared to flat-sheet configurations, hollow fiber modules show a higher packing density and are backwashable, but are more prone to clogging in the presence of fibrous material.

2.4 Critical flux

A higher permeate flux is typically favored in industrial operations. When the flux is higher, the balance among different forces involved in membrane filtration is far from the steady state conditions. Field et al. (1995) reported that there exists a permeate flux below which foulants do not accumulate on the membrane surface. This study marks the beginning of the “critical flux” concept. Bacchin et al. (2006) stated that when the permeate flux was below the critical value (i.e. sub-critical flux filtration), the filtration resistance was the same as the clean water resistance of the membrane. The existence of critical flux has been attributed to the back transport of solid particles to the bulk by Brownian diffusion or crossflow (Bacchin et al. 2006). Although the sub-critical flux is characterized by zero foulant deposition on the membrane surface, some studies have shown that even under these conditions, fouling can happen in the microfiltration of colloidal suspensions (Howell 1995, Pollice et al. 2005).

The critical flux determination can be performed by various techniques. The flux stepping method is the most commonly used technique in which the changes in TMP are monitored by increasing the permeate flux step by step (Kwon et al. 2000, Beier and Jonsson 2010). Direct Observation Through the Membrane (DOTM) which enables observation of the onset of particle deposition (Zhang et al. 2006) and particle mass balance measurements can also be used to determine the critical flux (Kwon et al. 2000). It has been argued that particle mass balance technique is unable to accurately recognize the critical flux that is established by the flux step technique (Bacchin et al. 2006).

In the literature, many parameters have been identified that can change the critical flux. The role of particle size has been a subject of debate. Madaeni (1997) suggested that the critical flux was higher for larger Latex particles. However, Kwon and Vigneswaran (1998) reported a change in the critical flux behavior with particle size.

They discussed that the critical flux reduces with particles with diameters smaller than 0.46 μm , while an increase can be obtained with particles larger than this diameter. They argued that this different behavior is characterized by different transport mechanisms for these particles, where larger particles tend to follow shear induced diffusion (Zydney and Colton 1986) and for smaller particles, Brownian diffusion which is inversely related to the particle size, is the dominant mechanism. A model for critical flux was proposed for particles with the size of 5-12 μm based on the modification of the shear induced diffusivity model, which connects the critical flux to the shear rate on the membrane surface (γ_w), particle radius (r_p) and length of the membrane (l_m) (Li et al. 2000):

$$J_{crit} = 0.06\gamma_w r_p^{4/3} l_m^{-1/3} \ln\left(\frac{C_w}{C_b}\right) \quad (2.7)$$

Since for particles larger than this range inertial lift may become important, a different model was suggested (Drew et al. 1991):

$$J_{crit} = 0.577 \frac{\rho \gamma_w^2 r_p^3}{16\mu} \quad (2.8)$$

ρ and μ are the density and the dynamic viscosity of the fluid respectively.

The effect of the hydrodynamic conditions has also been studied in the literature. Increasing the aeration intensity (Yu et al. 2003) and crossflow velocity (Madaeni et al. 1999) lead to the rise in the critical flux. Cui et al. (2013) attributed the changes in the critical flux by crossflow velocity to the flow regime. They suggested that an increase in crossflow velocity would not lead to an improvement in the critical flow when the crossflow velocity is within the laminar or turbulent region, however when

operating in the transition region the critical flux varies considerably with the crossflow velocity.

In the next chapter, the literature related to the context of current work is presented.

Chapter 3 Literature review

In Chapter 2, the basic concepts of membrane filtration that are frequently used in literature have been reviewed. In this chapter, a deeper look into some aspects of membrane filtration processes, including hydrodynamic characteristics and quantification, will follow. It should be noted that multiple review papers have already covered a wide range of topics in membrane filtration literature (Lin et al. 2013, Shi et al. 2014, Wang et al. 2014, Tijing et al. 2015), therefore here only the most important topics which are closely related to the context of the current study are reported.

3.1 Submerged hollow fiber membrane filtration

The filtration performance of submerged HF membranes is a function of the physical properties of the membrane as well as the hydrodynamic conditions in the reactor. Here, a review on the physical properties will be provided before presenting the effect of the hydrodynamic conditions.

3.1.1 The length and diameter of fibers

Fiber diameter impacts HF filtration in various ways, from shear induced fiber movement to changes in pressure drop. Small fiber diameters have been reported to cause high a pressure drop from shell side of HFs to the lumen side (Chang and Fane 2001). The impact of fiber diameter increases with the presence of turbulence: turbulence being more beneficial for fibers with smaller diameters (Fane et al. 2002). It has been suggested that the turbulence induced by air sparging would be more effective in moving fibers with smaller diameters. However, fibers with smaller diameters are more prone to breakage and high pressure drop (Chang and Fane 2001).

The use of long fibers can provide a higher membrane surface area that is beneficial for permeate extraction. When HFs are vertically oriented, using air scouring for the fouling reduction is useful. However, this will also have adverse implications on a number of parameter, namely, pressure drop, aeration energy demand, maintenance and flux distribution (Yoon et al. 2004). An increase in fiber length leads to a higher pressure drop which elevates a need for greater driving force to maintain the steady state condition (Günther et al. 2010). It also leads to a rise in aeration intensity because a low aeration is ineffective in a large reactor. The experimental results of the critical flux by Kim and DiGiano (2006) showed that for short fibers, there is a lower propensity in TMP increase over the long term. This was attributed to the fact that the local flux exceeds the critical flux in some areas in long fibers. Even though the average flux over the entire length of fiber is lower than the critical flux, high local fluxes would result in higher demand for aeration. This explains how a longer fiber can accelerate the overall fouling.

3.1.2 Fiber looseness

Introducing turbulence by air sparging and other means results in the fiber movement which induces shear stress on the membrane surface and enhances back transport to the bulk. Since a larger shear rate is highly desirable, a certain degree of looseness in fiber length relative to the two ends of the fiber is needed in HF membranes. Fiber-fiber collision is also a positive outcome of the fiber motion, because it helps remove the deposited foulants by mechanical means (Bérubé and Lei 2006). Although loose fibers can enhance the filtration performance (in some cases up to 40%) (Wicaksana et al. 2006), many studies have reported that there is a limited range of effective looseness for improving performance. For instance, Mahendran et al. (1997) proposed a maximum looseness of 5% to be effective and the fiber looseness more than that does not reduce the fouling rate any further.

Air induced turbulence is more effective in fouling rate reduction when using a degree of looseness (Wicaksana et al. 2006, Xia et al. 2013). The experimental investigation of HF membrane filtration in a vibratory setup showed that similar to air induced turbulence, fiber looseness can improve performance by reducing the fouling rate to a great extent (Li et al. 2014). They also reported a maximum looseness of 2% for bentonite suspensions beyond which the shear induced by vibration can no longer reduce the fouling rate (Figure 3.1).

Figure 3.1 Effect of fiber looseness fibers in membrane filtration of bentonite suspension with transverse vibrations (5×5 fiber bundles, fiber length=18 cm, vibration frequency=1 Hz) (adapted from Li et al. (2014))

3.1.3 Packing density

A distinctive advantage of HF membrane modules is the high packing density which directly affects the permeate production, the footprint, mass transfer coefficient, and fouling rate. Packing density is defined as the overall cross sectional membrane area per total area of the module. Generally, a higher packing density that leads to higher permeate extraction rate per module is deemed reasonable. However, an excessive packing density may not be useful, since it can cause over accumulation of solid

particles in the high flux operations. Besides, increasing the packing density per se does not improve the performance if the fibers are arranged in a haphazard manner. Zheng et al. (2003) studied the flow distribution in a randomly packed HF modules and indicated that based on a free surface model and a theoretical probability density distribution function, a significant mal-distribution of flow can be observed. Packing density can also greatly affect the lumen side mass transfer. Wu and Chen (2000) suggested that with packing densities lower than 50%, the mass transfer coefficient decreases with the packing density, and above this value the mass transfer coefficient increases. This was in contradiction with other research studies which reported that mass transfer coefficient decreases by increasing the packing density (Wang et al. 2003, Zhang 2011).

The examination of the impact of packing density in the vibratory membrane setup Li et al. (2014) by monitoring the rate of TMP rise in four HF membrane modules revealed that a consistent increase in the packing density does not cause consistent increase in the fouling rate. They observed that the fouling rate increases at first with the packing density in a 4 g/L yeast suspension and eventually it dropped. On the other hand, there was no consistent trend for membrane filtration of bentonite suspensions under various vibration amplitudes. This reveals the complexity of the role of packing density in membrane filtration systems under vibrations. In terms of engineering design, the impact of packing density can be summarized in the role that this factor plays in reducing the overall footprint and increasing the total permeate product which is favorable, and the increase in energy demand due to the higher solid accumulation on the membrane surface. Therefore, an optimum packing density can only be obtained by empirical evaluation of the filtration system. A Computational Fluid Dynamics (CFD) analysis of HF membrane module suggested that since there exists an optimal fiber distance for achieving the maximum efficiency of the vibratory membranes, a high packing density is not recommended (Zamani et al. 2013).

3.2 The role of aeration in process enhancement

In an aerobic reactor, aeration plays two most crucial roles. First, fine air bubbles provide the required oxygen for biomass survival (Le-Clech et al. 2006). Secondly, coarse bubble aeration is the most commonly used technique for membrane fouling reduction in industry. Generally, fouling reduction in membrane filtration can be linked to a number of hydrodynamic features such as shear stress increase, mass transfer enhancement, turbulence promotion, and fiber movement as discussed in section 3.1.2. Introducing air bubbles can induce turbulence in the HF membrane filtration if the fiber length is not too long. The turbulence affects the back transport of solid particles to the bulk by reducing the size of the concentration boundary layer, which makes the negative effect of concentration polarization less severe. The fouling reduction of the membranes has been ascribed to two other mechanisms, namely, falling film and wake effect. The falling film effect is described as follows: when air bubbles rise in the reactor and near the membrane surface, there is a downward shift of the thin water layer (film) between the rising bubbles and membrane surface to fill the void produced by ascending bubbles. Depending on the size of air bubbles, the local velocity of falling liquid can increase and this can enhance the mass transfer significantly by up two orders of magnitude (Ghosh and Cui 1999).

Eddies are generated when the falling film reaches the bottom of the bubble. This is called the wake effect, because wakes are produced by this liquid displacement. The wake characteristics of a single bubble has been classified into three groups of spherical, ellipsoidal and spherical cap bubbles, based on their size (Miyahara et al. 1988). No secondary flows or vortices are generated by spherical bubbles (diameter less than 1 mm) and the generated flow by these bubbles follows the Stokes law. The range of bubble diameter for ellipsoidal bubbles is from 1.5 to 15 mm. These bubbles move back and forth while rising in the reactor. The consequence of spherical cap bubble rise in the reactor is the production of strong vortices that can contribute to rise in back transport and shear stress. The shear stress that is generated by wakes can be extremely large in a short term and its magnitude can reach as high as two times

the shear stress caused by liquid movement in the fouling film (Bérubé et al. 2006, Bérubé and Lei 2006). The shear stress not only helps reduce fouling by membrane scouring, but it is also believed to influence the behavior of the biological ambience which is an important factor in membrane fouling considerations. Rochex et al. (2008) performed a series of experiments with varied shear rates from 0.055 to 0.27 Pa and indicated that the biofilm diversity and growth was lower for cases with low shear stress. A sequential aeration in bentonite suspension was performed by Guibert et al. (2002). A special setup was designed in which an intermittent aeration could be introduced in two separate locations. They noted that there was a difference in density between the regions highly affected by air bubbles and non-aerated zones. This difference resulted in an increase in mixing which is also recognized by other researchers as a prominent impact of aeration (Cui et al. 2003).

Although aeration is proved to be highly effective in fouling reduction, it bears considerable downsides which relate to high energy consumption and limited applicability. The energy consumption of air controlled fouling can be very high due to the fact that the shear rate generated by aeration is typically very weak and therefore, in order to maintain an acceptable flux without fouling a higher aeration rate is required. Moreover, it has been shown by researchers that the fouling improvement by aeration reaches a plateau which means that aeration has a limit in the fouling mitigation and beyond this limit no more improvement can be obtained (Chang and Fane 2001, Xia et al. 2013). To reduce the aeration related energy cost, an optimal aeration can be used. An alternative for continuous aeration can be intermittent aeration. Although intermittent aeration is somewhat less effective than continuous aeration mode in fouling prevention, it has the positive feature of low energy consumption (Tian et al. 2010).

3.3 Hydrodynamics of membrane filtration

Hydrodynamic conditions in membrane processes can be examined at macro and micro levels. The macro level standpoint refers to the study of the techniques which result in the promotion of shear stress on the membrane surface. For instance, the role of aeration as discussed in (3.2) as a technique for inducing shear stresses, tangential shear produced by the crossflow and also the secondary flow generation all fall under this category (Cui et al. 2003). From a micro point of view, the transport mechanisms that contribute to the back transport of particles to the bulk, such as Brownian diffusion, shear induced diffusion and eddy enhanced diffusion, are of considerable interest.

3.3.1 Particle size distribution

Particle size differentiation is the principle driver in membrane filtration, where particles that are larger than the membrane pore size will be trapped and the desired particles will pass through the membrane pores. However, there are occasions that some unwanted particles either pass through or penetrate the membrane pore and cause fouling by partially or fully blocking the pores. This may be due to mechanical or electrochemical interactions between the particles and the membrane pores (Cui et al. 2003, van der Marel et al. 2009). Additionally, the effect of particle size and concentration is reflected in a number of crucial parameters such as cake resistance, steady state flux, the rate of particle deposition, diffusion and back transport. According to the Carman-Kozney equation, the specific cake resistance (R_c) is related to the solid surface area (S_c) and the void fraction of the cake (ε_c) (Belfort et al. 1994):

$$R_c = 5(1 - \varepsilon_c)^2 \frac{S_c^2}{\varepsilon_c^3} \quad (3.1)$$

where for rigid spherical particles $S_c = \frac{3}{d_p}$.

Equation (3.1) means that particles with smaller diameters form cakes with higher specific resistance. It can also be explained by the fact that smaller particles tend to fill the remaining gaps in the cake structure easier and decrease the void fraction of the cake. A small particle size and high particle concentration helps the processes reach steady state conditions faster, mainly because at these conditions the steady state flux tends to be smaller (Wang and Song 1999, Tarabara et al. 2004). The cake layer thickness is affected by the rate of particle deposition which is larger when the particle concentration is high. As mentioned earlier (see Section 2.4), the governing transport mechanism for particles with smaller diameters is the Brownian diffusion which impacts the filtration performance extensively. A hydrodynamic study of anaerobic UF membranes conducted by Choo and Lee (1998) showed that the mean particle size reduces with the operation time that leads to an increase in specific cake resistance (Figure 3.2).

Figure 3.2 The change of specific cake resistance along with the particle size with operation time (adapted from Choo and Lee (1998))

They also discussed that smaller particles have lower rate of back transport to the bulk. Based on theoretical analysis of transport mechanisms in crossflow filtration, Sethi and Wiesner (1997) proposed a range of unfavorable particle size of 0.01 to 0.1 μm which corresponds to a minimum back transport efficiency, higher cake thickness and low permeability. Similar to Kwon and Vigneswaran (1998), they mentioned that with particle size larger than this range, the dominant transport mechanism is shear-induced diffusion. This indicates that the particle characteristics are significantly important in the membrane fouling process.

3.3.2 Sub-critical flux operation

In addition to aeration and crossflow, fouling prevention related to hydrodynamic condition can be linked to the low operational flux (Field et al. 1995) as well as flux homogeneity. Although the concept of critical flux (Section 2.4) has been debated by membrane researchers and a different term has been proposed to replace it, known as “weak form of critical flux” or “sustainable flux”, there is no argument about the fact that there exists a flux above which TMP rises at an extremely rapid rate. This is typical of all the membrane processes that three stages of membrane fouling have been recognized. A limited rapid rise in TMP has been suggested as a cause of strong interactions between membrane surface and solid particles. Secondly, sub-critical fouling, a steady long process of filtration with a relatively smaller rate of increase in TMP, has been associated with the flux (Guglielmi et al. 2007). The third stage which is broadly addressed as “TMP jump” refers to the stage of filtration in which the TMP increases extremely quickly.

3.3.3 Flux distribution and relaxation

The low flux operation is considered a potential means of minimizing membrane fouling which reduces membrane maintenance and replacement costs. However,

industrial operations work at a relatively high permeate flux due to stringent requirements on effluent volumetric flow rate. Thus, hydrodynamic complexities of membrane filtration need to be further investigated in terms of other factors such as flux distribution or homogeneity, packing density and filtration relaxation. The major cause of uneven flux distribution in HF membranes is the pressure drop along the fiber length. It is well known that TMP is higher near the permeate exit points. As pointed out in section 3.1.1 flux uniformity is obtained more in shorter fiber lengths. The unbalanced flux distribution can be further explained by the concept of “hydrodynamic resistance” that comprises two components: bundle resistance and flux competition (Yeo et al. 2006). The lateral flow into the fiber bundle causes a fall in the driving force that is ascribed to the location of individual fibers in the bundle. Additionally, there is a competition among fibers to extract permeate, with the fibers located at the center of fiber to be more affected by this competition. The role of relaxation is also an important hydrodynamic factor. Hong et al. (2002) conducted filtration experiments in activated sludge membrane bioreactors, monitoring the effect of different parameters on fouling. They proposed intermittent relaxation as an alternative method since lowering the flux for large treatment plants is not economically viable.

3.4 Alternative anti-fouling measures

3.4.1 Membrane vibration

Fouling mitigation approaches typically aim at inducing a relative motion between the membrane surface and the surrounding fluid to provoke a competent shear rate that is able to help in membrane scouring and diffusion enhancement. Aeration and crossflow can do so by moving the surrounding fluid, however, in recent decades, it has been argued that there might be a more effective way to reach this aim. Rotating membrane stacked disks (Viadero et al. 2000, He et al. 2007) or vibrating submerged membranes (Vane et al. 1999, Low et al. 2004) produce a massive shear rate. These

systems that are also referred to as “dynamic filtration” settings are claimed to be a more effective way of filtration enhancement compared to crossflow. Vibratory Shear Enhanced Processing (VSEP) was first commercially implemented by New Logic International (1992) for fouling mitigation. Since then it has been adopted for fouling prevention in various membrane applications, namely, MF, UF, NF and RO (Zouboulis and Petala 2008, Ahmed et al. 2010). In VSEP technology, a number of flat sheet membranes are placed in a torsional vibrating shaft. The vibration of the membranes positively affects the fouling performance by disturbing the CP and deposition layer. It has been argued that the flux in VSEP can be enhanced up to 10 times of that in crossflow. Compared to crossflow, VSEP generates a shear of one order of magnitude higher at about 150000 s^{-1} at 60 Hz. The correlation between flux and shear induced in vibratory systems has been described by a power law as:

$$J = c\gamma_{\max}^n \quad (3.2)$$

The filtration and vibration parameters impact empirical constants of c and n significantly. The power n was initially proposed to be $1/3$, but further investigations showed that a value of 0.2-0.5 is more suitable (Akoum et al. 2002, Jaffrin et al. 2004, Postlethwaite et al. 2004, Akoum et al. 2005, Petala and Zouboulis 2006). The dependence of n to vibration frequency can be seen for the microfiltration of yeast at frequencies lower than 60 Hz where n is estimated to be 0.19, but for higher frequencies, it is larger than that (Akoum et al. 2002). The expansion of VSEP in terms of commercial application has been hindered by the complexities in the scale up of the system, limited membrane area and higher cost (Jaffrin 2008, Jaffrin and Ding 2015).

The vibration of HF and flat sheet membranes in submerged reactors is another dynamic way of enhancing the performance. Intuitively, it is expected that the vibration would be more effective and easier in HF rather than flat sheet due to better flexibility and physical properties of HF membranes. Unlike VSEP, the vibration of

submerged membranes does not require high frequencies and even in some cases frequencies as low as 1-2 Hz have been illustrated to enhance the performance significantly (Genkin et al. 2006). For instance, in HF membrane vibration boundary layer separation and the production of secondary flows were postulated to be the main contributors for improved performance (Li et al. 2014). Axial vibration was used in flat sheet membrane filtration by Gomaa and Rao (2011). As can be seen in Figure 3.3, they reported a significant improvement in the filtration flux with frequencies up to 25 Hz and amplitudes of up to 1.5 cm.

Figure 3.3 Axial vibration of flat sheet membrane (adapted from Gomaa and Rao (2011))

Submerged HF on the other hand, can be vibrated longitudinally and transversely. Although both types of vibration can be effective in fouling reduction, Li et al. (2014) showed that even at a low frequency of 1 Hz the fouling is effectively mitigated by transverse vibration for both bentonite and yeast suspensions. Kola et al. (2014) conducted transverse vibration experiments in an anaerobic reactor. They reported

that depending on the magnitude of frequency, the vibration needs to be coupled either with relaxation or backwash to enhance the performance. For low frequency vibration, relaxation yields a better outcome, while at high frequency backwash is more efficient. They also compared the membrane filtration performance by monitoring TMP versus time at three hydrodynamic fouling mitigation techniques: gas sparging, crossflow and vibration. As can be seen in Figure 3.4, the filtration performance with vibration was much more efficient.

Figure 3.4 Changes of TMP with different fouling control techniques of gas sparging, crossflow velocity and vibration (Permeate flux of 30 L/m²h and MLSS concentration of 26 mg/L) (adapted from Kola et al. (2014))

The fouling prevention technique of vibration has also been implemented in lab-scale MBRs. Bilad et al. (2012) introduced a novel magnetically induced vibration for filtration of synthetic wastewater. They compared filtration with and without vibration and also intermittent vibration, and concluded that both continuous and intermittent vibrations are highly effective in preventing the growth of specific resistance and reduction in the critical flux. A special HF membrane filtration of mixed liquor in a lab-scale aerobic MBR was performed by Li et al. (2016) with a

transversely vibrating membrane module. The role of intermittent vibration was also examined. Similar to Bilad et al (2012), Li et al. (2016) observed that intermittent vibration is also capable of improving the performance by reducing the rate of TMP rise. A typical TMP profile for filtration of mixed liquor with a concentration of 4 g/L in this study can be observed in Figure 3.5.

Figure 3.5 TMP change with different intermittent vibration intervals (adapted from Li et al. (2016))

3.4.2 Turbulence promoters

Turbulence promoters are frequently used in crossflow membrane filtration in order to improve the efficiency of the process. The use of turbulence promoters has a few notable advantages in hydrodynamic considerations: (1) the mass transfer can be enhanced in the reactor, (2) the negative effects of CP and foulant deposition are alleviated by disturbing the boundary layer, (3) the wall shear can be increased in the vicinity of membranes and the scouring effect of crossflow is improved as a result

(Liu et al. 2012). These advantages make the crossflow filtration less energy intensive, as it is reported that with a similar dissipated power a significant increase in the permeate flow (~300%) can be obtained by using Kenics static mixers (Krstić et al. 2002). Krstić et al. (2004) reported that at the same feed flux a six-fold increase in energy consumption is coupled with 700% permeate flux improvement due to usage of static mixers which yielded a 25% decrease in overall specific energy demand. Zhen et al. (2006) also reported that the energy consumption was reduced to a great extent when using the turbulence promoters.

Xu et al. (2002 and 2003) used diverse configurations of turbulence promoters (Figure 3.6) in an MBR with ceramic membranes. The comparison of flux performance of these turbulence promoters indicated that for this MBR, using winding inserts yielded the best enhancement. This behavior was explained by the creation of rotational or secondary flow, fluid instabilities and the local increase of the velocity when introducing winding inserts. The pitch size is considered an important parameter in the application of winding inserts, with lower pitch length known to be more effective in enhancing flux (Hilal et al. 2008).

The positive effect of the shape of turbulence promoters can be modified by the shape of the channel. Chiu and James (2006) used the same type of turbulence promoters as Xu et al. (2002 and 2003) and observed that using helical inserts would lead to the best flux increase which may be due to better mixing by them in a star-shaped channel. The shape of the channel can also influence the intensity of secondary flow and the instabilities.

Figure 3.6 The configuration of turbulence promoters: (a) cylindrical inserts (b) helical inserts (c) winding inserts, length of pitch: 5, 10, and 20 mm (adapted from Xu et al. (2003))

Although turbulence promoters are typically coupled with crossflow, the use of this technique is not limited to crossflow filtration. Gomaa et al. (2011) examined the effectiveness of turbulence promoters in a vibratory flat membrane system. At a high frequency, vortex shedding and turbulence eddies are the main contributors to the removal of deposited cake by mixing and membrane scouring. As can be seen in Figure 3.7, they reported that using turbulence promoters in a vibratory membrane system effectively improve the permeate flux. A hydrodynamic study of submerged flat sheet membrane performance at the presence of turbulence promoters using CFD and experimental investigation confirmed the findings of Gomaa et al. (2011), that the membrane performance in terms of flux substantially enhanced by using turbulence promoters (Xie et al. 2016). It was also indicated that the average kinetic energy can change depending on the configuration of turbulence promoters' arrangement.

Figure 3.7 Flux performance of vibratory flat membranes at presence of turbulence promoters (TP) (adapted from Gomaa et al. (2011))

3.5 Summary

In this chapter, a review of literature relevant to the content of this study is presented. The hollow fiber membrane filtration and the most important physical and hydrodynamic properties of the system that affect the filtration performance are reviewed.

Although many techniques are currently used for fouling mitigation in submerged reactors, particularly submerged hollow fiber membrane reactors, a fundamental understanding of hydrodynamics of turbulence in these reactors is still lacking. Previous studies have addressed the impact of turbulence coupled with crossflow or vibration on membrane filtration. This understanding is crucial, and the role of turbulence and turbulence alone has not been separately addressed due to difficulties in distinguishing between turbulence and other hydrodynamic features of the system.

This understanding can help engineers and researchers look for more practical means for improving performance since turbulence can be generated in different manner.

Chapter 4 Turbulence characteristics of a vibratory perforated plate ¹²

4.1 Introduction

Turbulence is one of the most prominent unsolved physical questions, which is widely observed in almost all the engineering problems related to fluids and it is characterized by its stochastic properties. Turbulence is not only created by natural phenomena, but also it is generated in many of the engineering processes. There are many ways to create a turbulent ambient of which the following can be mentioned: Couette cylinders, shakers and stirrers, vibration, jets, grids and other shear-free or shear generated techniques. Shear generated turbulence can be seen in crossflow of aeration induced turbulence where the role of mean flow is notable (Chanson and Toombes 2002, Su and Mungal 2004). The turbulence that is generated by buoyancy is characterized as a type of shear-free turbulence which is usually induced by differences in the density of the fluid in different regions (Turner 1979). Two rotating cylinders embedded within each other are utilized in the Couette cylinders to generate turbulence. The state of turbulence of a fluid which is in between the two cylinders is affected by the physical properties of the fluid such as viscosity and also by properties of the cylinders such as radii and the angular velocities (Gibson and Thomas 1995). The higher viscosity and an increase in the distance would hinder the transition to turbulent flow and therefore would require higher angular velocities which would result in higher energy consumption. Shakers and stirrers which are typically used to promote better mixing, also produce turbulence (Guadayol et al. 2009, Mahmud et al. 2009). The range of turbulence is generally wide that depends on the type of stirrers and the variation in shakers' movement. Vibration of an object in a fluid can lead to production of turbulence as well. The physical properties of

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² Part of this chapter is published in: Pourbozorg, M., T. Li and A. W.-K. Law (2017). "Fouling of submerged hollow fiber membrane filtration in turbulence: Statistical dependence and cost-benefit analysis." *Journal of Membrane Science* 521: 43-52.

oscillating object affect the turbulence characteristics (Skrbek and Vinen 2009). The turbulence generated by jets will be discussed in the later part of this thesis.

Grids can also be used to generate turbulence. In the literature there are two types of turbulent flows associated with grids depending on whether the grid is stationary or not. The hydrodynamics of these turbulent flows are similar, however. It has been well established that turbulence in a stationary grid is driven by the mean flow which decays by a power law (Murzyn and Blorgey 2005), but an oscillating grid generates zero-mean turbulence (Hwang and Eaton 2004). There are also differences in the functional relationships that describe turbulence parameters. For instance, Thompson and Turner (1979) suggested that the integral length scale increases linearly with the distance from the oscillating grid, on the other hand, Roach (1987) argued that the length scale has a $h^{0.5}$ relationship with distance from a stationary grid. The turbulence generated by a vibrating grid is also characterized as a shear-free turbulence at distances considerably far from the grid (Cheng and Law 2001). These characteristics of grid turbulence make it easy to study the widely examined features of turbulence, namely, turbulence kinetic energy and turbulence eddies without a major concern about the presence of mean flow.

In the present study, a special setup by vibrating a perforated plate to generate turbulence in a hollow fiber membrane filtration has been designed. The turbulence generated by a stationary perforated plate in a wind tunnel was shown to have similar characteristics to grid turbulence using hot-wire anemometry (Liu et al. 2004). However, the hydrodynamic quantification of the turbulence produced by a vibrating perforated plate is yet to be performed. Since in this study, vibrating perforated plate was chosen as a source of turbulence, a study of turbulence characteristics was done. Here, the non-intrusive method of Particle Image Velocimetry (PIV) was used to quantify the turbulence characteristics. The principle of PIV will be discussed in the following and then the discussion on turbulence by a vibrating perforated plate will be elaborated in terms of velocity fluctuations, autocorrelation of velocity components and the energy spectrum.

4.2 Principle of Particle Image Velocimetry

4.2.1 Components of Particle Image Velocimetry

The three main components of PIV are laser, camera and seeding particles as can be seen in Figure 4.1. The laser light flashes in a double pulsed manner to the entire flow field and illuminates the seeding particles. The scattered light distributed by the seeding particles is captured by the camera on two distinct images. For evaluation, the images are divided into sub-images, with each sub-image called interrogation areas (IA). IAs can have different sizes of 16, 32 and 64 pixels depending on the size of the images. The size of IAs are selected in a way that there is a minimum impact on the velocity gradient. A smaller IA produces a higher number of velocity vectors and the probability of wrong measurements increases. The average particle displacement in every IA is then determined by cross correlation of the two images as defined by equation (4.1). The velocity vector fields are then calculated with the known time interval between every laser pulse.

$$(f * g) = \sum_{i=-\infty}^{\infty} \sum_{j=-\infty}^{\infty} f(i, j)g(i + m, j + n) \quad (4.1)$$

In equation (4.1), $f(i, j)$ and $g(i, j)$ are discrete functions which represent the intensity of velocity distribution in the first and second images. The discrete variables m and n denote the pixel offset between two images. It is much faster to use Fast Fourier Transform (FFT) to compute the cross-correlation function (CCF) than computing it in the time domain.

Figure 4.1 Components of Particle Image Velocimetry

The density, size and the number of seeding particles are most important factors in PIV. In PIV, the calculated velocity vectors are in fact the velocity of seeding particles which are moving with the flow. The diameter of the particles that is usually in the order of $10\ \mu\text{m}$ should be small enough to ensure a short response time such that they follow the flow accurately. It has to be noted that the size of particles is also important since it is compared with the wavelength of the laser. If the wavelength of the light is smaller than the particle diameters, the Mie's scattering theory is used to predict the light scattered by the seeding particles (Raffel et al. 2013). It is needless to say that the choice of an appropriate particle diameter is of crucial importance since particles need to be small enough to follow the flow and at the same time they need to be large enough to produce sufficient scattering for the camera to detect the movements. It has to be taken into account that the seeding particles should also be non-toxic, non-corrosive, and chemically inert.

4.2.2 Experimental setup for Particle Image Velocimetry

PIV was used in this study to quantify the turbulence characteristics inside the test tank. Here, a Litron product PIV system was used that included a dual-cavity frequency doubled Q-switched pulsed mini Nd:YAG laser with an energy level of maximum 400 mJ per pulse, and a CCD camera with a resolution of 1008×1018 pixels. Polyamide seeding particles with particle size of $50 \mu\text{m}$ were chosen as flow field tracers. The seeding density was adjusted to ensure that about 8~10 particles were usually observed within an interrogation area (IA) with a pixel size of 0.1 mm. The difference in density between the particles and flow should be small to avoid a significant velocity lag. For this purpose, using neutrally buoyant particles i.e. particles with identical density as the fluid would be beneficial (Melling 1997). In this case, the density of seeding particles was $1030 \text{ kg}\cdot\text{m}^{-3}$ which was very close to water.

To conduct the PIV measurements, a sheet of green light generated by the laser with a wavelength of 532 nm was illuminated onto the flow field in a double-pulse manner. The sheet of green laser light was shone through the centre of perforated plate. The images were then taken by the CCD camera from a plane perpendicular to the perforated plate. The double-pulsed images were then captured by the camera with the frequency at 5 Hz. The typical sampling duration was 140 s, i.e., a total of 700 double-pulsed images were taken for data processing. This duration was previously shown to be adequate for the statistical analysis of the turbulence fluctuations for grid-generated turbulence (Cheng and Law 2001). Using paired t-test it was seen that, the measured velocities were statistically indifferent at the 95% confidence interval.

The horizontal and vertical velocities were measured using the Particle Image Velocimetry (PIV) technique, which can be conveniently employed to obtain the planar flow distribution in an area to be sampled. This pre-analysis was done in the Dynamic Studio (Dynamic System product) software. The interrogation area was selected as 32×32 pixels with an overlap of 25%. After pre-analysis the instantaneous

velocity information were extracted for further analysis. The analysis were done using self-developed codes in MATLAB.

4.3 Experiments: Turbulence generated by a perforated plate

The oscillating grid turbulence is ideal for fundamental studies on turbulence related problems since it is homogenous and has zero mean velocity, thus more straightforward than boundary layers and open channel turbulence. However, its characteristics is complicated by the impact of physical features of the grid such as shape and size of the grid, and the stroke and frequency of vibration. These complexities result in observation of contradicting reports on the nature of this phenomenon. These differences clarify two things. First, in the experimental measurements and data analysis of this problem there may exist a notable amount of systematic error due to inaccuracies in the measurement instruments and also a degree of random error due to statistical insufficiencies. Second, the understanding of grid generated turbulence is still at its infancy even though it has already been studied for a few decades. For a small scale of operation, using perforated plates is advantageous in terms of controlling its variables, simpler design and easier production. In this chapter, the turbulence characteristics of a flow generated by a perforated plate have been investigated to establish the similarity and differences between grid generated turbulence and turbulence generated by a perforated plate. This will offer insights to improve the physical understanding of such turbulent flows while making it possible to study a simple case of membrane filtration in turbulence. It has to be noted the focus of this study is on the impact of generated turbulence on membrane filtration rather than a detailed study of a specific type of turbulence. The schematic diagram of the experimental setup is shown in Figure 4.2.

Figure 4.2 Schematic diagram of vibrating perforated plate

The turbulence generators were made of Polyvinyl Chloride (PVC) perforated plate. They had the same plate area (A_t) of $29 \text{ cm} \times 17 \text{ cm}$ but different numbers of square shaped voids of $1 \text{ cm} \times 1 \text{ cm}$ (details listed in Table 4.1) to make solidities (S_r) of 18%, 30%, 40%, 50% and 60%, respectively, with S_r defined as:

$$S_r = \frac{A_s}{A_t} \quad (4.2)$$

where A_s is the total solid area. It is expected that higher solidities would generate more intense turbulence inside the reactor. Schematics of P5 is displayed in Figure 4.3. P1-4 had the same dimensions with different numbers of voids.

Table 4.1 Characteristics of turbulence generators

Plate	Number of voids	S_r (%)
P1	27×15	18
P2	25×14	30
P3	23×13	40
P4	21×12	50
P5	20×10	60

Figure 4.3 Schematics of the turbulence generator plate (P5)

The frequency of vibration was changed from 1-5 Hz and the vibration stroke was modified from 4-16 mm.

Thompson and Turner (1975) was among the first studies that attempted to quantify turbulence generated by an oscillating grid and relate the result to operating parameters such as frequency and stroke. Although they confirmed that they observed

an agreement between the experimental results and theoretical decaying power law that was previously proposed, their experimental results showed deviation from other studies. They suggested that the integral length scale (L_e) changed only with the distance from the grid (h).

$$L_e = C_0 h \quad (4.3)$$

Hopfinger and Toly (1976) proposed a rather simple functional relationship among root mean square velocities (u_{rms} and v_{rms}), vibration parameters (frequency (f) and stroke (S)) and physical characteristics of the grid including mesh size (M) which is defined as the distance between two adjacent openings.

$$u_{rms} = C_1 f S^{1.5} M h^{0.5} \quad (4.4)$$

$$v_{rms} = C_2 f S^{1.5} M h^{0.5} \quad (4.5)$$

where C_1 and C_2 are constants that depend on the physical properties of the grid. These relationships were tested by many researchers who confirmed their validity (McDougall 1979). The study of turbulence below a shear-free gas-liquid interface by a split-film anemometer indicated that the turbulence characteristics were affected by the region close to the interface that is called “surface influenced layer”, with turbulence being highly anisotropic in this region. Therefore, the relationships that are proposed for isotropic state do not hold true for the entire flow field because of the presence of two distinct regions (Brumley and Jirka 1987, Nokes 1988).

4.4 Results and discussion

The velocity flow field was captured in a plane perpendicular to the perforated plate. Here, the region above the perforated plate was captured (see Figure 4.4), and the turbulence characteristics at this region were quantified since the hollow fiber membrane were placed in this region. The turbulence characteristics above and below the plate were similar as long as free-surface and wall boundaries were at a considerably far distance (Cheng and Law 2001).

Figure 4.4 A sample image from Particle Image Velocimetry

4.4.1 Instantaneous velocity and velocity flow field

Turbulence is characterized by fluctuations of the flow parameters. Instantaneous velocities of turbulent flows have fluctuations in both spatial and time domains. Reynolds decomposition states that the flow parameters have a mean and fluctuating components (Pope 2000). A sample of instantaneous velocity fluctuations at a single point in the tank ($x = 15$ cm, $h = 5$ cm) can be seen in Figure 4.5 for P5 vibrating at frequency $f = 2$ Hz and stroke $S = 16$ mm. In this figure, the dashed red line shows the mean value of the velocity across the time domain while the difference between instantaneous velocities and the mean velocity indicates the magnitude of the velocity fluctuations. PIV enables us to observe and quantify the horizontal and vertical velocity across the entire flow field.

Figure 4.5 Instantaneous velocity for vibration of perforated plate with $S_r = 60\%$, $S = 16$ mm, $f = 2$ Hz

Figure 4.6 shows the flow field for P1-P5 with $S = 16$ mm and $f = 5$ Hz. The velocity flow field of the area in Figure 4.3 with the same coordinates is displayed in this

figure. As in any given flow field representation of a cross section of a system the arrows represent the magnitude of the velocity. In this case, the magnitude varies between 0 and $0.015 \text{ m}\cdot\text{s}^{-1}$. When the solidity was low at $S_r = 18\%$ the magnitude of velocity is higher near the perforated plate (Figure 4.6 (a)), increasing the solidity not only helped increase the velocity fluctuation but also created a more uniform flow field that led to a more homogenous and isotropic turbulence. The energy transfer among turbulence eddies is highly affected by the intensity of turbulence. A more intense turbulent flow with higher velocity fluctuations and smaller time scales has higher length scales. In turbulence generated by a vibrating perforated plate, a higher eddy length scale can be obtained with a higher frequency of vibration and a higher solidity of the perforated plate as can be seen in this figure.

4.4.2 Velocity fluctuations

4.4.2.1 Effect of frequency

Hopfinger and Toly (1976) established the functional relationship between the velocity fluctuations and vibration variables of an oscillating grid (section 4.3). Equations (4.4) and (4.5) show that velocity fluctuations in such a system change linearly with frequency. Although Thompson and Turner (1975) reported a power law relationship for frequency dependence of velocity fluctuation with the power being $4/3$, the linear relationship proposed by Hopfinger and Toly (1976) has been accepted and approved by others (De Silva and Fernando 1992, Schreck and Kleis 1993). The values of u_{rms} and v_{rms} in a vibrating perforated plate were quantified and the changes with frequency can be seen in Figure 4.7. The results indicated that both horizontal and vertical fluctuations changed proportionally with frequency. This showed an agreement with the previous studies on grid generated turbulence which indicated that a perforated plate produced a turbulent ambient analogous to a grid in terms of fluctuating velocities (Hopfinger and Toly 1976). Further discussion on perforated generated turbulence can be found in section 6.4.

Figure 4.6 Velocity flow field of turbulence with perforated plate vibration ($S = 16$ mm, $f = 5$ Hz, $S_r =$ (a) 18%, (b) 30%, (c) 40%, (d) 50%, and (e) 60%)

4.4.2.2 Effect of vibration stroke and distance from the plate

The vibration stroke plays a vital role in velocity fluctuations similar to frequency. Previous studies have discussed that finding the relationship between velocity and stroke is more complicated mainly due to difficulties in varying stroke and also the fact that the values of velocity were not easily quantified (Hopfinger and Toly 1976). Earlier studies adopted the concept of a “virtual origin” to establish a point from which the distance (h) could be defined (Mohamed and LaRue 1990). Using this concept, they were able to quantify velocity with respect to both stroke and the distance from the plate. The results showed that velocity fluctuations follow a power law relationship with stroke ($u_{rms} \propto S^{1.5}$) and the distance ($u_{rms} \propto h^{0.5}$). Here, the velocity fluctuations versus vibration stroke were quantified and plotted in Figure 4.8. It was observed that the turbulence generated by a perforated plate changed with a power of 1.5 with vibration stroke similar to previous studies (Hopfinger and Toly 1976).

The distance from the vibrating or non-vibrating grid is a very important factor in turbulence characteristics. In the past, researchers have argued about the definition of the distance, and as mentioned earlier some suggested the idea of virtual origin in order to find the dependency of turbulence parameters on the distance. In most cases, the origin was adopted to be on the grid where the turbulence energy that is generated is nearly infinite (De Silva and Fernando 1994). In this study, the effect of the distance from the perforated plate was investigated and the results are shown in Figure 4.9.

Figure 4.7 Variation of (a) horizontal and (b) vertical velocity fluctuations versus $\ln f$ (vibration frequency) with different solidities (S_r)

Figure 4.8 Variation of (a) horizontal and (b) vertical velocity fluctuations versus $\ln S$ (vibration stroke) at different frequencies (f)

This figure shows that the changes in velocity fluctuation with distance were similar to previous studies ($u_{rms} \propto h^{-0.5}$) (Hopfinger and Toly 1976). The distance from the perforated plate also greatly impacted other turbulence parameters such as eddy length scale.

Figure 4.9 Variation of (a) horizontal and (b) vertical velocity fluctuations versus $\ln h$ (distance) at different frequencies (f)

4.4.3 Autocorrelation of velocity fluctuations

It is important to define a length or time scale that is a representative of the largest scales in turbulence. These scales can be used to interpret the energy production or dissipation process in a turbulent flow. Occasionally, the largest scales are defined based on the limitations that are imposed because of the physical characteristics of the system. For instance, the largest length scale in a pipe flow is comparable to the

pipe diameter. When the physical features of the system do not impose any constraints, the real challenge is to define and quantify the desired scales. The correlation coefficient between the velocity components of a turbulent flow is used to quantify the eddy length scale. The spatial domain in which this coefficient is quantified is very important. Firstly, the domain of the autocorrelation function for experimental and numerical results is limited. Additionally, there is uncertainty in choosing the appropriate domain. O'Neill et al. (2004) suggested that the spatial domain that is larger than $3\lambda_T$ can be an appropriate domain to quantify the autocorrelation function. λ_T is the Taylor microscale that is determined from:

$$\lambda_T = \frac{u'^2}{\left(\frac{du'}{dx}\right)^2} \quad (4.6)$$

Autocorrelation (R) is defined as:

$$R_{kk}(x_k, r) = \frac{\langle u_k(x_k, t)u_k(x_k + r, t) \rangle}{\langle u_k^2 \rangle} \quad (4.7)$$

where k is an integer not used as tensor index, and r the distance between two points in the flow. Depending on the direction of r and u_k , the autocorrelation function is either longitudinal or transverse. If r and u_k are in the same direction, it is longitudinal; otherwise if r is perpendicular to u_k , it is transverse.

Here, Figures 4.10 and 4.11 show the longitudinal and transverse correlation coefficients in the experiments. In all the cases, when $r = 0$ cm, $R = 1$ and the correlation coefficient rapidly decreased to values very close to zero and after this it fluctuated at low values until the fluctuation was negligible. For any given result, the

autocorrelation curves were similar at different frequencies. The dependency of integral length scale was only on the distance. The frequency of vibration did not significantly affect the correlation coefficient. The eddy length scale, therefore, was only a function of the distance (h) and physical properties of the vibrating grid. The differences among the correlation coefficients can be observed for different solidities which was a confirmation of previous findings (Hopfinger and Toly 1976). The details of eddy length scale quantification will be discussed in section 6.4.

Figure 4.10 Longitudinal correlation coefficient for $S_r =$ (a) 18%, (b) 30%, (c) 40%, (d) 50%, and (e) 60%

Figure 4.11 Transverse correlation coefficient for $S_r =$ (a) 18%, (b) 30%, (c) 40%, (d) 50%, and (e) 60%

4.4.4 Turbulence spectrum

The form of spectra in a turbulent flow without mean velocity is called the Eulerian frequency spectra (Tennekes 1975). The velocity fluctuations corresponding to the frequency ω in Eulerian frequency spectra are highly affected by turbulent eddies. The role of eddies in velocity fluctuations can be seen in two forms. First, the eddies with ω frequency contribute to the velocity fluctuation. Secondly, the dominant contribution to the fluctuations comes from energy containing eddies that move back and forth with a velocity of u_0 and transfer smaller eddies by advection (with a wave number k) hence creating a frequency of $\omega = u_0 k$. However, the advection hypothesis in the dominant energy containing eddies has been proved to be valid only for high Reynolds number flows (Yeung and Pope 1989).

The spatial decay of the turbulence kinetic energy with perforated plate vibration frequency of $f = 5$ Hz and different solidities can be seen in Figure 4.12. The red line indicates the Kolmogorov's $-5/3$ power law decay. The results indicated that an exact power law would fail to describe the energy decay. The energy spectrum decays slower at the beginning and the rate of decay changes after a turning point. This transition point has been noted to vary with various system characteristics and it is difficult to locate. The $-5/3$ power law was only valid for a small range. The findings were in agreement with previous studies on oscillating grid turbulence (De Silva and Fernando 1994).

Figure 4.12 Spatial decay of the turbulence kinetic energy with perforated plate vibration frequency of $f = 5$ Hz for $S_r =$ (a) 18%, (b) 30%, (c) 40%, (d) 50%, and (e) 60%

4.5 Conclusion

In this chapter, the turbulence generated by a perforated plate was investigated in terms of velocity fluctuations, correlation coefficient, and the energy spectrum. The turbulence characteristics were obtained from the post processing of the data collected from Particle Image Velocimetry. The observation of the velocity flow field indicated that when the solidity was low the magnitude of velocity is higher near the perforated plate. An increase in the solidity would lead to the expectation of an in the velocity fluctuation, and also it creation of a more uniform flow field that can lead to a more homogenous and isotropic turbulence.

The functional relationship between the velocity fluctuations and vibration parameters of the perforated plate indicated that the turbulence generated by means of perforated plate was directly related to frequency. It was also found that the vibration stroke had a 1.5 power relationship with both horizontal and vertical velocity fluctuations. The decay of turbulence intensities with distance from the plate was similar to that of oscillating grid. The longitudinal and transverse correlation coefficients were independent of the vibration frequency. However, the plates' solid ratio had an impact on the correlation coefficient. The results of turbulence energy spectrum indicated that an exact power law would fail to describe the energy decay. The energy spectrum decayed slower in the beginning and the rate of decay changed after a turning point. This transition point had been noted to vary with various system characteristics and difficult to locate. The $-5/3$ power law was only valid for a small range. In the next chapter, the effect of turbulence kinetic energy and eddy length scale on the fouling performance of a submerged hollow fiber membrane will be discussed.

Chapter 5 Hollow fiber membrane filtration in the presence of turbulence³

5.1 Introduction

In this chapter, the effect of turbulence on hollow fiber membrane filtration in terms of membrane fouling performance was investigated experimentally. In particular, a special setup with a turbulence generator using a vibrating perforated plate was constructed in the laboratory. The setup enabled the hollow fiber membrane filtration to be carried out within a design ambient with targeted levels of turbulence without mean shears. The non-intrusive laser imaging approach of Particle Image Velocimetry (PIV) was used to quantify the characteristics of the turbulent ambient. Subsequently, by monitoring the rate of TMP rise with constant permeate flux experiments using 4 g/L yeast feed suspensions, unique data sets were obtained that revealed the quantitative effects of turbulence on hollow fiber membrane filtration, which are not available in the literature so far. Overall, the results indicated that the presence of turbulence moderated the membrane fouling and reduced the corresponding rate of TMP rise ($dTMP/dt$). In addition, two key turbulence parameters, namely, turbulence kinetic energy (TKE) and eddy length scale, were found to be effective with the membrane fouling reduction, with the rate of TMP rise generally decreases when TKE or eddy length scale increases. At the same time, there exists an optimum length scale beyond which the eddy size (comparable to approximately ten times of the hollow fiber diameter in the present chapter) has no more influence on the fouling behaviour. A direct comparison between turbulence and membrane vibration for fouling control was also performed. The implications of the present results on the design of membrane bioreactors are discussed.

³ This chapter is based on: Pourbozorg, M., T. Li and A. W. K. Law (2016). "Effect of turbulence on fouling control of submerged hollow fibre membrane filtration." *Water Research* 99: 101-111.

The use of hollow fiber membranes in water and wastewater treatment industry has been extensive in the past decades (Celmer et al. 2008, Çulfaz et al. 2011, Robles et al. 2013). Higher surface area and excellent mass transfer properties are among the major reasons which lead to this broad usage (Moch 2000, Çulfaz et al. 2011). It is predicted that the high growth of the industry will continue in the near future (Fletcher et al. 2007).

For membrane bioreactors (MBRs), membrane fouling and concentration polarization remain the biggest hurdles in the design and operation. Fouling is defined as internal or external blockage of the membrane surface by foulants that accumulate during the treatment process (Drews 2010), which can result in TMP rises and flux declines. Various approaches, in particular air sparging (Le-Clech et al. 2003, Chan et al. 2011, Jankhah and Bérubé 2013), have been developed to alleviate the fouling. However, the effect of air sparging had been shown to be limited to a finite extent (Xia et al. 2013), and the energy consumption requirements can be high up to 70% of the total energy cost (Judd 2006, Drews 2010, Verrecht et al. 2010). Therefore, the search for a more cost effective alternative continues.

Alternative techniques which have been studied for the fouling control of membranes in recent years include membrane vibrations (Bilad et al. 2012, Kola et al. 2012, Li et al. 2013), Couette motion (Philp et al. 1994), and pulsations (Defrance and Jaffrin 1999). Membrane vibration produces shear stresses on the membrane surface that can scour and reduce the deposit of foulants. The improvement of membrane fouling depends on the orientation of vibration, which can be either longitudinal or transverse, with the latter shown to be more effective for hollow fiber membranes (Kola et al. 2014, Li et al. 2014).

The use of turbulence promoters has also been proposed for membrane fouling reduction in the literature. A turbulent environment is generally favoured in the membrane filtration systems as it improves the mass transfer in the system (Pitera and Middleman 1973, Judd 2006). Krstić et al. (2002) investigated the effect of a static

mixer as a turbulence promoter in a crossflow microfiltration arrangement. They concluded that the permeate flux improved more than 500% with turbulence for all the membranes studied. The significant improvement in the permeate flux implied a lesser need for high crossflow velocity which can result in lower energy consumption. Jokić et al. (2010) examined the use of mixers with different configurations to provoke turbulence in a crossflow microfiltration of yeast suspensions. They also reported a significant increase in the permeate flux.

Other types of turbulence promoters that were studied in crossflow filtration, included cylindrical inserts (Xu et al. 2003, Zhen et al. 2006), helical inserts (Xu et al. 2003, Zhen et al. 2006, Liu et al. 2012), winding inserts (Xu et al. 2003, Zhen et al. 2006), column cross-section inserts (Zhen et al. 2006), and twisted tape (Popović and Tekić 2011). Generally, these studies reported in a qualitative manner that the turbulence generated by the promoters decreased the membrane fouling and led to a significant reduction of fouling rate (in terms of the rate of TMP rise) on top of the crossflow effects. However, the quantitative influence of the turbulence alone to the membrane filtration was generally not documented separately due to the difficulty in distinguishing the two effects. The only exception was from Yeo et al. (2007) who investigated the use of air sparging for hollow fiber fouling reduction using advanced laser imaging techniques. They found that the rate of TMP rise during their constant flux experiments could be correlated to both the mean shear and turbulence kinetic energy (TKE) around the fibers induced by the bubbling, and that the two effects were of almost equal importance in the quantitative relationship. Their study remained the only study available in the literature that provided the distinctive influences of turbulence on membrane filtration as far as the author is aware.

In terms of engineering application, considering that turbulence can be generated by different means (air sparging, jet, grid, etc.), it is critical to confirm in a quantitative manner the role of turbulence in membrane filtration processes. Although the positive effect of turbulence on mass transfer and fouling mitigation had been discussed in earlier studies (Liu et al. 2012), the details on the physical mechanism have not been

delineated fully, and the balance between the beneficial uses of turbulence and the associated turbulence energy dissipation has not been examined in detail. The primary objective of this chapter was to improve the physical understanding on the sole effect of turbulence in membrane filtration, which has not been examined before. With the improved understanding, the balance between the energy dissipating aspect of turbulence agitation can be quantitatively evaluated and its beneficial use towards membrane fouling control, and ultimately the cost effectiveness of the difference approaches using turbulence and crossflows in an MBR can be appraised.

In the present chapter, it is aimed to quantify the effect of turbulence on hollow fiber membrane filtration in a comprehensive manner. This was accomplished by means of a special experimental setup that enabled the hollow fiber membrane filtration to be carried out in a design ambient with various targeted levels of turbulence without mean shears. The non-intrusive laser imaging approach of Particle Image Velocimetry (PIV) was used to quantify the characteristics of the ambient turbulence. Subsequently, by monitoring the rate of TMP rise during constant flux membrane filtration experiments, unique data sets were acquired that revealed the effects of turbulence without the presence of crossflows. In particular, the quantitative effects of two key parameters were identified, namely, TKE and eddy length scale (or eddy size) on the membrane filtration. In the following, the experimental setup and methods are first described. The experimental results are then discussed in details.

5.2 Experiments

5.2.1 Main experimental setup

A schematic diagram of the main experimental setup is shown in Figure 5.1. The setup included a test tank, a turbulence generator, a motor and a membrane module. The test tank was made of Perspex with dimensions of 50 cm (L) $\times$ 40 cm (W) $\times$ 50 cm (H). The turbulence generator had a vibrating perforated plate connected to a DC

brushless motor with a crank moving mechanism which can be operated in a range of diverse frequencies and strokes. The details of the perforated plate will be described in the later section of materials and experimental procedures.

During the experiments, several parameters, such as frequency and stroke, were varied to establish a turbulent environment in the test tank. The membrane module was attached onto a holding bracket located above the turbulence generator plate. The position of the module can be shifted within a range of 10 to 20 cm from the plate, so that the module can be placed under different turbulent conditions. The membrane filtration equipment included a peristaltic pump, a balance, a data logging system, and a pressure transducer. The permeate flux was controlled and monitored by a MasterFlex peristaltic pump (Cole-Parmer) with a digital balance (UX6200H, Shimadzu) and the data logging system, while the TMP was measured by a pressure transducer (Precision digital).

5.2.2 Experimental setup for Particle Image Velocimetry

The experimental setup for PIV was explained in Chapter 4. It has to be noted that the plane where images were taken during PIV experiments was perpendicular to the perforated plate and parallel to the hollow fiber membranes. The spatial average of the PIV experimental results was used to report turbulence effect on membrane filtration performance in this study.

Figure 5.1 Schematic diagram of experimental setup

5.3 Material and experimental procedures

5.3.1 Yeast suspension

Yeast (*Saccharomyces cerevisiae*) is broadly used in many industries such as beer production, wine brewing, etc. In addition, its characteristics of easy accessibility and better chemical cleaning make it suitable for studies on fouling mechanisms (Jokić et al. 2010). Yeast suspensions made with Dry Baker's Yeast (saf-instant, Levure Seche de Boulanger, France), were used as the feed for the membrane filtration experiments in the present study. In each experiment, 300 g of yeast particles were added to 1.5 L of tap water and mixed for a duration of 15 minutes. After the yeast particles were fully mixed, the suspension was then added to the tank to make a concentration of 4 g/L.

5.3.2 Hollow fiber membrane module

The membrane module used in this study included sixteen Polyacrylonitrile (PAN) hollow fiber membranes from Ultrapure Pte Ltd in Singapore. The fibers were arranged in 4×4 pattern. The distance between each two adjacent fibers was 5.2 mm. The membrane module's metal casing had a squared shape configuration as shown in Figure 5.2. The fibers were joined to the metal casing with epoxy at both ends (see Figure 5.3). The hollow fibers had inner/outer diameters of 1.0/1.7 mm, with the nominal pore size of 0.1 micron and length of 30 cm. The minimum distance between the centre of hollow fiber module and the plate was 10 cm.

Figure 5.2 Dimensions of membrane module metal casing

Figure 5.3 Hollow fiber membrane module

5.3.3 Turbulence generator

As discussed earlier in section 4.3, a vibrating rectangular perforated plate made of Polyvinyl Chloride (PVC) was used to produce turbulence in the reactor. The dimensions of the plate (see Figure 5.4) were $29\text{ cm} \times 17\text{ cm}$, with a total of 19×11 circular voids of 1 cm^2 . With this configuration, the plate had a solidity ratio of 58%. In each row of the plate, the distance between adjacent circle voids was 16.55 mm, and the row distance was 15.8 mm. The vibration frequency of the plate was fixed at 2 Hz, while the amplitude varied from 4 to 16 mm. During vibration, the water flowed through the holes in the plate in an oscillatory manner. With this oscillatory motion, interactions of jets and wakes occurred near the plate. At a distance far from the plate, the turbulence a homogeneous and isotropic turbulence is expected when these coherent features of the flow almost vanish.

Figure 5.4 Dimensions of the turbulence generator plate

5.3.4 Experimental procedures

The constant flux experiments were conducted at $15 \text{ L}/(\text{m}^2 \cdot \text{h})$. The permeate flux was controlled to be 1% accuracy by monitoring and automatically adjusting the TMP to yield a constant volume of permeate recorded at an interval of 5 s. Every experimental condition was repeated at least three times, and the results provided here are represented with error bars to address the level of uncertainty. TMP data analysis using t-test showed no statistical difference at the 95% confidence interval. The null hypothesis was that the different sets of data have the same mean values. Each experiment lasted for 90 mins. After each experiment, the chemical cleaning of fibers was performed by submerging the fibers into a 0.5% sodium hypochlorite solution for 45 minutes, which was reported by Wang et al. (2014) to be able to remove the organic and biological foulants. This cleaning process resulted in the recovery of fiber performances in terms of permeability. If the permeability was recovered to 95% or

above, the fibers were reused, otherwise they were replaced with new fibers instead to make a new module.

As discussed above, the experiments with membrane filtration were carried out in a wide range of turbulent ambient conditions, by varying the vibration strokes, S , of the perforated plate, and adjusting the distance, h , between hollow fiber membrane module and turbulence generator plate, as shown in Figure 5.1. The experimental conditions are tabulated in Table 5.1.

Table 5.1 Operational conditions for different turbulence states at a fixed frequency $f = 2$ Hz

Test #	Stroke (mm)	Distance (cm)
Test 1	4	10
Test 2	4	12
Test 3	4	14
Test 4	4	16
Test 5	4	18
Test 6	8	10
Test 7	8	12
Test 8	8	14
Test 9	8	16
Test 10	8	18
Test 11	16	10
Test 12	16	12
Test 13	16	14
Test 14	16	16
Test 15	16	18

5.3.5 Additional experiments of vibrating hollow fibers

A separate set of experiments were also conducted to compare the effect of turbulence on hollow fiber filtration to that of vibrating the hollow fibers themselves directly. Both approaches induce a relative movement of the membrane surface and surrounding fluid, producing oscillating shears for fouling reduction without the presence of mean shears. Both can also be adjusted such that the total energy involved for the fouling control can be similar. Their key difference is however that turbulence encapsulates a spectrum of eddies with varying fluctuating frequencies and amplitudes, whereas the membrane vibration is typically carried out only with a single amplitude and frequency (Li et al. 2014).

The schematic diagram for the vibrating hollow fiber experiments is shown in Figure 5.5. The experiments were conducted in a similar tank made of Perspex with dimensions of 48 cm (L) $\times$ 42 cm (W) $\times$ 50 cm (H). The same membrane module in Section 4.2.2 was adopted. A total of three tests were conducted and the experimental conditions are listed in Table 5.2. Note that the experimental conditions were carefully selected such that the membrane vibration would involve velocity magnitude for membrane vibration ranging from 0.87×10^{-2} to 1.56×10^{-2} m/s that were similar to the characteristic velocity with turbulence (to be discussed in section 5.5.6). The same yeast suspensions for the turbulence experiments were also chosen for these three tests. With the parallel conditions, it is aimed to gain further insight between the turbulence effects and shear-enhanced vibration directly through the comparison of the experimental results.

Table 5.2 Experimental conditions for membrane vibrations

Test #	Frequency (Hz)	Stroke (mm)
Test 16	0.25	16
Test 17	0.8	16
Test 18	1	16

Figure 5.5 Schematic diagram of membrane module vibration setup

5.4 Analysis

5.4.1 Review of Particle Image Velocimetry in membrane filtration

PIV is one of the flow measurement techniques used in flat sheet and hollow fiber membrane processes. Shear rate on a flat membrane surface was quantified using Titanium dioxide (TiO_2) as flow field tracers by Gaucher et al. (2002). They suggested that the inhomogeneous fouling was due to heterogeneous distribution of wall shear that is greatly affected by fluid velocity, channel height and the position of inlet and outlet. Wereley et al. (2002) combined PIV and particle tracking velocimetry (PTV) to study hydrodynamics of a rotating cylindrical membrane. For this purpose, two types of tracer particles with different diameters were applied. The smaller particles with a diameter of 10-25 μm were used for PIV while the larger particles with a diameter of 150-300 μm were utilized for PTV. The velocity flow field and particle concentration profiles indicated that particles tend to move towards the concentration polarization layer at low velocity gradient, suggesting that in their system a higher velocity gradient would be favorable to disrupt the CP. Yeo et al.

(2007) applied PIV in a two-phase air-water system in submerged hollow fiber membrane filtration. They studied the shear induced by air bubbles on membrane surface by varying air bubble characteristics (bubble size and bubble frequency), fiber looseness and channel width. They reported that a higher frequency of smaller bubbles can decrease the rate of TMP rise as high as an order of magnitude. This was attributed to accumulation of highly frequent small shear stress that is induced by small bubbles, while the shear stress by larger bubbles is not efficient at low frequency. This finding was argued to be a crucial step towards minimizing the significant energy loss of MBRs that use MF and UF membranes (Fane et al. 2005).

5.4.2 Particle Image Velocimetry

Before the membrane filtration experiments, a series of experiments with seeding particles (without yeast particles) inside the test tank was first conducted to quantify the turbulent conditions induced by the vibrating perforated plate using PIV. The nominal diameter of the seeding particles is around 50 μm . The particle size was carefully chosen in consideration of the sizes of the IA and the time between the laser pulses, such that optimal scattered light images during the double laser pulsing can be reproduced for accurate cross-correlation determination of the velocity vector maps. Note that the presence of yeast particles which had a much smaller size would affect the quantification processing. Based on the PIV results, the turbulence characteristics of Reynolds shear stress (RSS), TKE and integral length scale (L_e) were determined. Their definitions are reviewed in the following sections before detailed discussions are presented.

It should be noted that the presence of yeast particles during the membrane filtration experiments can potentially modify the turbulent conditions inside the reactor (Yuan and Michaelides 1992, Tsuji et al. 1994, Pang et al. 2011, Abdelsamie and Lee 2012). However, Balachandar and Eaton (2010) stated that the turbulence characteristics of a multiphase flow containing very small volume fraction of particles were nearly the

same as a single-phase flow. Since the volume fraction (Φ_v) of the dispersed particles in this study was only 4 g/L or $\Phi_v = 0.005$ by volume, it can be assumed that the turbulent conditions remained identical with and without the yeast particles.

5.4.3 Reynold Shear Stress

Reynolds stresses arise from the Reynolds decomposition of the mean and fluctuating values in the Navier-Stokes equation for incompressible fluids (Tennekes and Lumley 1972) as below:

$$\frac{\partial u_i}{\partial t} + \rho \frac{\partial}{\partial x_j} (u_i u_j) = -\frac{\partial p}{\partial x_i} + \mu \frac{\partial^2 u_i}{\partial x_j \partial x_j} \quad (5.1)$$

$$u_i = \bar{u}_i + u'_i \quad (5.2)$$

$$p = \bar{p} + p' \quad (5.3)$$

where u_i is velocity in i -direction, ρ density of fluid, μ viscosity of fluid, p pressure, $\bar{u}_i$ the mean velocity in i -direction, and u'_i the velocity fluctuations in i -direction.

Time averaging of the above Navier-Stokes equation results in (Tennekes and Lumley 1972):

$$\frac{\partial \bar{u}_i}{\partial t} + \rho \frac{\partial}{\partial x_j} (\bar{u}_i \bar{u}_j + \overline{u'_i u'_j}) = -\frac{\partial \bar{p}}{\partial x_i} + \mu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} \quad (5.4)$$

$$\overline{u'_i u'_j} = \bar{u}_i \bar{u}_j - \bar{u}_i \bar{u}_j \quad (5.5)$$

The terms $\tau'_{ij} = \rho \overline{u'_i u'_j}$ in equation (5.4) are the components of the Reynolds stress tensor. From a physical point of view, the orthogonal ($i \neq j$) components of RSS represent the transport of momentum in the direction perpendicular to the momentum's direction.

5.4.4 Turbulence Kinetic Energy

The TKE represents the mean kinetic energy linked with eddies in the turbulent flows (Tennekes and Lumley 1972). TKE (or K) can be quantified by the summation in equation (5.6) as:

$$K = \frac{1}{2} \overline{(u'_i u'_i)} \quad (5.6)$$

In the present study, in order to obtain TKE values from the two-dimensional PIV data, an assumption was made that the turbulence fluctuations parallel to the perforated plate were similar, i.e.

$$\overline{u'_1 u'_1} = \overline{u'_3 u'_3} \quad (5.7)$$

where $i = 1$ and 3 represent the two planar coordinate axes that were parallel to the hollow fibers and the vibrating perforated plate. It has to be noted that this assumption is specific to the flow configuration being addressed, and preliminary measurements were performed which showed that the assumption is approximately valid in the domain (Appendix). This indicated that the turbulence was homogeneous and

isotropic in a horizontal plane. With the assumption, equation (5.6) can be rewritten as:

$$K = \frac{1}{2} (\overline{2u_1' u_1'} + \overline{u_2' u_2'}) \quad (5.8)$$

where u_1' and u_2' can be obtained from the PIV measurements.

5.4.5 Integral Length Scale

The integral length scale represents the correlated distance of the fluid motion (O'Neill et al. 2004). It is considered as a measurement of the energy containing eddy size (Davies et al. 1963, Roach 1987). To determine L_e , the autocorrelation (R) of the velocity between two points is calculated as mentioned in Chapter 4. After quantifying autocorrelation of velocity, L_e can then be computed as:

$$L_e = \int_0^{\infty} R_{kk}(x_k, r) dr \quad (5.9)$$

Both TKE and L_e were adopted in this study as the representative turbulence parameters. It should be noted that the combination of these two parameters provides an understanding of the eddy viscosity (Drazen and Melville, 2009).

5.5 Results and discussion

5.5.1 Mean Velocity

The oscillating perforating plate was chosen as the turbulence generator in present study so that the membrane filtration can be carried out under turbulence but without the presence of mean shears (i.e. crossflows). The turbulence generated by an oscillating grid had been assumed to have a zero mean velocity in the past (De Silva and Fernando 1994). For verification, the mean velocity distribution was examined inside the test tank using the PIV results under various test conditions. The flow fields were captured in a plane perpendicular to the perforated plate and parallel to the hollow fibers. The results are shown in Figure 5.6. The horizontal axis (x) is the direction parallel to the perforated plate and hollow fiber membranes. The vertical axis (h) represents the vertical distance from the perforated plate. The origin of the plot indicates the point on the intersection of perforated plate and laser light, on the left edge of the plate when the plate was at its lowest position. The mean velocity was calculated based on the PIV measurements averaging over the duration of 140 seconds.

From Figure 5.6, it was found that mean velocities did exist but with a small magnitude inside the test tank. They were also generally higher away from the plate. In the region where the membrane filtration took place (i.e. $h = 10$ to 20 cm), the maximum mean velocity was found to be 0.02 m/s. The magnitude was similar among the range of stroke values and frequencies in the experiments, and was small comparing to the velocity of the turbulence fluctuations (section 5.5.3). For example, with $f = 2$ Hz and $S = 16$ mm velocity fluctuations was typically around 0.025 m/s in the vicinity of membrane fibers while mean velocity did not exceed 0.008 m/s which is three times less than fluctuations. Hence, it is believed that the effect of mean velocities to the membrane filtration was not significant compared to that of the turbulence fluctuations in the current work.

Figure 5.6 Mean velocity distribution of the fluid in the test tank (measurements were taken at a plane perpendicular to the perforated plate) ($f = 2$ Hz, $h = 10$ cm): (a) Test 1, $S = 4$ mm, (b) Test 6, $S = 8$ mm, and (c) Test 11, $S = 16$ mm

5.5.2 Values of Reynolds Shear Stress

The turbulence generated by means of oscillating grid was assumed to be shear free (Cheng and Law 2001). De Silva and Fernando (1994) suggested that this is the case since the mean shears induced by jets and wakes cancel each other. Here, it is noted that the typical configuration in earlier studies included square or cylindrical crossed bars with the solidity ratio of $\sim 10\%$ (Lyn 1997, Cheng and Law 2001). However, the solidity ratio of the vibrating perforated plate in the present study was substantially higher close to 60% . Therefore, to verify the shear free conditions in the experiments, an analysis of the RSS was conducted.

Figure 5.7 shows the RSS at three different turbulence states based on similar h values. The horizontal axis (x) is the same as that in Figure 5.6. In other words, in each figure, only the stroke changed and other conditions remained the same. RSS in these experiments had a range of -0.63×10^{-5} to $0.83 \times 10^{-5} \text{ m}^2 \cdot \text{s}^{-2}$. Thus, it was confirmed that the turbulence inside the tank was shear free with RSS values near zero. The confirmation was particularly important in this study, because the setup enabled the examination of the effect of turbulence on membrane filtration without mean shear stresses on the membrane surface. As discussed in section 5.1, the combination of turbulence and mean shears in past studies made it difficult to identify the distinctive effect of turbulence on the filtration processes (Wicaksana et al. 2006, Yeo et al. 2007).

Figure 5.7 Reynolds Shear Stress (RSS) for three different turbulent conditions ($f = 2 \text{ Hz}$), $h =$ (a) 10 cm, (b) 12 cm, (c) 14 cm, (d) 16 cm, and (e) 18 cm

5.5.3 Values of Turbulence Kinetic Energy

In the present study, TKE variations were achieved primarily by changing the strokes of the vibration of the perforated plate. Generally, it can be expected that TKE increases with an increase in the stroke of vibration. The results of TKE for Tests 1, 6 and 11 are shown in Figure 5.8 for illustration. They confirmed that a higher stroke in the oscillation of the perforated plate generated more intense turbulence. For example, the average TKE value across the length of the fibers at $h = 10$ cm with the lowest stroke ($S = 4$ mm) was $0.23 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$. It increased to $2.65 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$ with the medium stroke ($S = 8$ mm), and further to $3.52 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$ with the highest stroke ($S = 16$ mm). The effects of TKE on the fouling control of the fibers will be discussed in the next sections.

Figure 5.8 Turbulence kinetic energy (TKE) along the hollow fibre membranes ($L_e = 0.79 \times 10^{-2} \text{ m}$)

5.5.4 Variation of Integral Length Scale

The variation of L_e with the distance from the perforated plate (h) was investigated. In the literature, a linear dependence of L_e to the distance from a vibrating grid was first proposed by Thompson and Turner (1975) and subsequently confirmed by other studies (Hopfinger and Toly 1976, Roach 1987, Cheng and Law 2001). However, the solidity of the vibration grid used in these earlier studies was typically less than 40%, whereas in the present study the solidity ratio of the perforated plate was close to 60%. Thus, an independent investigation of the variation was needed.

The results of the longitudinal (L_L) and transverse (L_T) integral length scales are shown in Figure 5.9. From the figure, it can be seen that both L_L and L_T did also increase linearly with increase of h , similar to the trend for vibration grids reported in other earlier studies (Cheng and Law 2001). In addition, their values were approximately the same despite the scattering. In other words, the turbulence was nearly isotropic.

5.5.5 Effect of turbulence on fouling control

In order to verify the accuracy of the measurements, multiple experiments were conducted for each experimental condition. The reported results were averaged values of repeated three experiments with error bars of standard deviation. Figure 5.10 shows the transient variation of TMP during the membrane filtration experiments under different TKEs at the position of $h = 10$ cm. TKE was highest at the highest stroke, i.e. $S = 16$ mm. It was found that a higher TKE generally induced a slower rate of increase in TMP, as expected physically. For example, when the TKE was at $3.52 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$, the TMP increased gradually from 12 to about 30 kPa in 1 hour constant flux filtration, while the TMP rises were faster to 74 and 92 kPa at smaller mean TKEs of 2.65×10^{-4} and $0.23 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$, respectively, for the same period of filtration.

Figure 5.9 Linear relationship (dashed line) between (a) longitudinal and (b) transverse integral length scale and the distance (h) from perforated plate

Figure 5.10 TMP versus time for three turbulent conditions (K = turbulence kinetic energy)

The membrane fouling rate ($d\text{TMP}/dt$) versus eddy length scale for different TKEs is shown in Figure 5.11. For each condition, it was observed that more intense turbulence (i.e. higher TKE) reduced membrane fouling rate as discussed above. For instance, at $h = 12$ cm when the TKE rose from 0.17×10^{-4} to $0.98 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$, $d\text{TMP}/dt$ reduced from 1.39 to 1.10 kPa/min. It declined further to 0.42 kPa/min as a result of an increase in TKE up to $2.38 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$. In quantitative terms, the reduction in fouling rate from the stagnant condition due to turbulence needs to be investigated with a thorough statistical analysis.

Figure 5.11 Rate of change of TMP at different integral lengths

The transient variation of TMP during the membrane filtration experiments with different L_e is shown in Figure 5.12. It can be observed when L_e increased from 0.79×10^{-2} to 1.62×10^{-2} m, the fouling rate decreased from 0.42 to 0.11 kPa/min. However, when L_e was further increased from 1.62×10^{-2} to 2.00×10^{-2} m, no further reduction in fouling rate was observed. The transition at $L_e = 1.62 \times 10^{-2}$ m occurred for all the experiments in the present chapter.

Figure 5.12 Temporal variation of TMP in turbulent conditions with different integral length scales

The joint influence of TKE and L_e on the membrane fouling rate is further illustrated in a three-dimensional manner in Figure 5.13. The general trends reported for TKE and L_e in Figures 5.11 and 5.12, respectively, remained evident in Figure 5.13. However, the scattering on the experimental results was also obvious, which would imply that additional factors due to higher order characteristics of the turbulence (such as skewness, etc.) might also have affected the membrane fouling rates. Nevertheless, the experimental results also clearly suggested that these two parameters can represent the dominant effects by turbulence in terms of fouling control.

The significance of the results above is that the fouling rate in MBRs can be reduced by increasing the TKE or L_e . In a real reactor, the turbulence length scale (or eddy size) is typically constrained by the spacing between the reactor's wall and the membrane module. The current results thus imply that membrane fouling would be worsened if sufficient spacing is not provided. Kang et al. (2008) had earlier performed a CFD study on an MBR, and the results showed that the membrane fouling increased when the spacing reduced. The present results were consistent with

their observation and also highlight the existence of a minimum spacing beyond which the spacing will not be important.

Figure 5.13 Experimental results of turbulence kinetic energy (K) and integral length scale (L_e) on the fouling rate of hollow fiber membranes

5.5.6 Comparison between turbulence and membrane vibration on fouling control

Turbulence can be considered to be consisted of a spectrum of energy - containing eddies of different sizes (Tennekes and Lumley 1972). Hence, the effect of turbulence on membrane filtration can be viewed as the action of these energy containing eddies sweeping over and scouring the membrane surface, which in turn leads to the fouling reduction. To gain further physical insight, a simplifying concept of “dominant eddy” as a gross representation of the action of the spectrum of eddies can be sought as discussed below.

An identifiable ‘eddy’ can be conceived to be a localized turbulent motion over a region of size l , which is at least moderately coherent over this region. This eddy would also have a characteristic velocity $u(l)$ and timescale $\tau_c(l) = l/u(l)$. Here, the gross representative of eddies is used in the larger size range by a dominant eddy with the length scale l_0 which is comparable to the eddy length scale L_e above. In a fully developed turbulence, the corresponding characteristic velocity of the dominant eddy $u_0 = u(l_0)$ is of the order $u_0 = (2K/3)^{1/2}$ (Chu 1994). The dominant eddy of size L_e thus has an intrinsic time period of $\sim L_e/u_0$.

A selected data set among the turbulence experiments with different u_0 and L_e is shown in Table 5.3. The corresponding intrinsic time scale of these experiments is also shown in the table. Hence, in these experiments, the action of turbulence on membrane filtration can be conceptualised due to an oscillating dominant eddy of fluctuating velocity of magnitude u_0 and with a dominant period of τ_c shown in the table.

The shear stresses on the membrane surface due to turbulence are induced by the relative motion of the fluid in the boundary layer above the fixed membrane surface. An alternative view can be established for the situation, i.e. rather than the fluid oscillating next to a stationary membrane fiber, it is the fiber itself that is oscillating in a stationary fluid. Both can conceptually produce relative motion between the membrane and fluid, and induce shear stresses on the membrane surface that reduce fouling. This is in fact the basis of how the technique of membrane vibration is proposed as an alternative for fouling control (Li et al. 2013, Li et al. 2014). In this regard, it is noteworthy to compare the current results of the turbulence experiments with that from the membrane vibration experiments, and to draw insights into the physical understandings.

Table 5.3 Characteristics of selected turbulence experiments

Test #	Velocity scale (u_c) ($\times 10^{-2}$ m/s)	Length scale ($\times 10^{-2}$ m)	Time scale (s)
Test 1	0.39	0.79	2.03
Test 6	1.33	0.79	0.59
Test 11	1.53	0.79	0.52

As described above, a separate set of membrane vibration experiments was performed for the comparison. The experimental conditions are shown in Table 5.2. The vibration stroke was set to be 16 mm and the vibration frequency ranged between 0.25 - 1 Hz. The parameters were chosen such that the vibration of fibers would be performed with velocity and time scales compared to the turbulence experiments. For example, Test 16 had a stroke $S = 16$ mm which was the characteristic length scale for the turbulence experiments. The characteristic time scale was based on the vibrating period i.e. the inverse of the frequency ($\tau_c = 1/f$).

Figure 5.14 shows the transient variation of TMP during the membrane filtration with the same feed of 4 g/L yeast suspension in the membrane vibration experiments. As can be seen from the figure, the rate of TMP rise was smaller with higher vibration velocity. The TMP increased from 10 to 94 kPa at $u_c = 0.39 \times 10^{-2}$ m/s after 1 hour, while the corresponding TMP rise for $u_c = 1.33 \times 10^{-2}$ and 1.53×10^{-2} m/s were 54 and 18 kPa, respectively. Figure 5.15 shows a direct comparison of the rate of TMP rise between turbulence and membrane vibration. Clearly, the results showed that the fouling rate was similar between the two cases. For example, at a characteristic velocity of 1.53×10^{-2} m/s, fouling rates of 0.32 and 0.31 kPa/min were induced by turbulence and membrane vibration, respectively.

Figure 5.14 TMP versus time with membrane vibration at different characteristic velocities (u_c)

The above agreement demonstrates that the mitigation mechanism for fouling control is similar between the two actions of turbulence and membrane vibration. Both actions rely on the relative motion between the fluid and membrane surface to induce shear stresses that scour the foulants and prevent them from depositing on membrane surface.

Figure 5.15 Rate of the change of TMP versus characteristic velocity for both turbulence and membrane vibration experiments

5.6 Conclusion

In this chapter, the quantitative effect of turbulence on hollow fiber membrane filtration was experimentally investigated in terms of membrane fouling control. In particular, a special setup with a turbulence generator using a vibrating perforated plate was constructed in the laboratory. The setup enabled the hollow fiber membrane filtration to be carried out in an ambient environment with targeted levels of turbulence without mean shears. Subsequently, membrane filtration experiments were performed with constant flux using 4 g/L yeast feed suspensions.

The hydrodynamic characterisation indicated that the turbulence generated by the vibrating perforated plate had a zero mean shear stress despite the high solidity of the plate. Mean velocities did exist to a small extent inside the test tank and they were generally higher away from the plate, but their magnitude was much smaller compared to the turbulence fluctuations at the same location. The integral length scale

also increased linearly with the distance from the turbulence generator plate, similar to earlier studies on grid generated turbulence with much lower solidity ratios.

The experimental results from the constant flux experiments showed that the presence of turbulence led to a significant improvement in fouling control of submerged hollow fiber membrane filtration. The fouling rate generally decreased with an increase in turbulence kinetic energy. The increase in integral length scale also reduced the fouling, but beyond an optimal value the fouling rate did not reduce any further. This demonstrates for the first time that there exists an optimal turbulence length scale (approximately ten times of the hollow fiber diameter in the present study) for membrane fouling control.

Finally, a direct comparison between two sets of experiments with turbulence and membrane vibration was performed. The results showed that the two actions produced similar effect to the fouling control of submerged hollow fiber membrane filtration, thus confirming that the oscillating shears produced by the relative motion between the fluid and the membrane surface is the dominant mechanism for the fouling mitigation.

Chapter 6 Statistical dependence and energy demand analysis of membrane filtration with turbulence⁴

6.1 Introduction

In Chapter 5, the effect of shear-free turbulence on the fouling control of submerged hollow fiber membrane filtration was investigated in a laboratory reactor. Quantitative details were reported from 15 experiments of dead-end filtration of organic yeast suspensions, linking the fouling rate to the turbulence kinetic energy and integral length scale in a quantitative manner for the first time in literature. In this chapter, the scope was expanded to a full range of turbulence conditions with a total of 79 experiments, to establish the statistical dependence between the energy consumption due to turbulence dissipation and improved productivity with reduced membrane fouling so that the energy demand trade-off can be evaluated. The turbulence was generated by various vibrating perforated plates. Increasing vibration frequency/stroke or solidity of the perforated plate resulted in more intense turbulence inside the reactor, and that the eddy length scale increased with solidity in general. Hollow fiber membrane filtration experiments were then performed within the turbulent ambient in both inorganic Bentonite and organic yeast suspensions. The variance analysis of the results further confirmed the link between the membrane fouling rate and both turbulence kinetic energy and eddy length scale and their cross interactions, as well as that an optimum eddy length scale existed beyond which its influence diminished. A energy demand analysis of membrane fouling in turbulence is then presented for evaluation. Finally, the effect of turbulence on membrane filtration performance was also examined in conjunction with the fiber bundle characteristics of the membrane module. An optimized fiber spacing and fiber looseness were identified that consistently performed the best in all experiments,

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allowing the fluctuating turbulence eddies to penetrate and mobilize the fibers in the most efficient manner against fouling.

At present, membrane filtration has a significant overall market share of ~15% in the water treatment industry (Neoh et al. 2016). Various types of membrane, such as reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF) and microfiltration (MF), are used in different filtering operations (Stephenson et al. 2000). Among them, hollow fiber (HF) membranes are used extensively due to their distinct advantages of better flexibility and higher surface to volume ratio (Pankhania et al. 1994, Kim et al. 2015).

The most prominent issues associated with membrane applications, and HFs in particular, are fouling and concentration polarization (Guo et al. 2012). It has been discussed that the method for fouling control primarily utilizes shear stress generation by the relative motion between the surrounding fluid and membranes (Wicaksana et al. 2006, Jaffrin 2008). To achieve this, various techniques have been proposed in the literature, such as crossflow (Wakeman and Tarleton 1987, Elcik et al. 2016), air sparging (Luo et al. 2015, Miyoshi et al. 2015), pulsation (Howell et al. 1993, Blandin et al. 2015) and membrane vibration (Li et al. 2016). With crossflow and air sparging, the shear stress is generated by moving the fluid surrounding the membrane surface. The action typically produces a turbulent environment inside the reactor at the same time, which is also generally favoured in membrane filtration due to the enhancement in mass transfer (Judd 2006). Alternatively, in membrane vibration, the membrane moves actively instead and the surrounding fluid is stationary. This relative motion also produces shear stresses on the membrane surface which reduces membrane fouling. The crossflow velocity (Vyas et al. 2002, Choi et al. 2005), aeration intensity (Le-Clech et al. 2003, De Temmerman et al. 2015) and operating characteristics of membrane vibration (Li et al. 2014) are important factors that govern the effectiveness among these methods.

A higher crossflow velocity or aeration rate typically intensifies the shear stress on the membrane surface as well as the turbulence in the reactor (Li and Wang 2006). Other means of augmentation have also been implemented to further increase the turbulence intensity, such as using turbulence promoters in crossflows (Xu et al. 2002, Jokić et al. 2010). Krstić et al. (2004) observed that the use of static mixer improved the permeate flux by more than 700%. At the same time, the flux enhancement was also associated with a great increase in energy consumption, which would be undesirable since high operational costs hinder the membrane usage (Schäfer et al. 2001). Thus, although the positive influence of turbulence on membrane filtration has been generally confirmed in the literature both in terms of fouling prevention and mass transfer improvement, the statistical dependence between the two is yet to be quantified sufficiently for energy demand evaluation. To our knowledge, only a limited number of attempts had been made so far to decipher the underlying effect of turbulence on membrane filtration (Yeo et al. 2007). In particular, in Chapter 5 a unique laboratory reactor with turbulent ambient but without the presence of mean flows was developed to examine membrane fouling in shear-free turbulence, and presented indicative results based on 15 experiments performed.

The current chapter focuses on establishing a statistical relationship between membrane fouling and turbulence characteristics, by performing extensive experiments in the same setup as Chapter 5. A total of 79 experiments with a wide range of turbulence characteristics were performed for this objective, and the turbulence kinetic energy (K) and integral length scale (L_e) were measured using the non-intrusive Particle Image Velocimetry (PIV) approach. The full set of data enabled the determination of the statistical relationships and energy demand evaluation. In addition, since the fouling rate is also highly dependent on the operating characteristics of the hollow fiber membrane module (Martínez and Rodríguez-Maroto 2007), the examination of the effect of fiber spacing and fiber looseness is included in this chapter. In the following, the experimental results are discussed in details.

6.2 Experimental setup and operating procedures

6.2.1 Experimental setup

The experimental setup was the same of that of Chapter 5. A total of five turbulence generators were used in this chapter, with details described in the next section of materials. The same turbulence promoters as described in Chapter 4 were used in this chapter (Table 6.1). The vibration stroke (S) could be manually adjusted from 4 to 16 mm, while the vibration frequency (f) could be varied from 1 to 5 Hz to induce different turbulence intensities inside the reactor.

Table 6.1 Characteristics of turbulence generators

Plate	Number of voids	S_r (%)
P1	27×15	18
P2	25×14	30
P3	23×13	40
P4	21×12	50
P5	20×10	60

6.2.2 Materials

In this chapter, the feed included both the inorganic Bentonite and organic yeast suspensions. The Bentonite (Sigma-Aldrich) particles and yeast (saf-instant, Levure Seche de Boulanger, France) were the same as those used in Li et al. (2014), with nominal particle sizes of $5.83\mu\text{m}$ and $4.95\mu\text{m}$, respectively. They were chosen for their easier availability and widespread usage in microfiltration. In addition, both can

form a cake layer on the membrane surface, and their sizes are within the range of shear induced diffusion.

6.2.3 Operating procedures

After each membrane filtration experiment, a 0.5% sodium hypochlorite solution was used for the chemical cleaning of fibers to recover their performance. It has been reported that such solution is effective in the cleaning of organic filtration (Shorrocks and Bird 1998, Mohammadi et al. 2003). The fibers were submerged into the sodium hypochlorite solution for 45 minutes. Afterwards the permeability of HFs was measured. The fibers were only reused if the permeability was recovered to 95% and above, otherwise new fibers were used instead.

The preparation procedures were similar for both suspensions. 300 g of either Bentonite or yeast particles were first suspended in 1.5 L water and stirred for 15 min. The mixture was then added to the test tank to make a concentration of 4 g/L. Every experiment was repeated at least three times, and the statistical difference among the results was evaluated using paired *t*-test with a 95% confidence interval.

6.3 Results and discussion

6.3.1 Effect of solidity on Turbulence Kinetic Energy (TKE)

TKE is directly related to the turbulence intensity; hence higher TKEs imply more intense turbulence. Using a vibrating perforated plate with solidity of ~60%, it was observed that TKE varied significantly when the vibration stroke or frequency changed, however their linkage was not examined in details. In the following, the

variations of TKE with frequency, stroke and solidity of the perforated plate are first discussed with TKE measurements using the same technique of PIV.

For vibrating grids, the magnitude of TKE was reported previously to be a function of f , S , h and the mesh size (M) (Thompson and Turner 1975, Hopfinger and Toly 1976) as:

$$K=f_1(f, S, h, M) \quad (6.1)$$

The grid solidity (S_r) in these studies was generally around 20-40%, and it was not listed as a factor of significant importance. As discussed earlier in section 5.4, the experiments were started with a low solidity basing on the earlier work done by Cheng and Law (2001), but it was found that the induced turbulence intensity was insufficient for fouling control in membrane filtration. Thus, a high solidity value of ~60% was adopted for investigative purpose to realize the effect of turbulence on fouling moderation in a measurable manner, and the indicative results with 15 experiments had been reported. However, the vibration energy consumption with the solidity of ~60% was relatively high. In order to evaluate the statistical relationship between the turbulence generation and energy consumption, experiments were performed in this study with a total of five different solidities from 18% to 60%. For each S_r , the turbulence characteristics were measured in details. To enable the analysis for S_r , the earlier relationship in equation (6.3) is expanded as follow:

$$K=f_2(f, S, h, M, S_r) \quad (6.2)$$

Dimensional analysis using repeating variables yields:

$$\frac{K}{f^2 h^2} = f_3\left(\frac{M}{h}, \frac{S}{h}, S_r\right) \quad (6.3)$$

Since the earlier studies had established that (De Silva and Fernando 1994):

$$\frac{K}{f^2 h^2} \propto \left(\frac{M}{h}\right)\left(\frac{S}{h}\right)^3 \quad (6.4)$$

Thus, it can be obtained:

$$\frac{Kh^2}{f^2 S^3 M} = f_4(S_r) \quad (6.5)$$

Figure 6.1 plots $\frac{Kh^2}{f^2 S^3 M}$ versus S_r for the results obtained in the present study and including the data reported in literature. The difference between the values for $\frac{Kh^2}{f^2 S^3 M}$ computed in this study and previous studies can be attributed to the significant difference in the mesh sizes (defined as the distance between adjacent voids in this study) seen in Table 6.1. Hopfinger and Toly (1976) pointed that the functional relationship between turbulence intensities and grid oscillations is highly dependent on the physical characteristics of the grid.

Table 6.2 Values of mesh size of perforated plates and grids in previous studies

Researchers	Mesh size (mm)
Thompson and Turner (1975)	50
Hopfinger and Toly (1976)	50, 100
Mcdougall (1979)	50
Brumley and Jirka (1987)	63.5
De Silva and Fernando (1994)	29.3, 47.6, 62.0
Cheng and Law (2001)	50
Current study (P1)	10.7
Current study (P2)	11.5
Current study (P3)	12.0
Current study (P4)	13.0
Current study (P5)	15.0

With respect to the measurements, the best-fit trend line has the following form:

$$\frac{Kh^2}{f^2 S^3 M} = 51.16 S_r - 10.71 \quad 18\% < S_r < 60\% \quad (6.6)$$

This indicated that S_r is an important factor in the magnitude of TKE in this study. The understanding is crucial for the optimization of the design of vibrating perforated plates as turbulence generators in environmental applications.

Figure 6.1 Variation of $Kh^2 / f^2 S^3 M$ versus solidity (S_r) of perforated plate

6.3.2 Effect of solidity on Integral Length Scale

TKE is not the only parameter of significant importance in a turbulence environment. Turbulence energy spectrum has a very wide frequency range, and the turbulence eddies associated with the different frequencies all act on the membrane surface and produce shear. It is not yet clear how these eddies act together towards fouling control. Earlier in section 5.5.5, it was proposed to first examine using the dominant eddy concept to characterize the eddy size effects. In the context of membrane filtration, the significance of dominant eddy size can be viewed as the overall role that the energy containing eddies play in reducing fouling. If the length scale and velocity scale of the dominant eddy are l and u respectively, then its time scale can be estimated as l/u . Conceptually, the dominant eddy size can be taken as CL_e where L_e is the coherent integral length scale and C is a coefficient that depends on the phenomenon. It was found that $C \approx 1$ for fouling considerations by comparing with equivalent membrane vibration experiments. Note that combining TKE and L_e

yields the eddy diffusivity which is an important turbulence parameter for mass transport.

Similar to TKE, currently there is insufficient information about the dependence of the integral length scale with solidity. Based on non-dimensional analysis similar to above, it can be derived that:

$$\frac{L_e}{h} = f_5(S_r) \quad (6.7)$$

In this study, the integral length scale was quantified with the coherent analysis of time series data of the PIV measurements from the experiments with the five different solidities. The experimental results from the present study as well as reported in the literature are plotted in Figure 6.2. Again significant scattering can be observed which was attributed to the different shape of the perforated plate as discussed before, as well as the fact that the previous studies used point-based measurements (most were intrusive), and assumptions were made to achieve the multipoint coherent analysis that might have contributed some inaccuracies in these studies. With respect to the current measurements, the best fit trend line can be obtained using a polynomial as follows:

$$\frac{L_e}{h} = 0.16S_r - 0.02 \quad 18\% < S_r < 60\% \quad (6.8)$$

The results thus demonstrated that the solidity also had a strong effect on the integral length scale. This finding suggests that achieving a larger dominant eddy size would require a perforated plate with higher solidity.

Figure 6.2 Variations of L_e/h versus solidity (S_r) of perforated plate

6.3.3 Membrane fouling reduction

6.3.3.1 Inorganic Bentonite suspensions

As discussed before, earlier studies observed that an increase in the intensity of turbulence with turbulence promoters or air bubbles would reduce fouling (Jokić et al. 2010, Miyoshi et al. 2015). In the present study, a number of membrane filtration experiments were first performed in inorganic Bentonite suspensions without turbulence, as well as with turbulence generated by a perforated plate with solidity $S_r = 60\%$, vibration stroke $S = 16$ mm and frequency $f = 1$ Hz. The results, shown in Figure 6.3, suggested that a relatively small magnitude of turbulence ($K = 0.99 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$) was effective in preventing membrane fouling in Bentonite suspensions. The dependence was further examined by intensifying the turbulence with increasing vibration frequency to 2 and 3 Hz, which corresponded to $K = 5.12 \times 10^{-4}$ and $11.36 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$, respectively. As illustrated in the same figure, no fouling at these higher values of TKE can be observed implying that the permeate flux was already below

the critical flux under these conditions. Since the fouling rate for bentonite was very low with small magnitudes of TKE, the experiments were concentrated on yeast suspensions in the following.

Figure 6.3 TMP of Bentonite suspensions with various turbulence kinetic energies (K)

Table 6.3 Experimental conditions of hollow fiber membrane filtration in turbulent ambient

Test #	f (Hz)	S (mm)	S_r (%)	h (cm)	$K (\times 10^{-4} \text{ m}^2 \text{ s}^{-2})$	$L_e (\times 10^{-2} \text{ m})$	$d\text{TMP}/dt$ (kPa/min)
1	1	16	18	10	0.02	0.60	1.78
2	1	16	18	12	0.02	0.65	1.66
3	1	16	18	14	0.01	0.79	1.65
4	1	16	18	16	0.01	0.87	1.62
5	1	16	18	18	0.01	0.94	1.47
6	2	16	18	10	0.10	0.60	1.59
7	2	16	18	12	0.07	0.65	1.40
8	2	16	18	14	0.05	0.79	1.43
9	2	16	18	16	0.03	0.87	1.29
10	2	16	18	18	0.03	0.94	1.06
11	3	16	18	10	0.20	0.60	1.43
12	3	16	18	12	0.15	0.65	1.37
13	3	16	18	14	0.10	0.79	1.15
14	3	16	18	16	0.08	0.87	1.02
15	3	16	18	18	0.06	0.94	1.36
16	4	16	18	10	0.34	0.60	1.28
17	5	16	18	10	0.53	0.60	1.20
18	1	16	30	10	0.25	0.67	1.68
19	1	16	30	12	0.18	0.76	1.59
20	1	16	30	14	0.14	0.87	1.50
21	1	16	30	16	0.10	0.96	1.32
22	1	16	30	18	0.08	1.14	1.02
23	2	16	30	10	0.94	0.67	1.57
24	2	16	30	12	0.73	0.76	1.49
25	2	16	30	14	0.50	0.87	1.43
26	2	16	30	16	0.42	0.96	0.98
27	2	16	30	18	0.32	1.14	0.95
28	3	16	30	10	2.00	0.67	1.23
29	3	16	30	12	1.57	0.76	1.19
30	3	16	30	14	1.15	0.87	1.05

Table 6.2 (cont'd)

31	3	16	30	16	0.92	0.96	1.02
32	3	16	30	18	0.72	1.14	0.69
33	4	16	30	10	5.01	0.67	1.09
34	5	16	30	10	6.51	0.67	0.56
35	1	16	40	10	0.48	0.91	1.25
36	2	16	40	10	2.27	0.91	1.16
37	3	16	40	10	5.45	0.91	1.09
38	4	16	40	10	10.19	0.91	0.86
39	5	16	40	10	15.52	0.91	0.46
40	1	16	50	10	0.63	0.91	1.33
41	2	16	50	10	3.28	0.91	1.06
42	3	16	50	10	8.01	0.91	0.80
43	4	16	50	10	14.00	0.91	0.81
44	5	16	50	10	25.73	0.91	0.33
45	1	16	60	10	0.99	1.33	1.00
46	1	16	60	12	0.69	1.43	1.00
47	1	16	60	14	0.56	1.67	0.99
48	1	16	60	16	0.52	1.77	0.99
49	1	16	60	18	0.49	2.02	0.99
50	2	16	60	10	5.12	1.33	0.78
51	2	16	60	12	3.58	1.43	0.78
52	2	16	60	14	2.68	1.67	0.45
45	1	16	60	10	0.99	1.33	1.00
46	1	16	60	12	0.69	1.43	1.00
47	1	16	60	14	0.56	1.67	0.99
48	1	16	60	16	0.52	1.77	0.99
49	1	16	60	18	0.49	2.02	0.99
50	2	16	60	10	5.12	1.33	0.78
51	2	16	60	12	3.58	1.43	0.78
52	2	16	60	14	2.68	1.67	0.45
53	2	16	60	16	2.07	1.77	0.70
54	2	16	60	18	1.91	2.02	0.69
55	3	16	60	10	11.36	1.33	0.79
56	3	16	60	12	7.20	1.43	0.75
57	3	16	60	14	5.72	1.67	0.46

Table 6.2 (cont'd)

58	3	16	60	16	5.10	1.77	0.59
59	3	16	60	18	4.07	2.02	0.57
60	4	16	60	10	18.96	1.33	0.73
61	4	16	60	12	16.46	1.43	0.59
62	4	16	60	14	13.16	1.67	0.29
63	4	16	60	16	10.06	1.77	0.45
64	4	16	60	18	8.46	2.02	0.53
65	5	16	60	10	36.13	1.33	0.48
66	5	16	60	12	27.32	1.43	0.32
67	5	16	60	14	20.30	1.67	0.24
68	5	16	60	16	19.89	1.77	0.26
69	5	16	60	18	12.16	2.02	0.32
70	1	4	60	10	0.02	1.33	1.52
71	2	4	60	10	0.10	1.33	1.42
72	3	4	60	10	0.23	1.33	1.33
73	4	4	60	10	0.40	1.33	1.43
74	5	4	60	10	0.56	1.33	1.41
75	1	8	60	10	0.19	1.33	0.91
76	2	8	60	10	0.74	1.33	0.89
77	3	8	60	10	1.88	1.33	0.85
78	4	8	60	10	3.00	1.33	0.75
79	5	8	60	10	4.48	1.33	0.53

6.3.3.2 Yeast suspensions

The experimental conditions of the membrane filtration experiments with organic yeast suspensions under turbulence are tabulated in Table 6.2. It should be noted again that these experiments were much more extensive in scope than those in Chapter 5. The filtration of yeast suspensions under the same turbulence intensities as Bentonite suspensions is first plotted in Figure 6.4 for comparison. As mentioned in section 6.4.3.2, the fouling rate in Bentonite suspension was very low with a relatively small magnitude of TKE. However, with yeast suspensions, it can be observed that the fouling rate was much higher. The different fouling behaviours can

be attributed to the nature of yeast and Bentonite particles. Yeast contained cell debris and macromolecules that could be adsorbed and deposited on the membrane surface to increase the hydraulic resistance (Belfort et al. 1994). In addition, yeast had smaller particle size, which resulted in the larger specific cake resistance (Belfort et al. 1994), smaller diffusion rates (Choo and Lee 1998) and smaller back transport (Chellam and Wiesner 1997). Thus the membrane fouling in the yeast suspension was more significant.

Figure 6.4 TMP of yeast suspensions with various turbulence kinetic energies (K)

6.3.3.3 Analysis of variance

Statistical investigation of the effect of turbulence on the membrane fouling was performed using analysis of variance (ANOVA) for two-factor factorial experiments. To perform ANOVA, sum of squares (SS) for all the factors and their interaction was calculated. The procedure for computation of SS for each factor and their degree of freedom (D.O.F) can be found in reference (Montgomery 2012). Mean squares (MS) and F_0 are then:

$$MS_f = \frac{SS_f}{\nu_f} \quad (6.9)$$

$$F_0 = \frac{MS_f}{MS_E} \quad (6.10)$$

where ν_f is D.O.F of the factor and MS_E is the means square of error. The comparison between F_0 and the control limit F_{α, ν_1, ν_E} can help indicate the significance of the factors on the response. If F_0 is larger than F_{α, ν_1, ν_E} the factor has significant effect on the response.

The measured fouling rates in the experiments are also listed in Table 6.2. They were determined as the initial linear rise of TMP with time (typically within the first 60 minutes). The large amount of available data from the total of 79 experiments in this study enabled the determination of the statistical dependence of fouling rate ($dTMP/dt$) with TKE (K) and integral length scale (L_e) using the approach of factorial analysis of variance (ANOVA) with each factor having three levels as indicated in Table 6.4. The summary of ANOVA is shown in Table 6.5. The significance level (α) was 0.05 in this analysis. As can be seen in this table, F_0 for both factors was larger than F_{α, ν_1, ν_E} , therefore, the null hypotheses were rejected. This indicated both TKE and integral length had a significant effect on fouling rate. It was also found that the cross interaction between TKE and integral length scale also affected membrane fouling. Thus, the underlying functional relationship is complex.

Table 6.4 Factors chosen in two-factor factorial analysis

Factor	Levels
K ($\times 10^{-4} \text{ m}^2 \text{ s}^{-2}$)	0.54, 1.98, 5.08
L_e (cm)	0.65, 1.33, 1.77

Table 6.5 ANOVA table for statistical analysis of effect of turbulence kinetic energy (K) and integral length scale (L_e) and their cross interaction on the fouling rate of hollow fiber membranes

Source of variation	Sum of squares	Degrees of freedom	Mean square $\times 10^{-2}$	F_0	F_{α, v_1, v_E}
K	0.69	2	34.50	300.84	3.56
L_e	0.78	2	38.92	339.29	3.56
KL_e	0.32	4	10.71	93.41	2.93
Error	0.02	18	0.11		
Total	1.81	26			

The coupling effect of TKE and L_e on membrane fouling rate can be directly seen in Figure 6.5. It was obvious that given a specific length scale a higher TKE would reduce the fouling rate in general. In addition, the lowest fouling rate among the experiments was 0.24 kPa/min at $K = 20.30 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$ and $L_e = 1.67 \text{ cm}$ (Test # 67). With a similar TKE of $18.96 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$ but a smaller length scale $L_e = 1.33 \text{ cm}$ (Test # 60), the fouling rate increased from 0.24 to 0.78 kPa/min. However, with a similar TKE of $19.89 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$ and a larger length scale $L_e = 1.77 \text{ cm}$ (Test # 68), the fouling rate stayed nearly the same at 0.26 kPa/min. This trend was generally representative of the overall results, and further reinforced the existence of an

optimum eddy size beyond which it has no more influence as indicated in section 5.5.5. This optimum eddy size is important for the design of the membrane reactor geometry and membrane module characteristics for fouling consideration.

Figure 6.5 Rate of increase in TMP versus turbulence kinetic energy (K) and eddy length scale (L_e)

6.3.4 Effect of fiber spacing and fiber looseness under turbulence

The above experiments were performed with tight fibers. In HF membrane filtration, fiber spacing (FS) and fiber looseness are also important factors for optimizing performance. Postlethwaite et al. (2004) illustrated that a larger spacing among HF membranes in a membrane module can enhance the permeate flux. Li et al. (2014) also investigated the impact of fiber spacing on fouling performance with membrane vibration, and found that reducing the fiber spacing had an adverse impact on the fouling. However, the influence of fiber bundle characteristics on the effect of turbulence in submerged membrane filtration has not been studied before. Thus, it is examined here to provide the information for membrane module design.

Five different fiber spacing (with fiber layout shown in Figure 6.6) were examined under the integral length scale of $L_e = 1.33$ cm (with $S_r = 60\%$, $S = 16$ mm and $h = 10$ cm), and the turbulence kinetic energy of $K = 5.12 \times 10^{-4}$ and $11.36 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$ with the vibration frequency of $f = 2$ Hz and 3 Hz, respectively. It should be noted that the turbulence characteristics were at the centre of the HF membrane module. The results of the membrane filtration experiments are shown in Figure 6.7. When FS was increased from 3.2 to 6.2 mm, the fouling rate decreased, however a further increase of FS from 6.2 to 10.2 mm caused a jump in fouling rate. This indicated an optimum fiber spacing of FS = 6.2 mm in the present study, which can be explained as follow. Fouling is a result of filtration extraction subject to surrounding hydrodynamic conditions, i.e. turbulent eddies here. When FS was increased from 3.2 to 6.2 mm, the membrane fouling was reduced due to lesser flux competition as well as the scouring effect of eddies that were able to penetrate the bundle with acceleration (due to channelling among the fibers). When FS was further increased to 10.2 mm, however, the channelling effect reduced with the larger space, and as a result membrane fouling was not mitigated as effectively.

Figure 6.6 Layout of fiber bundles, fiber spacing (FS) = (a) 3.2 mm, (b) 4.2 mm, (c) 5.2 mm, (d) 6.2 mm, and (e) 10.2 mm

Figure 6.7 Effect of fiber spacing and looseness on the rate of transmembrane pressure ($dTMP/dt$), $L_e=1.33$ cm, $K =$ (a) $4.72 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$, and (b) $11.36 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$

Fiber looseness is also an important design factor in HF membrane modules which can be adjusted to boost performance. In commercial applications, Mahendran et al. (1997) suggested a range of 1-5% for fiber looseness. The effect of fiber looseness had been studied in conjunction with fouling control mechanisms such as aeration

(Wicaksana et al. 2006, Xia et al. 2013) and membrane vibration (Li et al. 2013, Li et al. 2014). These studies generally pointed out that an increase in fiber looseness would be advantageous due to fiber movement as well as the shear enhancement. The membrane filtration with different fiber looseness was also tested here in turbulence ambient with the kinetic energy of $K = 11.36 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$ (with $S_r = 60\%$, $S = 16 \text{ mm}$, $f = 3 \text{ Hz}$ and $h = 10 \text{ cm}$). As can be seen from the results in Figure 6.7, when the fiber looseness increased from 0 to 2%, the membrane fouling was greatly reduced which was attributed to the dominant effect of fiber movement induced by the looseness in turbulence. However, when the fiber looseness further increased to 3%, no further improvement was observed. This limit was probably due to the fact that the dynamic fiber movement induced by the turbulence eddies had reached a maximum despite the higher looseness.

6.3.5 Energy demand analysis

It has been discussed that the high cost of membrane related technologies, e.g. MBRs, is one of the most important factors which limits the growth of this industry (Schäfer et al. 2001). The major cost is reflected in the energy consumption related to maintenance activities such as aeration, backwashing, etc (Fletcher et al. 2007). Here, the power consumption of the five turbulence generators (solidities from 18% to 60%) under different vibration frequencies of 1-5 Hz was measured using a clamp meter (vibration stroke was fixed at 16 mm). The results are plotted in terms of TKE in Figure 6.8. Generally, either larger solidities or frequencies induced higher TKE and larger power consumption. In addition, when TKE was below $5 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$, the power increased very fast with TKE, which was due to the lower efficiency of the turbulence generators with either small solidities or low vibration frequencies. When TKE was larger than $5 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$, however, the power increased much slower. The results showed that it would be more advantageous to operate turbulence generators with large TKEs if there is a corresponding significant gain in fouling reduction.

Figure 6.8 Relationship between power consumption and turbulence kinetic energy (K)

The trade-off between the power consumption due to turbulence dissipation and the membrane fouling rates ($S = 16 \text{ mm}$, $h = 10 \text{ cm}$) is further illustrated in Figure 6.9. Generally, higher power consumption resulted in lower membrane fouling rate for all the experiments. For example, when the power increased from 15.8 to 20.3 W, the membrane fouling rate reduced from 0.84 to 0.48 kPa/min, i.e. 66% reduction. Li et al. (2014) reported that a 21W power consumption in air bubbling system would lead to only 10% fouling reduction with the same feed solution and membrane fibers used in this study. Comparing the ratio of dissipated power to permeate flux between these two cases, it can be concluded that the energy consumption for fouling mitigation using turbulence generators would be lower than air bubbling.

Since the power consumption is a major indicator of the overall operational cost, it is beneficial to demonstrate how the design parameters can be optimized with a energy demand analysis, which is given in the form of an example here. Assume that a maximum fouling rate of 0.6 kPa/min is deemed acceptable. Table 7.2 shows that

the fouling rate in fifteen turbulence conditions met this target. These conditions can be evaluated in terms of power consumption (the condition with the lowest power consumption would indicate the most desirable operating conditions). In this case, $TKE = 5.72 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$ and $L_e = 1.67 \text{ cm}$ (with $S_r = 60\%$, $S = 16 \text{ mm}$, $f = 3 \text{ Hz}$ and $h = 14 \text{ cm}$) together yielded the lowest energy consumption that led to $\frac{dTMP}{dt} = 0.46 \text{ kPa/min}$. Such energy demand analysis can be performed given the statistical dependence, to minimize the energy wastage towards membrane fouling control.

Figure 6.9 Power consumption of the perforated plates versus the rate of increase in transmembrane pressure ($dTMP/dt$) for different solidities

6.4 Conclusion

In this chapter, the effect of turbulence generated by vibrating perforated plates on the fouling reduction of submerged hollow fiber membranes was examined in a comprehensive manner. The turbulence generation with different solidities was first evaluated using post processing of velocities measured by Particle Image Velocimetry. It was found that the turbulence kinetic energy strongly depended on the solidity. Integral length scale was also examined and it was also found to increase with the solidity.

The statistical analysis of fouling dependence on the turbulence characteristics indicated that the fouling rate is cross dependent on both factors. Higher turbulence kinetic energy is generally more favourable, while an optimal eddy length scale exists for fouling consideration. The effect of hollow fiber bundle characteristics on membrane filtration performance in turbulence was also examined. An optimum fiber spacing was observed which yielded the most efficient filtration, which might be due to the synergetic effect of filtration extraction and the penetrating interactions between the turbulence eddies and hollow fiber membranes. A fiber looseness of 2% improved the performance to a maximum degree. Finally, given the statistical dependence, the energy demand evaluation between the energy consumption with turbulence and the improved productivity with reduced membrane fouling is presented.

Chapter 7 Effect of jets on fouling control of submerged hollow fiber membranes

7.1 Introduction

Earlier, it has been discussed that different types of fouling control practices have been implemented in both small scale and large scale industrial units. The selection of the proper fouling control strategy is constrained by the specific requirements of the system. For instance, in most of the industrial operations, the volume of permeate required per day is relatively high, hence, having fluxes less than a certain limit is not feasible (Mutamim et al. 2013). As previously mentioned in section 2.2, aeration is the most common practice in fouling mitigation, however, in anaerobic membrane bioreactors clearly it cannot be used to alleviate fouling, thus other techniques such as crossflow, vibration, turbulence, or ultrasound need to be employed (Liao et al. 2006). Although shear stress imposed by crossflow is useful for this purpose, having crossflow as fouling prevention technique has its own complications. It is known that inorganic substances and fine biological colloids are major contributors to the membrane fouling in anaerobic filtration (Choo and Lee 1996). The implications of particle size are also discussed previously (see section 3.3.1). Choo and Lee (1998) discussed that crossflow would break up large biological flocs and create finer particles that is unfavorable for fouling control in anaerobic reactors.

An alternative to crossflow in anaerobic membranes and membrane reactors in general can be turbulence. In Chapters 5 and 6, the benefits of inducing turbulence have been discussed. As discussed in Chapter 4, there are different means of inducing turbulence, including the use of jets. Jet turbulence is a boundary layer flow originating from a source of momentum. Jet flows frequently happen in nature and engineering application whenever a fluid with different characteristics specially velocity enters another fluid ambient. The jet flow is characterized by a number of parameters including nozzle diameter, discharge velocity, discharge orientation, and

ambient characteristics such as ambient velocity, ambient depth (in case of discharge in water). It is typically separated into developing zone and fully established region (Figure 7.1). The advantage of jet turbulence compared to grid turbulence is that the discharge velocity of jet can be adjusted relatively easier to control the turbulence features. Besides, the driving force for the jet that depends on the source of momentum (e.g. pump) can be controlled for better efficiency in energy dissipation.

Figure 7.1 Schematic representation of a jet penetrating in a fluid at rest (Law and Wang 2000)

In membrane applications, in-situ water jets have not been used for fouling prevention so far, although the use of air jet has been introduced as a potential means of membrane cleaning (Zha and Jordan 2005). Other researchers have introduced water jets as an external means for the physical cleaning of membrane (Hai et al. 2008). In this study, a novel experimental setup was designed and tested. The setup allowed us to investigate the use of in-situ water jets on the fouling prevention of submerged hollow fiber membranes, by monitoring the rate of membrane fouling with various jet velocities. In addition, the combined effect of grid turbulence and constant jets

was thoroughly examined in terms of experimental impact and statistical significance on fouling. In the following, the experimental setup and the results are presented.

7.2 Experimental setup

The experimental setup consisted of a membrane filtration setup, and a jet generator. The membrane filtration setup was the same as previously described in section 5.3. The hollow fiber membrane module was placed in the test tank as can be seen in Figure 7.2. The constant jet generator included a submersible pump with a maximum flowrate of 125 l/min, a flow meter and a frame consisting sixteen jet nozzles with a 0.5 mm diameter. The permeate flux was controlled to be 1% accuracy by monitoring and automatically adjusting the TMP to yield a constant volume of permeate recorded at an interval of 5 s. A filter was embedded in the submersible pump to prevent the solid particles from entering and causing clogging. The discharge velocity of the jet could be controlled using the flow meter. The configuration of jet nozzles is shown in Figure 7.3. The jet frame was fixed on top of the membrane module (see Figure 7.4). Yeast suspensions were used for the membrane filtration. The preparation of the feed suspensions was described in section 4.4.1.

Figure 7.2 Schematic diagram of experimental setup for constant jet experiments

Figure 7.3 Layout of constant jet nozzles

Figure 7.4 Membrane module and jet nozzle frame

7.3 Results and discussion

7.3.1 Constant jet experiments

The hollow fiber membrane filtration was conducted under various discharge jet velocities. It was observed that at the discharge velocity of 10 m/s, TMP did not increase within 60 minutes which indicated that no fouling occurred. The expectation was that the higher discharge rate would be more effective in fouling control, since the shear rate induced by jet on the membrane surface was higher. Figure 7.5 shows the results of the experiments which are the confirmation of expected outcome.

Figure 7.5 Rate of change of TMP at various discharge velocities of jet (V_j)

7.3.2 Critical flux variation

The effect of discharge velocity variation and also turbulence characteristics of the critical flux of hollow fiber membranes used in this study was investigated. Critical flux was measured using the concept of flux stepping. In the flux stepping method, critical flux can be obtained by measuring the changes in TMP in a limited period of time (5-20 mins) by increasing the flux step by step, as can be seen in Figure 7.6. When the TMP in the defined period of time rises steeply the critical flux is obtained. The changes in critical flux with the discharge velocity of jet can be seen in Figure 7.7. The result indicated that a higher discharge velocity would lead to a higher critical flux. This finding was in agreement with the fact that critical flux was higher at higher shear rate in crossflow filtration (Le-Clech et al. 2003).

Figure 7.6 The concept of flux stepping method for critical flux determination

Figure 7.7 Critical flux (J_{crit}) variation of hollow fiber membrane filtration with discharge velocity of jet

The critical flux was also measured for the membrane filtration under various turbulent ambient. The effect of both turbulence kinetic energy (TKE) and eddy length scale were investigated. In Chapter 5, it was observed that at higher TKEs the filtration performance of membrane improved. This improvement in terms of critical flux can be observed in Figure 7.8. TKE and L_e quantified in chapter 5 were utilized here. A higher TKE would increase the critical flux. It was observed that at TKE lower than $4.7 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$, the critical flux increased rapidly with K. This can be due to inefficiency of low kinetic energy in fouling mitigation that was discussed in Chapter 6. At higher values of TKE, the critical flux rises at a relatively lower rate. The results of critical flux determination at different eddy length scales are shown in Figure 7.9. As can be seen in this figure, the critical flux initially increases when the length scale increases to 1.67 cm after which the increase no longer occurs. The critical flux reaches maximum at $L_e = 1.67$ and then decreases. The presence of a maximum critical flux when varying the length scale was similar to the ideas of an optimum eddy length scale that was discussed earlier in section 4.6.

Figure 7.8 Critical flux (J_{crit}) variation of hollow fiber membrane filtration with turbulence kinetic energy (K)

Figure 7.9 Critical flux (J_{crit}) variation of hollow fiber membrane filtration with eddy length scale (L_e)

7.3.3 Combination of constant jet and turbulence induced by perforated plate

The implementation of perforated plate turbulence and a constant jet have been shown to be effective in performance enhancement of HF membrane filtration. The combined effect of these two is investigated in this chapter. A total of eight experiments that are listed in Table 7.1 were conducted. In these experiments the turbulence kinetic energy, eddy length scale and constant jet discharge velocity had each two levels (low (-) and high (+)). The results of membrane filtration experiments for these experiments conditions are shown in Figure 7.10. Generally, it can be seen that when any of the factors were at high level (+) the rate of TMP rise was lower. With $K = 25.0 \times 10^{-4} m^2 s^{-2}$, $L_e = 1.67$ cm and $V_j = 5$ m/s (all the factor at high level: ++++) no fouling was detected in 60 minutes (Figure 7.10 (d)). However, if any of the factors was at a low (-) level instead, the fouling was observed.

Table 7.1 Experimental conditions for combined effect of constant jet and turbulence induced by a perforated plate

	S_r (%)	f (Hz)	S (mm)	h (cm)	$K \times 10^{-4}$ (m ² ·s ⁻²)	L_e (cm)	V_j (m·s ⁻¹)
1	60	4	8	10	5.88	1.33	3
2	60	4	8	10	5.88	1.33	5
3	60	4	16	10	25.0	1.33	3
4	60	4	16	10	25.0	1.33	5
5	60	3	16	14	5.88	1.67	3
6	60	3	16	14	5.88	1.67	5
7	60	5	16	14	25.0	1.67	3
8	60	5	16	14	25.0	1.67	5

Since each factor had two levels these experiments can be categorized as 2^k experiments. Statistical analysis using factorial analysis of these 2^k experiments was performed. In the statistical analysis, the effect of a factor is indicated by subtracting the response value when a factor is at its high level (+) from the response value when factor is at its low level (-). The higher the difference between these values, the more influential the factor is on the response. If the effects of one factor are different at different levels of another factor, there is interaction between these two factors. This means that the impact of different factors needs to be considered together when they have interactions. In the experiments, the results of the analysis of variance can be seen in Table 7.2 indicating that all the factors had significant impact on the variation of response values. The significance of turbulence kinetic energy and eddy length scale confirmed the results of ANOVA in Chapter 6. The discharge jet velocity had also great influence on the outcome. The interesting finding was that although the three factor interaction $KL_e V_j$ had the lowest effect (as it is expected in the statistical analysis), it had considerable effect on the output as $F_0 > F_{\alpha, V_1, V_E}$.

Figure 7.10 Changes in TMP with time with $L_e = 1.33 \text{ cm}$: (a) and (b) $K = 5.88 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$, (c) and (d) $K = 25.0 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$

Table 7.2 ANOVA table for statistical analysis of effect of turbulence kinetic energy (K), integral length scale (L_e) and discharge jet velocity (V_j), and their cross interactions on the fouling rate of hollow fiber membranes

Source of variation	Sum of squares $\times 10^{-2}$	Degrees of freedom	Mean square $\times 10^{-2}$	F ₀	F _{α, V_1, V_E}
K	18.00	1	18.00	806.13	4.49
L_e	47.25	1	47.25	2115.97	4.49
V_j	24.67	1	24.67	1104.79	4.49
KL_e	1.14	1	1.14	51.27	4.49
KV_j	0.78	1	0.78	34.89	4.49
$L_e V_j$	2.36	1	2.36	105.77	4.49
$KL_e V_j$	0.13	1	0.13	6.03	4.49
Error	0.36	16	0.02		
Total	94.70	23	94.70		

7.4 Conclusion

In this chapter, the effect of a constant jet on the fouling performance of hollow fiber membrane filtration was investigated. The higher jet velocity was found to be more effective in fouling control due to higher shear rate induced, and also led to a higher critical flux. It was also found that critical flux increased with turbulence kinetic energy. On the other hand, the critical flux had a maximum with eddy length scale beyond which it actually declined.

The statistical analysis of combination of perforated plate turbulence and constant jet indicated that the three factors under study, turbulence kinetic energy, eddy length scale and discharge jet velocity had significant impact on the fouling performance of

hollow fiber membrane filtration. The interaction between every two factors and the three-factor interactions were also found to be important in the performance enhancement. The conducted experiments at presence of perforated plate turbulence and jet revealed the improvement of fouling due to inclusion of jet turbulence.

Chapter 8 Turbulence pressure fluctuations

8.1 Introduction

In Chapter 5, it was discussed that turbulence parameters such as turbulence kinetic energy and eddy length scale are important hydrodynamic factors that can influence the performance of a membrane filtration system. It was also mentioned in Chapter 6 that identifying the state of turbulence can help optimize the energy consumption in the system. So far, the non-intrusive method of Particle Image Velocimetry was used to quantify the turbulence. However, the use of PIV cannot be expanded to harsh environmental applications due to several limitations. First and most obvious, the reactor walls need to be transparent. In addition, PIV cannot be performed in mixtures with the presence of high particle concentrations. In the past, various other measurement techniques, such as Laser Doppler Anemometry (LDA) and ultrasound, have also been developed to quantify the hydrodynamic characteristics inside the reactor (Lund and Rojas 1989, Tropea 1995). However, almost all suffer from similar limitations as PIV. Hence, it is reasonable to look for alternative approaches for quantification purposes.

In this study, the pressure sensing measurement technique which was attempted in Xia (2013) for clean water with air bubbling is further developed in this study with additional mixed liquor, as it can potentially serve as an attractive alternative to be applied widely in the industry to pursue system optimization and energy minimization, due to its easy implementation, low operating cost as well as robustness. The analysis of pressure fluctuation signals (PFS) is a promising approach to identify the hydrodynamics of the multiphase reactors. The measurement of the pressure signals is easier to implement and cheaper compared to other techniques. However, the main drawback is that the pressure fluctuations cannot be easily converted to the velocity information due to the turbulent nature of the flows inside the multiphase reactors. So far, PFSs have been used to quantify the flow

characteristics in bubble column reactors mainly in the high air flow regimes (Al-Masry et al. 2007). To the knowledge of the author, the use of low air flow rates was only limited to a few studies including Lin et al. (2001) and Xia (2013). In addition, the previous studies mainly focused on the static pressure fluctuations, and did not include the dynamic pressure. In the literature, the main interest has been given to identify the transition from homogenous to heterogeneous regime. This chapter includes the presentation of the experimental procedure of the data collection for the pressure fluctuation signals, the data analysis itself. These work are to support the objective to further develop a novel dynamic pressure sensing approach to quantify the flow characteristics of multiphase reactors.

8.2 Analysis

The main objective in the theoretical derivation of the governing equation is to link the pressure fluctuations to other measurable hydrodynamic characteristics such as velocity distribution, and to establish a relationship between the dynamic pressure and other turbulence parameters such as TKE.

The theoretical derivation begins with the Navier-Stokes equation as follow (Pope 2000):

$$\frac{\partial u_i}{\partial t} + \rho \frac{\partial}{\partial x_j} (u_i u_j) = -\frac{\partial p}{\partial x_i} + \mu \frac{\partial^2 u_i}{\partial x_j \partial x_j} \quad (8.1)$$

According to the Reynolds decomposition, each quantity could be written as a summation of the mean and fluctuating values (over bar and prime are indication of mean and fluctuation, respectively), therefore the velocity and pressure can be written as:

$$u_i = \bar{u}_i + u'_i \quad (8.2)$$

$$p = \bar{p} + p' \quad (8.3)$$

where u_i is the velocity in the Cartesian coordinates ($i=1, 2, 3$), and p is the instantaneous pressure. Substituting (8.2) and (8.3) into (8.1), it can be obtained that:

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial u'_i}{\partial t} + \rho \frac{\partial}{\partial x_j} (\bar{u}_i \bar{u}_j + u'_i \bar{u}_j + \bar{u}_i u'_j + u'_i u'_j) = -\frac{\partial \bar{p}}{\partial x_i} - \frac{\partial p'}{\partial x_i} + \mu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} + \mu \frac{\partial^2 u'_i}{\partial x_j \partial x_j} \quad (8.4)$$

Time averaging of the Navier-Stokes equation yields (Pope 2000):

$$\frac{\partial \bar{u}_i}{\partial t} + \rho \frac{\partial}{\partial x_j} (\bar{u}_i \bar{u}_j + \overline{u'_j u'_i}) = -\frac{\partial \bar{p}}{\partial x_i} + \mu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} \quad (8.5)$$

Equation (8.5) is known as Reynolds averaged Navier-Stokes equation (RANS).

Subtracting (8.5) from (8.4) and after rearranging the terms, we have:

$$\frac{\partial p'}{\partial x_i} = \mu \frac{\partial^2 u'_i}{\partial x_j \partial x_j} - \frac{\partial u'_i}{\partial t} - \rho \frac{\partial}{\partial x_j} (\bar{u}_i u'_j + \bar{u}_j u'_i + u'_i u'_j - \overline{u'_i u'_j}) \quad (8.6)$$

Multiplying both sides of equation (8.6) by p' results in:

$$p' \frac{\partial p'}{\partial x_i} = p' \mu \frac{\partial^2 u'_i}{\partial x_j \partial x_j} - p' \frac{\partial u'_i}{\partial t} - p' \rho \frac{\partial}{\partial x_j} (u'_i \bar{u}_j + \bar{u}_i u'_j + u'_i u'_j - \overline{u'_i u'_j}) \quad (8.7)$$

When time averaging equation (8.7), it can be simplified by making a number of assumptions:

1. The correlation between pressure fluctuations and first and second order derivatives of velocity fluctuations is negligible (Tennekes and Lumley 1972):

$$\overline{p' \frac{\partial^2 u_i'}{\partial x_j \partial x_j}} \cong 0 \quad (8.8)$$

$$\overline{p' \rho \frac{\partial u_i' u_j'}{\partial x_j}} \cong 0 \quad (8.9)$$

$$\overline{p' \rho \frac{\partial \overline{u_i u_j'}}{\partial x_j}} \cong 0 \quad (8.10)$$

2. For simplification purposes, it is also assumed:

$$\overline{p' \frac{\partial u_i'}{\partial t}} = 0 \quad (8.11)$$

Using the above assumptions, we have:

$$\overline{p' \frac{\partial p'}{\partial x_i}} = -\rho p' \frac{\partial}{\partial x_i} (\overline{u_i' u_j'} - \overline{u_i' u_j'}) \quad (8.12)$$

Since $\overline{p' \frac{\partial}{\partial x_i} (\overline{u_i' u_j'})} = 0$, and Reynolds Shear Stress are negligible as discussed in

Chapter 5 and also in the literature (Lee et al. 2001), equation (8.12) can be rewritten as:

$$\overline{p' \frac{\partial p'}{\partial x_i}} = -\overline{\rho p' \frac{\partial}{\partial x_i} (u'_i u'_j)} \quad (8.13)$$

This yields:

$$\overline{p' \frac{\partial p'}{\partial x_i}} = 2\overline{\rho p' \frac{\partial K}{\partial x_i}} - \overline{\rho p' \frac{\partial}{\partial x_i} (u'_i u'_j)} \quad (8.14)$$

Since the Reynolds stresses are zero $\frac{\partial}{\partial x_i} (u'_i u'_j) = 0$, then:

$$\overline{p' \frac{\partial p'}{\partial x_i}} \sim 2\overline{\rho p' \frac{\partial K}{\partial x_i}} \quad (8.15)$$

This equation indicates that gradient of turbulence kinetic energy is related to the dynamic pressure fluctuations at a location where pressure measurements were conducted. Thus, the changes in the dynamic pressure fluctuation can serve to predict the changes in turbulence kinetic energy, and as a means to identify the changes in the system behavior.

8.3 Experiments

8.3.1 Experimental setup

Figure 8.1 shows the schematic diagram of the experimental setup for the dynamic pressure measurements. The setup consisted of a bubble column reactor, a

submersible pressure sensor and a data logging system. The submersible pressure sensor (a Kistler Instrument's Product) was connected to a power supply box (Kistler Instrument Pte Ltd), which served the function of signal activation. The power supply box was further linked to a data acquisition system (DAQ) (a National Instrument's product).

Figure 8.1 Schematic diagram of the experimental setup for the PFS measurements

The PFSs were collected and stored in a computer system. The bubble column had an inner/outer diameter (ID/OD) of 142/152 mm. The height of the column was 1.3 m. The column had 9 holes with a diameter of 27 mm on its side, with 0.1 m interval. Each hole had a diameter of 27 mm. The submersible pressure sensor was placed in the BC reactor through these holes. The submersible pressure sensor had a diameter of 26.9 mm and a length of 127 mm. It was capable of data-logging with a response time of 5×10^{-6} s. The range of pressure measurement was from 0 to 0.2 bar, and the

output was based on the voltage ranging from 0 to 10 V. Two solutions, namely, clean tap water and mixed liquor, were used, and the solution was filled up to one meter height. The properties of mixed liquor were different in the different experiments as shown in table 8.1.

Table 8.1 Properties of mixed liquor for different experiments

Test Number	COD (mg/l)	TSS (mg/l)	VSS (mg/l)
(1)	128	7.48	5.76
(2)	71	7.38	5.44
(3)	56	6.58	5.22
(4)	166	7.7	5.98
(5)	359	9.5	7.36
(6)	19	3.24	2.7
(7)	140	2.58	2.34

8.3.2 Methodology

The PFS data collections were carried out for two-phase and three-phase systems at three different locations, which represented three different heights in the bubble column (BC) reactor. The pressure inside the BC reactors was subjected to a wide range of fluctuations. Figure 8.2 shows a sample of instantaneous pressure at 0.3 m from the bottom of the reactor with 0.5 L/min air flow rate. It can be seen that the value of dynamic pressure varied significantly in this system. The locations where the data were taken, were at heights of 0.3 m, 0.5 m and 0.7 m from the bottom of the reactor (referred as location (1), (2) and (3) respectively). The air flow rate increased from 0 to $0.42 \text{ m}^3 \text{ s}^{-1}$ (2.5 L/min) at an interval of $0.017 \text{ m}^3 \text{ s}^{-1}$ (0.1 L/min) with the instantaneous dynamic pressure signals recorded. Before carrying out the

experiments, accuracy verification was done to make sure that the mean value of the pressure was stable.

Figure 8.2 Instantaneous pressure at 0.3m from the bottom of the bubble column with the air flow rate of 0.5 L/min

In this study, three experiments were conducted with tap water as solution to confirm the sensor's accuracy. Figure 8.3 shows the result of the accuracy verification experiments for five different air flow rates. The results indicated that the differences between the mean values were less than 1%, therefore the readings were stable. As mentioned previously, the sensor was placed in the reactor through one of the nine holes on the side of the reactor. The tip of the sensor had a distance of 4 cm from the wall boundary of the reactor. This distance was set to eliminate the wall effects. When the sensor was properly placed, the air compressor was switched on to supply air continuously into the reactor. The sampling rate was set to 100 Hz, and the total number of the data collected was 10000 for each experiment which corresponded to the duration of 100 s. The number of data points was large enough to make sure that the necessary information of the flow regime was captured. Sasic et al. (2005) also used the frequency of 100 Hz as the maximum frequency of sampling. According to

Johnsson et al. (2000), this frequency should be sufficient to determine the dominant frequency of fluidized beds. Post-processing was needed to extract the hydrodynamic information from the dynamic pressure signals.

Figure 8.3 Comparison of the mean pressure values of three experiments at five different air flow rate (Location of pressure sensor in Data sets 1-3: 0.5 m)

8.4 Results and discussion

The results of pressure fluctuations are analyzed in this section. It should be noted that the analysis approaches mainly followed Xia (2013).

8.4.1 Statistical Analysis, mean and standard deviation

Mean and standard deviation were two statistical parameters calculated in this report. The instantaneous pressure values were obtained using the submersible pressure sensor. The dynamic pressure values were extracted using:

$$p' = p - \bar{p} \quad (8.15)$$

8.4.1.1 Mean

For discrete pressure signals the mean (η) represented the average of the signals, and it is also a representation of the center of the data distribution, as follow (Smith 1997):

$$\eta = \frac{\sum_{i=1}^N y_i}{N} \quad (8.16)$$

where N is the number of data (pressure signals) and y_i is the magnitude of each pressure signal. Figure 8.4 displays the mean pressure changes against the air flow rate in the clean tap water and mix liquor solutions. It can be seen that the mean pressure increased as the air flow rate rose for both solutions. Xia (2013) explained that the air flow rate correlates with the liquid level, therefore as the air flow rate increases, the water level also rises corresponding to the increase of static pressure. The comparison between the values of mean pressure in water and mixed liquor indicated that these values were slightly higher in water. Figure 8.5 shows the comparison of the mean pressure for both solutions at the 0.5 m height of BC reactor. The presence of solid particles caused the liquid level rise to be lower than without the particles. This indicates that the difference of the mean pressures for the clean tap water and mixed liquor would likely depend on the solid particle characteristics.

Figure 8.4 Mean pressure ($\bar{p}$) for (a) tap water and (b) mixed liquor at three locations

Figure 8.5 Comparison of the mean pressure values between water and mixed liquor (ML)

8.4.1.2 Standard deviation

Standard deviation (STD) is one of the most common methods of signal analysis. It is an indication of the amount of dispersion from the mean value, and is computed as:

$$STD = \sqrt{\frac{\sum (y_i - \bar{y})^2}{N}} \quad (8.17)$$

where, y_i is the individual data, $\bar{y}$ is the mean value and N is the total number of the data. Figure 8.6 displays the STD of the dynamic pressure versus air flow rate for tap water in the three experiments. As can be seen in this figure, there was a change in the gradient of the standard deviation which corresponded to a change in the flow regime for the tap-water solution. Figure 8.7 shows STD of mixed liquor against the air flow rate for all the variations of ML. The change in the gradient of STD was only

observed for the tap water solution, while in the mixed liquor the trend did not follow the same pattern.

The STD of the pressure fluctuations typically increased as the air flow rate increased, until a certain air flow rate was reached. In the experiments, the gradual increase of the STD was expected unless there was a change in the flow regime. According to Lin et al. (2001), there were two transitions in the flow regime. As the superficial gas velocity increased, the standard deviation continued to rise after the first transition until the second transition happened. The first transition in Lin et al. (2001) agreed with the transition in the current experiments which occurred when the air flow rate reached $0.13 \text{ m}^3 \cdot \text{s}^{-1}$ (0.8 L/min), and represented the transition from pseudo-laminar flow to turbulent flow. As Lin et al (2001) explained when the flow behavior changes from laminar to turbulent the pressure fluctuations would change due to change in bubble size and interactions. Xia (2013) measured the pressure fluctuations in similar conditions at two locations. It was concluded that the existence of a local maximum in the standard deviation curves, implied that the turbulence had reached the saturation point. In the present study, the STD had similar behavior after transition.

The definition of turbulence for single phase flow is relatively straightforward. However, there is no exact definition for turbulence in multiphase flows. The reason why the flow before transition is called “pseudo-laminar”, is that the dominant phase inside the BC reactors goes through a series of changes in the flow behavior. When the air bubbles are just introduced in the reactor, the dominant phase starts to move. Intuitively, with a low air flow rate, the flow is primarily laminar, but experiences sporadic turbulence when the bubble rises. It is therefore not exactly turbulent, nor fully laminar (because of the involvement of air phase).

Figure 8.6 Standard deviation of pressure fluctuations for tap water: (a) 0.3 m, (b) 0.5 m, and (c) 0.7 m

In three-phase reactors (mixed liquor solutions), the flow is much more complex than a two-phase reactor, and the detection of a transition point in the flow regime cannot be achieved similar to a two-phase system due to the complexities. As can be seen in Table 8.1, the characteristics significantly differed in every experiment. Therefore, it was quite challenging to identify when the change in the flow regimes occurred within the range of air flow rate tested. As discussed, the impact of solid particles on the behavior of pressure signals is also not yet fully defined. However, a few features of the mixed liquor solution are considered to be likely important in the STD's behavior, i.e. size of solid particles, concentrations and, possibly biological reactions which might occur and modify the characteristics. A change of solution properties could therefore lead to a drastically different hydrodynamic behavior inside the reactor.

Comparisons were made for the STD of different experiments to observe the consistency of the trend. Figure 8.8 compares the STD in three different experiments (sample #5, 6, and 7) for ML.

8.4.2 Chaotic Analysis: Hurst exponent, Lyapunov Exponent and Correlation Dimension

Chaotic analysis has been used by many researchers who study pressure signals in the bubble column reactors and fluidized beds. In the present study, three chaotic parameters were calculated: Hurst exponent, Lyapunov exponent and Correlation dimension. They are described in the following.

Figure 8.7 Standard deviation of pressure fluctuations for mixed liquor (sample # 4)
solution: (a) 0.3 m, (b) 0.5 m, and (c) 0.7 m

Figure 8.8 Comparison of the Standard deviations of pressure fluctuations for mixed liquor (sample # 5, 6, and 7): (a) 0.3 m, (b) 0.5 m, and (c) 0.7 m

8.4.2.1 Hurst exponent

Hurst exponent can be used to identify the long term memory of time series analysis. Drahoš et al. (1992) used the Hurst exponent to determine the basic hydrodynamic regime of BC reactors computed from the rescaled range. The method of computation is explained in Drahoš et al. (1992). It is briefly summarized in the following:

$$\text{Mean} \quad \overline{x_k} = \frac{1}{\tau} \int_{t_k}^{t_k+\tau} x(t) dt \quad (8.18)$$

where $\overline{x_k}$ and $x(t)$ are mean and instantaneous values, respectively.

$$\text{Standard deviation (} S_k \text{)} \quad S_k = \left\{ \frac{1}{\tau} \int_{t_k}^{t_k+\tau} [x(t) - \overline{x_k}]^2 dt \right\}^{0.5} \quad (8.19)$$

$$\text{Accumulated departure} \quad X_k = \int_{t_k}^{t_k+\tau} [x(u) - \overline{x_k}] du \quad (8.20)$$

X_k is the accumulated departure.

$$\text{Range (} R_k \text{)} \quad R_k = \max X_k(t) - \min X_k(t) \quad (8.21)$$

$$\text{Rescaled range} \quad \left(\frac{R}{S} \right)_k = \frac{R_k}{S_k} \quad (8.22)$$

where R and S are range and standard deviation, respectively.

The average of (R/S) can be obtained for the N sub-periods as:

$$\left(\frac{R}{S}\right)_T = \frac{1}{N} \sum_{k=1}^N \left(\frac{R}{S}\right)_k \quad (8.23)$$

The evolution of $\left(\frac{R}{S}\right)_T$ with different sub-period length T can be tracked as:

$$\left(\frac{R}{S}\right)_T = c.T^H \quad (8.24)$$

c is a constant. The Hurst exponent (H) can then be computed as:

$$H = \frac{d(\ln(R/S)_T)}{d(\ln T)} \quad (8.25)$$

In this study, the Chaos Data Analyzer (CDA) software (Figure 8.9) developed by Sprott (2003) was utilized for the computation of chaotic parameters. Several kinds of fractal components can be computed using this software.

Figure 8.9 Chaos data analyzer

The Hurst exponent is equal to 0.5 for random signals with no correlation between past and future increments. An H value larger than 0.5 implies the persistent behaviour of the time-series, i.e., an increase in the time series is possibly superseded by another increase and vice versa. On the other hand, an anti-persistence data has Hurst exponent less than 0.5 indicates, i.e. the preceding event will be reversed (Briens et al. 1997). Figure 8.10 (a) and (b) show the persistent and anti-persistent times series.

Figure 8.10 (a) persistent time series ($H=0.95$), and (b) an anti-persistent time series ($H=0.043$) (Hurst 1951)

Figures 8.11 and 8.12 show the development of Hurst exponent in the present experiments against the air flow rate in tap water and mixed liquor. The values of H did not exceed 0.5 in present experiments, which signified the negative correlation of dynamic pressure signals. The small value of H also suggested that the flow inside the reactor was highly irregular and unsteady. Rather than long-term correlation, the PFSs were towards short-term correlated, which also confirmed the chaotic nature of the system. Xia (2013) also reported that the two-phase system is highly anti-persistent. She explained that for the large air flow rates, the magnitude of H approached a plateau and the level of chaotic instability was not further enhanced. This behavior was also observed in the present experiments as can be seen in the figure.

Figure 8.11 Hurst exponent (H) of pressure fluctuations for tap water: (a) 0.3 m, (b) 0.5 m, and (c) 0.7 m

Figure 8.12 Hurst exponent (H) of pressure fluctuations for mixed liquor (sample # 4): (a) 0.3 m, (b) 0.5 m, and (c) 0.7 m

8.4.2.2 Largest Lyapunov exponent

A system can be characterized as dissipative or conservative using the largest Lyapunov exponent (LLE $\sim \lambda$) that signifies the instability of a dynamic system. The rate of separation of two trajectories is explained by LLE. The number of Lyapunov exponent is equal to the dimension of the phase space. If the dynamic system is chaotic, at least one of the Lyapunov exponents is positive (Ruelle 1979, Wolf et al. 1985). The value of $\lambda < 0$ corresponds to a dissipative system, with an indication of periodic orbits. LLE being negative means system has more tendency towards stability (Elert 2007). For a system to be stable, all the values of LLE need to be negative. $\lambda > 0$ is a characteristic of a conservative system which is chaotic. If there is one positive LLE exists in the system, then the system is unstable. Finally, if $\lambda = 0$, firstly the system is conservative and secondly it is in stable (steady state) mode.

As can be seen in Figures 8.13 and 8.14, λ was always positive in the present experiments, therefore the system is chaotic. Xia (2013) hypothesized that LLE reaching a plateau implies the establishment of the turbulence saturation conditions in the system. The hypothesis is yet to be fully verified. The method of computation is explained in (Rosenstein et al. 1993). It is briefly summarized in the following:

$$\text{Average divergence:} \quad d(t) = Ce^{\lambda t} \quad (8.26)$$

where C is a constant.

$$\text{Reconstructed trajectory:} \quad X = (X_1 \ X_2 \ \dots \ X_M)^T \quad (8.27)$$

$$\text{State of the system at discrete time } i: \quad X_i = (x_i \ x_{i+J} \ \dots \ x_{i+(m-1)J}) \quad (8.28)$$

For an N -point time series, the relationship between constants of M , N , m and J is:

$$M = N - (m - 1)J \quad (8.29)$$

$$\text{Distance from the nearest neighbor point: } d_j(0) = \min_{X_{\hat{j}}} \|X_j - X_{\hat{j}}\| \quad (8.30)$$

$$\text{Lyapunov exponent: } \lambda_l(i) = \frac{1}{i\Delta t} \frac{1}{(M-i)} \sum_{j=1}^{M-i} \ln \frac{d_j(i)}{d_j(0)} \quad (8.31)$$

8.4.2.3 Correlation Dimension

As van den Bleek and Schouten (1993) suggested, small changes in initial conditions greatly impact chaotic systems which are non-linear and deterministic. Depending on the rate which the difference develops, three kinds of systems are introduced (Vial et al. 2000): completely ordered, stochastic and chaotic systems. A system is completely ordered when the rate of growth is zero. Stochastic systems, on the other hand, have infinite rate of growth, and for a chaotic system this rate is strictly positive. Correlation dimension is among the most popular fractal dimension methods for chaotic analysis of a one dimensional signal which seems random. Lin et al. (2001) claimed that a sudden change in chaotic measures, e.g. correlation dimension, corresponds to a transition in the flow regime.

Figure 8.13 Largest Lyapunov exponent (LLE) of pressure fluctuations for tap water:
(a) 0.3 m, (b) 0.5 m, and (c) 0.7 m

Figure 8.14 Largest Lyapunov exponent (LLE) of pressure fluctuations for mixed liquor (sample # 4): (a) 0.3 m, (b) 0.5 m, and (c) 0.7 m

When the behavior of the system is reconstructed in a d dimensional space where d corresponds to the state variables of the system, (i.e. embedding dimensions), the computation of correlation integral and correlation dimension is possible (Vial et al. 2000). The trajectories in this space converge to what is called the attractor. The reconstruction procedures of attractors from a time series $x(t)$ is described by Takens (1981).

$$\xi_i = [x(t_i), x(t_i + \tau), x(t_i + 2\tau), \dots, x(t_i + (d-1)\tau)]^d \quad (8.32)$$

where τ represents the time delay. Correlation integral (C_D) is used to characterize the correlation dimension, and it is computed using the following equation:

$$C_D(r) = \lim_{n \rightarrow \infty} \left[\frac{1}{N^2} \sum_{\substack{i,j=1 \\ i \neq j}}^N He(r - \|\xi_i - \xi_j\|) \right] \quad (8.33)$$

where He is Heaviside step function (for $r < 0$, $He = 0$ and for $r \geq 0$, $He = 1$). The correlation dimension (D_c) and the correlation integral have a power-law relationship in a deterministic system.

$$C_D(r) \propto r^{D_c} \quad (8.34)$$

Hu et al. (2009) suggested that a change in the slope of the correlation integral plots corresponds to a transition in the flow regime. Figures 8.15 and 8.16 show the correlation dimensions against the air flow rate for tap water and mixed liquor in the present study. The flow regime transition was not observed, because the behavior of the correlation dimension against the air flow rate did not have any sudden changes.

This might be because the correlation dimension highly depends on the choice of embedding dimension and the time delay. The embedding dimension was selected from a number between 1 and 10, and the values greater than 5 correspond to random data. Therefore, care should be taken when the correlation dimension is being used for the pressure signals analysis.

8.5 Conclusion

In this chapter, the utilization and development of a novel dynamic pressure sensing approach was examined to quantify the hydrodynamic characteristics of both two-phase (air-water) and three-phase (mixed liquor-air) reactors. Statistical analysis as well as fractal analysis were carried out to identify the flow structure. The analysis of the standard deviation of pressure fluctuation signals implied that the two-phase system had a transition point, however a similar transition point in the three-phase system was not identified. The presence of solid particles was confirmed to have a significant impact on the flow hydrodynamics. The analysis of Hurst exponent and Largest Lyapunov indicated that both the tap water and mixed liquor systems were highly anti-persistent and chaotic. The correlation dimension information did not yield any transition points for the two solutions, therefore care should be taken when applying this method for PFS analysis. Overall, this application of the dynamic pressure sensing technique still requires further confirmation in order to quantify the hydrodynamic characteristics in multiphase reactors.

Figure 8.15 Correlation dimension (D_c) of pressure fluctuations for tap water: (a) 0.3 m, (b) 0.5 m, and (c) 0.7 m

Figure 8.16 Correlation dimension (D_c) of pressure fluctuations for mixed liquor (sample # 7): (a) 0.3 m, (b) 0.5 m, and (c) 0.7 m

Chapter 9 Conclusions and Recommendations

9.1 Conclusions

In this chapter, the conclusions drawn based on the studies in this thesis are summarized as follows.

A special setup with a turbulence generator using a vibrating perforated plate was constructed in the laboratory. The turbulence generated by a perforated plate was investigated in terms of velocity fluctuations, correlation coefficient, energy spectrum, turbulence kinetic energy and integral length scale. The turbulence characteristics were obtained from the post processing of the data collected from Particle Image Velocimetry. These characteristics were used to interpret the relationship between changes in turbulence parameter and fouling behavior of hollow fiber membranes. The solidity of the plate as an indicator of difference in physical characteristics, and also the distance from the plate played an important role in the magnitude of velocity. At distances closer to the plate and at higher solidities the turbulence had a higher velocity magnitude.

While quantifying turbulence characteristics is typically difficult, here using Particle Image Velocimetry was sufficient to gain insights about the hydrodynamic characterisation of an oscillating plate. These insights were used for the grand objective of the present study i.e. to raise the fundamental understanding of the role of turbulence in membrane filtration. A valuable conclusion drawn was that the turbulence generated by the vibrating perforated plate had a zero mean shear stress despite the high solidity of the plate. This was of particular importance because it allowed the study of fouling with varying turbulence kinetic energy and integral length scale. Mean velocities did exist to a small extent inside the test tank, and they were generally higher away from the plate, but their magnitude was much smaller compared to the turbulence fluctuations at the same location. The integral length scale

also increased linearly with the distance from the turbulence generator plate, similar to studies on grid generated turbulence with much lower solidity ratios. The evaluation of turbulence generation with different solidities indicated that the turbulence kinetic energy strongly depended on the solidity. Integral length scale was also examined and it was also found to increase with the solidity.

Gaining insights on the hydrodynamic characteristics of the turbulence generated by a vibrating perforated plate, made it possible to achieve one of the main objectives of this study. The quantitative effect of turbulence on hollow fiber membrane filtration in terms of membrane fouling control was examined experimentally. This was performed by integrating the vibratory turbulence generator with a constant flux hollow fiber membrane filtration. The specific characteristics of the setup allowed the hollow fiber membrane filtration to be carried out in a zero mean shear turbulent ambient environment. Previous studies have shown the performance improvement with turbulence in conjunction with other fouling prevention techniques. Here, the experimental results showed that the presence of turbulence and turbulence alone led to a significant improvement in the fouling control of submerged hollow fiber membrane filtration. Intuitively it is expected that increase in both turbulence kinetic energy and eddy length scale would lead to fouling reduction. This can be explained by the presence of a relative motion between the membrane surface and surrounding fluid. This motion would produce an oscillating shear that can lead to fouling control. Both turbulence and membrane vibration did reduce fouling to a great extent as it was observed in this study. However, in case of turbulence it was found that while the fouling rate generally decreased with an increase in turbulence kinetic energy, the increase in integral length scale did not improve performance continuously. Fouling reduction with integral length scale was limited to an optimal value. Increasing integral length scale beyond this optimal value did not improve fouling performance. This demonstrates for the first time that there exists an optimal turbulence length scale for membrane fouling control.

Fouling performance of a hollow fiber membrane module was further investigated in term of the statistical dependence on turbulence kinetic energy and integral length scale. Turbulence kinetic energy and integral length scale were both statistically significant factor in fouling reduction. Hollow fiber bundle characteristics of fiber spacing and fiber looseness were also examined in a turbulent ambient. In the oscillatory turbulent ambient fiber spacing and fiber looseness were found to have optimal values. The presence of an optimum fiber spacing might be due to the synergetic effect of filtration extraction and the penetrating interactions between the turbulence eddies and hollow fiber membranes.

The effect of constant jets on the fouling performance of hollow fiber membrane filtration was investigated. A higher jet velocity was found to be more effective in fouling control due to higher shear rate leading to a higher critical flux. It was also found that critical flux increased with turbulence kinetic energy. On the other hand, the critical flux had a maximum with eddy length scale which indicated that increasing length scale did not continually increased critical flux.

Combining oscillatory turbulence and constant jet enabled the statistical analysis of turbulence kinetic energy, eddy length scale and discharge velocity of constant jet on hollow fiber membrane's fouling. The analysis indicated that not only the single factors but also their interactions had a significant impact on the fouling performance.

The utilization of a novel dynamic pressure sensing approach was examined to quantify the hydrodynamic characteristics of two-phase (air-water) and three-phase (mixed liquor-air) bubble column reactors. The use of dynamic pressure sensor can serve as a quantifying technique to gather the flow filed information. However, using these sensors was proven to have major difficulties. The analysis of the standard deviation as statistical analysis and Husrt exponent and Largest Lyapunov as fractal analysis has been used to identify the flow structure. of pressure fluctuation signals The statistical analysis led to identification of a transition point in the two-phase

water-air system. This was in agreement with previous studies. However, transition points in three-phase system were not identified. The presence of solid particles was confirmed to have a significant impact on the flow hydrodynamics. The results of fractal analysis of both systems indicated that they were highly anti-persistent and chaotic. The correlation dimension information did not indicate any transition points for the two solutions, therefore care should be taken when applying this method for PFS analysis. Overall, this novel dynamic pressure sensing technique can be applied to quantify the flow regime transition in the two-phase reactors, however the understanding of three-phase flows remains uncertain.

9.2 Recommendations

The following recommendations are suggested as potential directions for future research work.

In this study, the impact of turbulence on the fouling performance of hollow fiber membrane filtration was comprehensively studied. Since the size and concentration of particles change the turbulence characteristics, studying the effect of turbulence in higher concentrations of particles and also using various particle sizes would shed light further on the system optimization using turbulence. The correlation between these parameters and turbulence can be crucial in enhancing the performance.

Other means of turbulence generation e.g. propellers etc. can be used to reduce the fouling rate. The performance of different turbulence generators can be studied to find the most efficient turbulence generator in fouling and energy reduction.

In terms of hydrodynamic quantification, the role of solid particles in a simple two or three-phase reactor on the dynamic pressure signals can be explored to understand

whether pressure fluctuation signals can provide the necessary hydrodynamic information.

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Appendix

In isotropic turbulence, the normal components of Reynolds stress tensor are identical and therefore, estimating kinetic energy with a single component of normal stress is feasible. In the present setup, however, the generated turbulence is not entirely isotropic. Hence, preliminary experiments were performed to verify the validity of this assumption. PIV experiments were conducted in vertical planes perpendicular to the x-h plane, and the turbulence fluctuation were computed at several locations. As can be seen in the following table, the preliminary results demonstrated a good agreement to this assumption. The statistical significance of these measurements was also checked using paired t-tests for data gathered at planes parallel to the perforated plate (i.e. the same distance from the plate). There was no evidence of statistical difference in these measurements.

Table A) Turbulent fluctuations at various x location

x (cm)	h (cm)	$\overline{u_2' u_2'}$	$\overline{u_3' u_3'}$	Standard error	Relative percent error (%)
6	10	1.34×10^{-4}	1.26×10^{-4}	3.56×10^{-6}	2.47
6	14	8.13×10^{-5}	7.92×10^{-5}	1.02×10^{-6}	1.27
6	18	5.49×10^{-5}	5.67×10^{-5}	9.16×10^{-7}	1.64
15	10	1.39×10^{-4}	1.28×10^{-4}	5.45×10^{-6}	1.38
15	14	7.99×10^{-5}	7.94×10^{-5}	2.43×10^{-7}	3.06
15	18	5.35×10^{-5}	6.09×10^{-5}	3.72×10^{-6}	6.51
22	10	1.31×10^{-4}	1.28×10^{-4}	1.69×10^{-6}	1.3
22	14	6.19×10^{-5}	5.68×10^{-5}	2.55×10^{-6}	4.3
22	18	5.41×10^{-5}	5.71×10^{-5}	4.26×10^{-6}	2.68

From Figure 5.8, it can be seen that TKE did vary to some extent along the x-direction by approximately ($\pm$) 10 %. Hence, the interpretation of the filtration results from the present analysis should also bear in mind the associated uncertainties due to this variation along the membrane fibre length, in addition to the uncertainties in the PIV measurements with the repeated experiments reported above.