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Membrane bioreactor for domestic wastewater treatment: principles, challanges and future research directions

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ABSTRACT

Membrane bioreactors (MBRs) have recently become widely accepted as an advanced technology for treatment of domestic and industrial wastewaters. The objective of this review is to provide overview on MBR technology for wastewater treatment application. It includes discussions on the fundamental, core problems (membrane fouling), recent effective development approach (dynamic filtration systems) and future research direction of MBRs. Since MBRs integrate a conventional activated sludge process with membrane filtration, and both fundamental aspects are discussed first. Later, a comprehensive discussion about membrane fouling, the main problems in MBR, is provided, including fouling control strategies. The discussion on the MBR membranes and relation between membrane properties and MBR performance is also provided. This review also includes one of the most promising MBR technologies that specifically design to manage membrane fouling: dynamic filtration systems. Lastly, insight into an approach to address MBRs challenges and recent research and developments are provided.

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1. INTRODUCTION

Membrane bioreactors (MBRs) integrate an activated sludge bioreactor with membrane filtration. They offer a better effluent quality and a more robust technology in treating wastewater. Because of stricter effluent standards and high water reuse demands, MBRs have recently become widely accepted as an advanced option for treatment of domestic and industrial wastewaters. Recently, MBRs have growing number of installations and capacities, as well as providers. The global MBR market had a value of ≈ $10 million in 1995, which increased to ≈ $217 million in 2005. The annual average market growth rate is 9.5 which is 12%, faster than any of other advanced wastewater treatment processes.

MBR has many advantages over the conventional activated sludge process (ASP). They include a higher biomass concentration, smaller footprint, less sludge production, decoupled sludge (SRT) and hydraulic retention time (HRT), and highly-improved and constant effluent quality. However, MBRs widespread installations is restricted by membrane fouling problems, which limit the achievable permeate flux, reduce the sustainability of operation, increase the cleaning frequency, reduce the lifetime of the membrane, etc. This drawback leads to a high capital expenditure (capex) and operational expenditure (opex), and thus lowers its competitiveness (Drews, 2010; Le-Clech *et al.*, 2006; Meng *et al.*, 2009).

Extensive studies have been reported regarding MBRs, mostly in order to understand and provide solution to manage membrane fouling. In many cases, contradictions were found because of the following reasons (Drews, 2010):

1. The complexity and inter-relationship of multi-parameters of the system is sometimes denied and researchers jump to conclusions.
2. A wide variety exists of experimental conditions, feed composition, biological parameters, filtration parameters, sample preparations and evaluation methods.
3. Often, terminology is established without clear definition.

Therefore, additional care is required when addressing published data. Developing MBR technology requires an inter-disciplinary approach and the study of MBR fouling requires an integrated knowledge of not only biological wastewater treatment technology and membrane technology, but also engineering background.

Based on previous works (Bilad et al., 2014; Bilad, et al., 2015; Bilad et al., 2012a; Bilad et al., 2012b; Bilad et al., 2011; Bilad, 2016), this review provides overview on MBR technology for wastewater treatment application. It includes discussions on MBRs fundamental, core problems and future research. Since MBRs integrate a conventional ASP with membrane filtration, both aspects will be discussed thoroughly. Later, a comprehensive discussion about membrane fouling, the main problems in MBR, including fouling control strategies is provided. The discussion on the MBR membranes and relation between membrane properties and MBR performance is also included. This review also covers one of the most promising MBR technologies that specifically design to manage membrane fouling, namely dynamic membrane filtrations. Finally, perspectives on future developments and important research area are addressed.

2. MEMBRANE TECHNOLOGY

Membrane processes are currently being used in many industrial sectors. In some applications, (such as in desalination, water and wastewater treatment), they have a high industrial relevance and have become a standard technological solution (Shannon *et al.*, 2008). In water and wastewater treatment, the growth of membrane applications has been exponential over the last two decades. This is due to the drivers of tighter regulations, water scarcity, and significant advances in membrane process performances (Fane, 2011). The market of membranes for municipal water treatment is growing at over 10% (p.a.) reaching USD 1.6 billion in 2011 and even gross at 20% (p.a.) for desalination.

2.1. Definitions

A membrane is a “selective barrier between two phases” that is used to perform a separation. A feed passes the membrane under the influence of a driving force and is split into a retentate that is retained/rejected by the membrane and a permeate that passes through the membrane. The schematic illustration of a common pressure driven membrane filtration is shown in **Figure 1(a)**. Depending on the ability to reject certain compound(s), common pressure driven membranes and their specifications can be divided into reverse osmosis (RO), nanofiltration (NF) ultrafiltration (UF) and microfiltration (MF) (**Figure 1(b)**).

Two main parameters are normally used to determine the performance of a membrane, namely flux (J) or permeability (L), respectively defined as in ***Equations*** **(1)** and **(2)**, and rejection (R) defined as in ***Equation*** 3. Flux or permeability measures how good a membrane allows the permeate to pass; rejection measures how good a membrane retains a certain compound.

$$J = \frac{V}{A\,t} \qquad (\mathrm{L/m^2\,h}) \qquad (1)$$

$$L = \frac{J}{\Delta P} \qquad (\mathrm{L/m^2\,h\,bar}) \qquad (2)$$

$$R = 1 - \frac{C_p}{C_f} \qquad (3)$$

where V is the permeate volume, A is the membrane area (m^2), t is the filtration time (h), ΔP is the average pressure difference (bar) between feed and permeate (also called trans membrane pressure (TMP)), C_p is the solute concentration in the permeate, and C_f is the solute concentration in the feed.

Membranes can be prepared in different forms, such as flat-sheet (FS), hollow fiber (HF) and tubular. In order to be applicable for a filtration process, a bundle of fibers or a multi-sheet set are assembled to form a module. A module consists of a number of membrane elements. The typical membrane modules for pressure driven membrane filtration are plate-and-frame (FS), hollow fiber (HF), (multi)tubular (MT), capillary tube and spiral wound. The typical module assembly and the modules that are normally used in MBRs are shown in **Figures 2(a)** and **(b)**, respectively.

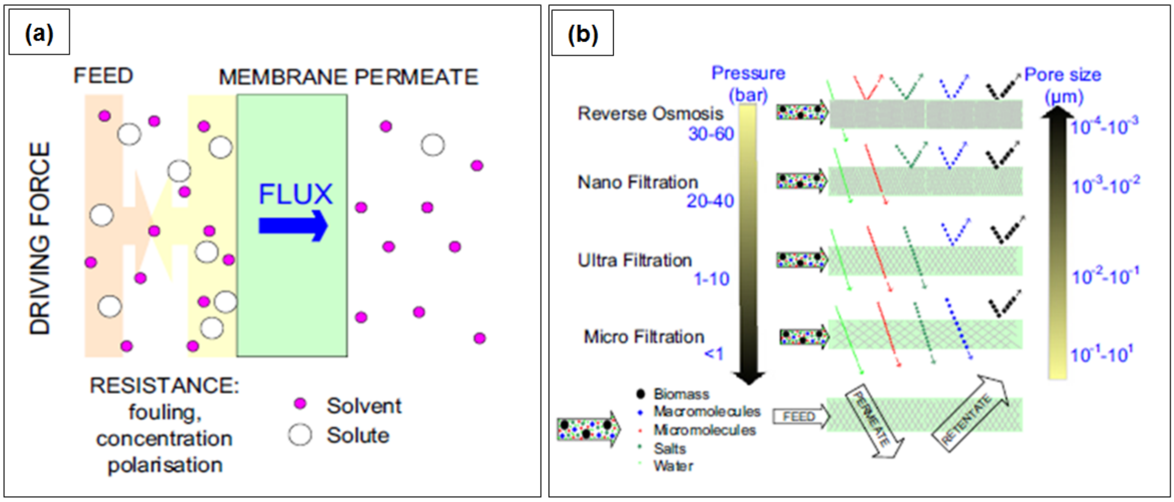


Figure 1. (a) Basic scheme of a membrane filtration process and (b) Schematic illustration of different solute rejections in pressure driven membrane processes (Bilad *et al.*, 2014).

2.2. Operation and filtration process

There are two common ways to perform a filtration: dead-end or cross-flow. In the dead-end, the permeation is driven by pressure different, with no concentrate stream. In the cross-flow, feed is pumped tangentially along the membrane surface and is split into permeate and retentate (concentrate) streams. The feed is introduced in the first end of the membrane module and the retentate exits at the other end. The pressure is generated by restricting the flow at the other end. Both systems can be operated at a constant flux or at a constant TMP. In practice for an MBR application, filtration is performed under a constant flux operation And because of occurrence of membrane fouling, TMP increases over time.

Fouling can occur in many forms. Foulants can be adsorbed in the pore structures, foulants can block the membrane pores, foulants can accumulate and form a cake layer, etc. By incorporating the occurrence of fouling, the filtration resistance can be calculated as in **Equations (4)** and **(5)**. This resistance in series model helps to identify the contribution of each fouling components.

$$J = \frac{\mathrm{TMP}}{\eta\, R_T} \qquad (4)$$

$$R_T = R_m + R_i + R_{pb} + R_c \ \text{(1/m)} \qquad (5)$$

where η is the dynamic viscosity of permeate (Pa s), R_T the total filtration resistance, and R_m, R_i, R_{pb}, R_c the filtration resistance originating from membrane, internal fouling, pore blocking and cake layer, respectively.

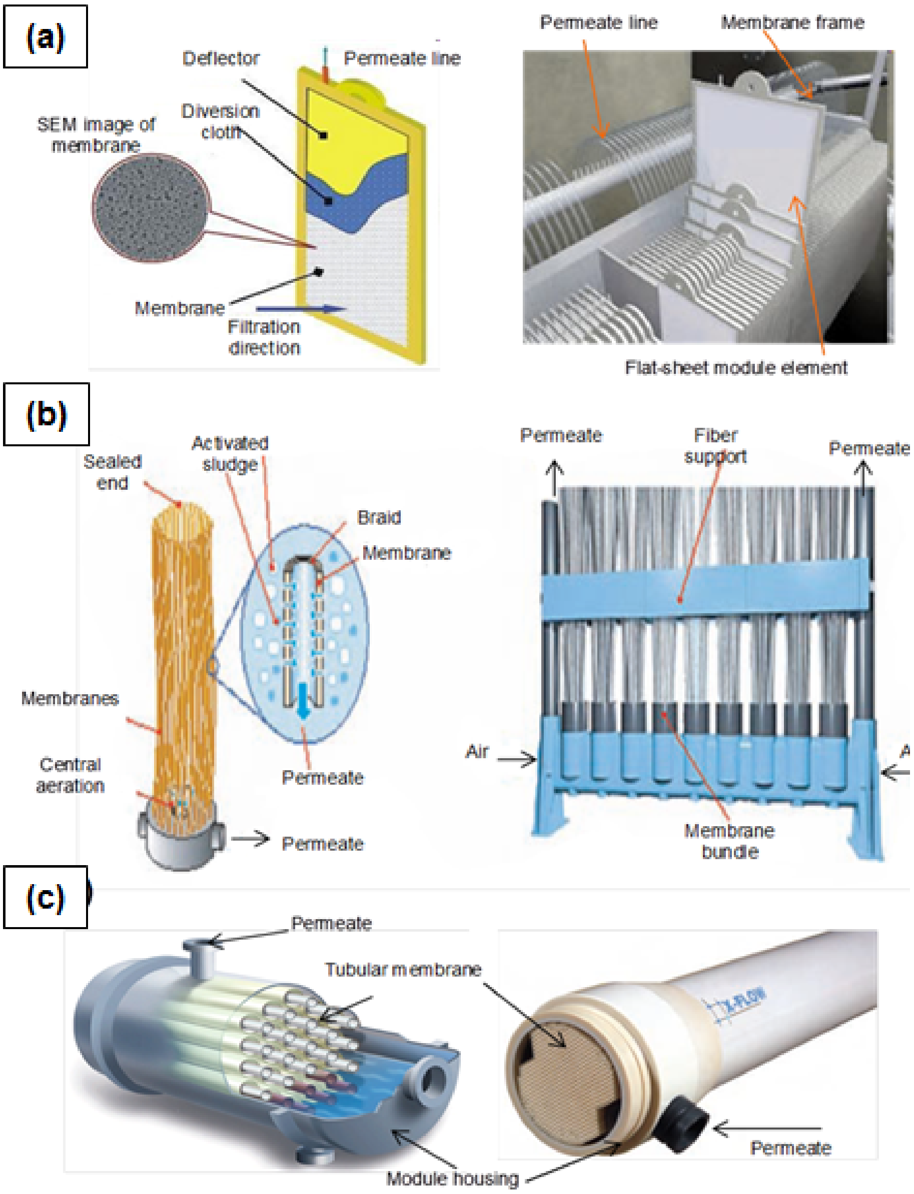


Figure 2. Typical arrangement of membranes in membrane modules used in MBRs (Judd, 2008): (a) a FS module of KUBOTA, (b) a HF module of KOCH and (c) a MT module of X-flow.

To maintain the long-term membrane performances and managing membrane fouling, the filtration is normally done in cycles, which involve relaxation or backwash (known as physical cleaning methods), as well as maintenance and intensive chemical cleanings. Another method to control fouling is by interrupting or disturbing the fouling development using the shear-rate induced from the relative movement of fluid to membrane, or movements of the membrane itself (Jaffrin, 2008). The former is done by applying high cross-flow velocities in a cross-flow system or by introducing a secondary flow in a dead-end system (**Section 3**), while the latter is done by shaking or vibrating the membranes in dynamic filtration systems.

3. Membrane Bioreactors (MBRs)

3.1. Definition, process and operation

In MBRs, organic constituents in wastewater are consumed as a substrate for microorganisms, and the treated water is separated by a membrane filtration. In the bioreactor, microorganisms are present in the form of microbiological flocs together with their metabolic products. They convert the organic pollutants present in the wastewater into biomass and metabolic products, mainly CO_2 and H_2O (under oxic conditions). The effluent quality parameters are normally determined using standard methods, such as chemical oxygen demand (COD), biochemical oxigen demand (BOD), total nitrogen (TN), etc. Three basic operational parameters are used to control the biological performance: SRT, HRT and food to microorganism ratio (F/M) (**Equations (6)-(8)**, respectively).

$$SRT = \frac{\mathrm{V}}{Q_w} \qquad \text{(days)} \qquad (6)$$

$$HRT = \frac{\mathrm{V}}{Q_f} \qquad \text{(days)} \qquad (7)$$

$$F/M = \frac{\mathrm{S_f}}{HRT\ X} \text{(gCOD/gMLSS)} \qquad (8)$$

where V is the bioreactor volume (L), Q_f is the feed flow rate (L/day), S_f is the feed substrate concentration (g/L) represented as COD, and X is the mixed liquor suspended solid (MLSS) (g/L).

The feed properties significantly influence the mixed liquor properties. (Drews, 2010; Le-Clech *et al.*, 2006; Meng *et al.*, 2009) The dynamic diversity of microorganisms in the sludge also differs as well as their metabolite products. The MBRs fed with highly biodegradable substrates may experience less fouling, or vice versa. Therefore, the effectiveness and the efficiency of an MBR performance may also differ.

MBRs can be divided into submerged and side stream configurations depending on the way to couple the membrane module (**Figure 3**). In the submerged MBR, the modules are immersed in the bioreactor, and the filtration is driven by vacuum pressure. The filtration tank often separated from the bioreactor tank, in which the mixed liquor is circulated between them. Fouling is controlled by coarse air bubbles sparging, which creates a tangential flow over the membrane and induces mixing. In a side stream MBR, the modules are coupled to the bioreactor by an external sludge recirculation loop to create cross-flow velocity. Mixed liquor is pumped under pressure over the modules, and the TMP can be further increased by suction at the permeate side of the membrane. High cross-flow velocities are applied to control fouling, sometimes aided by air sparging (Le-Clech *et al.*, 2006). Most of the commercial MBRs are configured as submerged MBR, (Judd, 2008) which will therefore be the main focus of this review.

Filtration operation consists of several cycles: filtration, maintenance cleaning, and intensive cleaning (**Figure 4**). The filtration cycle is normally combined with physical cleaning via relaxation or backwashing. The relaxation is performed by temporarily stopping the filtration, and the backwash is performed by pumping the permeate in the reversal direction. At certain interval, maintenance or even intensive cleanings can be required. Cleaning procedures and their interval are plant-specific and normally follow the technical guidance from the membrane providers. (Judd, 2008)

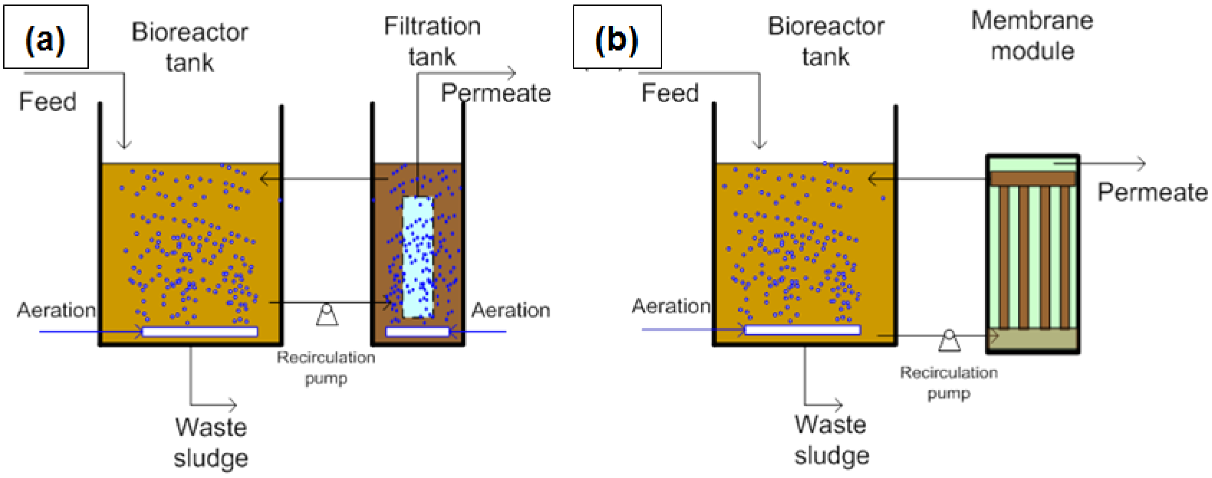


Figure 3. Schematic illustration of (a) a submerged MBR and (b) a side stream MBR.

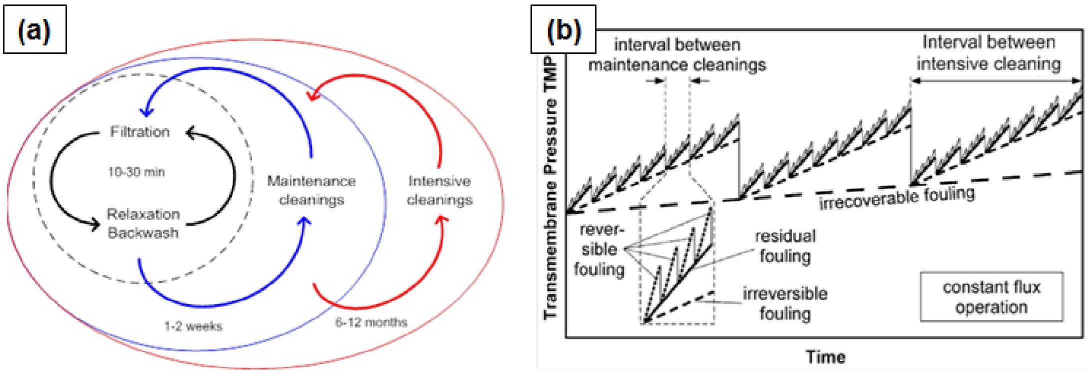


Figure 4. Schematic representation of (a) filtration and cleaning cycles and (b) different fouling rates during long-term operation of full-scale MBRs, adapted from (Kraume *et al.*, 2009).

3.2. Fouling: Definition, process and mechanism

In its strict form, fouling in MBRs is the coverage of the membrane surface (external and internal) by deposits, which adsorb, get trapped or simply accumulate, resulting in permeability loss and reflected by a increase of TMP during the operation. (Drews, 2010) This results in a typical trade-off or optimization problem: at higher flux, capex decreases while opex increases.

In more details, the MBR mixed liquor consists of biomass, variable amounts of particulates, colloidal and dissolved fractions, all of which are potential foulants (Drews, 2010; Le-Clech *et al.*, 2006; Meng *et al.*, 2009; Meng *et al.*, 2010). During the initial filtration, colloids, solutes, and microbial cells, all summed up as foulants, partly pass through and precipitate on the membrane surfaces, due to convective flow of permeate. As filtration continues, the cake layer is developed, and the deposited cells multiply to form a more complex biofilm. (Liao *et al.*, 2004; Ramesh *et al.*, 2006; Wang *et al.*, 2006) However, the aggressive fouling development is limited (temporarily) by applying a physical and chemical cleaning during the operation.

Fouling can be classified based on the nature of the foulants into biofouling, organic and inorganic fouling. Biofouling refers to the deposition and growth of biomasses or flocs on the membrane surface. The process might start with the deposition of cell(s) followed by cell growth and establishment of a biofilm (Drews, 2010; Liao *et al.*, 2004; Ramesh *et al.*, 2007). On the other hand, organic and inorganic fouling refers to the deposition of biopolymers/organic materials and inorganics from the feed, respectively. They occur simultaneously in a very complex mechanism. Most attentions have been given to organic and biofouling due to their dominance. Only limited studies report the dominance of inorganic fouling in a submerged MBR process. (Lee & Kim, 2009)

Fouling can also be classified into internal fouling, pore blocking, and cake layer formation, depending on the location of the foulants and their impact on the filtration resistance (See **Equations** **(4)** and **(5)**). Internal fouling is caused by the penetration of foulant into the membrane pores. It occurs when the foulant is smaller than the pore mouth. On the other hand, the larger foulants block the pore mouth. The accumulation of foulants that cover the membrane surface is referred to as “cake layer". The cake layer can be comprised of cells, extracellular polymeric substances (EPS) and soluble microbial products (SMP), etc. This cake can also perform as a secondary filtration layer, normally referred to as a dynamic membrane. In this case, the cake porosity plays a more important role than the membrane properties in a membrane filtration process. (Meng *et al.*, 2009)

The affinity of foulants to membrane surfaces is strongly affected by their nature (Le-Clech *et al.*, 2006). The membrane-foulant interaction, together with foulant location, affect their removability. Based on their removability, fouling can be classified into reversible, residual, irreversible and irrecoverable fouling (Drews, 2010; Meng *et al.*, 2009) (**Figure 4**). Reversible fouling can be removed by physical means (such as relaxation and/or backwash under tangential flow conditions) (Meng *et al.*, 2009). In this type of fouling, foulants have a weak affinity to the membrane surface. The residual or irreversible fouling can only be removed by maintenance and intensive cleaning. The irrecoverable fouling is permanent fouling that cannot be removed by any means. The gradual accumulation of the irrecoverable fouling eventually determines the membrane life-time. The severely fouled membranes then have to be replaced by new ones.

3.3. Critical flux concept

Flux is one of the most important parameters in membrane filtration. Different fluxes give different fouling rates. The highest value at which no fouling occurs is called the critical flux (CF or J_C) in its strictest form. (Field *et al.*, 1995) Beyond this flux, higher fluxes lead to more membrane fouling. Operation in this flux is however undesirable because it is too-low and thus leads a reduced productivity.

In the activated sludge filtration, like in an MBR, no such CF in strict form exists (Le Clech *et al.*, 2003). The CF is slightly different than from the one mentioned earlier (Field *et al.*, 1995). The CF values are in that case defined based on a threshold fouling rate, *i.e.*, >10 Pa min−1, or by picking the flux value where a linear relationship between flux and TMP ceases to appear. (Le Clech *et al.*, 2003; van der Marel *et al.*, 2010) A threshold value is used to express the fouling rate, because a flux below which fouling is completely absent simply does not exist. In practice, fluxes below this CF (*i.e.* 2/3 of CF) are selected as operational fluxes. This flux is referred to as sustainable flux or sub-critical flux (Field & Pearce, 2011). The operational flux selection is aimed to meet the economical objective of optimizing capex and opex. High operational fluxes lead to higher productivity per membrane area, thus reducing capex. On the other hand, high fluxes promote fouling, so higher opex is required to perform the cleaning cycle. Low operational fluxes increase the capex but reduce the opex.

The CF has been extensively used as a quantitative parameter for the filterability of different membranes and/or different feeds. In activated sludge filtration, the CF is generally regarded as the flux above which cake or gel formation by particles or colloids (Howell, 1995) occurs, *i.e.* convection of these materials towards the membrane by the permeate drag flow exceeds the back transport velocity of material from the membrane (van der Marel *et al.*, 2009). The CF is usually measured by flux-step methods. (Le Clech *et al.*, 2003; van der Marel *et al.*, 2009; Wu *et al.*, 2008) Flux-stepping is preferred since the control over flux is easy. Several methods have been proposed by different authors, such as the flux-step method (Le Clech *et al.*, 2003) and the improved flux-step method (van der Marel *et al.*, 2009). The latter also provides the long-term fouling rate using the term of critical flux for irreversibility (JCir). In addition, many methods were also developed to quantify the filterability, such as the Membrane Bioreactor-VITO Fouling Measurement (Huyskens *et al.*, 2008), The Delft Filtration Characterization method (Evenblij *et al.*, 2005), Berlin filtration method (de la Torre *et al.*, 2010) and the filtration index (FI). (Rosenberger & Kraume, 2002)

3.4. Fouling stages

The evolution of fouling is reflected in the TMP profile during the operation. A typical TMP profile of a long-term MBR operation consists of three stages (**Figure 5)** (Cho & Fane, 2002; Zhang *et al.*, 2006). Stage-1 is a short period of rapid TMP increase, especially for fresh membranes. It occurs within few hours (often overseen) and irreversible because of passive adsorption and initial pore blocking by foulants. In stage-2, TMP slowly increases and lasts for few days to weeks. During this stage, further pore blocking is expected and a more established cake is formed. Deposited sludge flocs and micro-organisms form micro-colonies and continue to grow and replicate form a biofilm. (Liao *et al.*, 2004; Ramesh *et al.*, 2006; Wang *et al.*, 2006) During stage-2, the foulant build-up does not diminish, thus the fouling phenomenon becomes self-accelerating towards the end of this stage. Stage-3 is characterized by an abrupt rise of TMP over a short period because of the rapid increase of local flux exceeding the CF since a significant part of membrane surface is already occupied by foulants (Cho & Fane, 2002). More specific phenomena, such as sudden change of the biofim or cake layer structure (Zhang *et al.*, 2006) and sudden increase of the EPS content at the bottom of the cake layer (Hwang *et al.*, 2007), were proposed to explain stage-3. The aim of fouling control is practically to prolong stage-2 as long as possible to sustain the filtration.

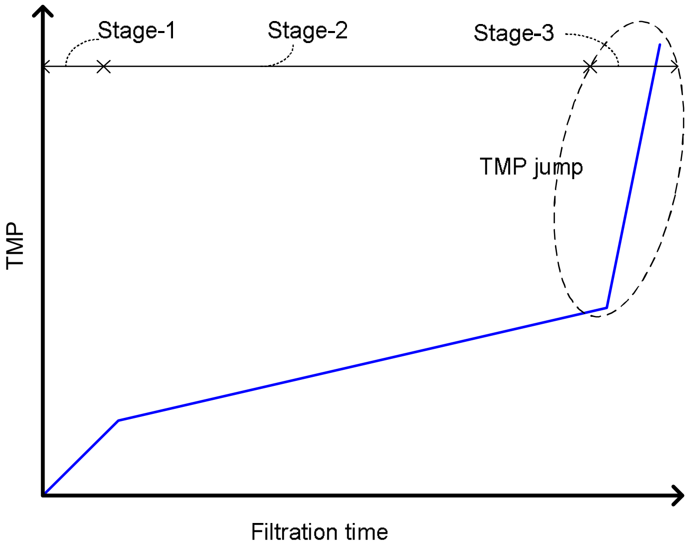


Figure 5. Illustrations of a typical TMP-profile for long-term MBR operation. The circle highlights the occurrence of a TMP jump.

3.5. Fouling factors and control strategies

The factors that affect the fouling can be classified into feed properties, membrane properties and hydrodynamics. They are inter-related with each other and it is very difficult, if not impossible, to isolate an individual specific parameter to investigate its effect independently.

3.5.1. Feed

The mixed liquor properties are the end product of combined operational parameters, mostly from biological aspects, such as SRT, HRT, dissolved oxygen (DO), F/M ratio, and bioreactor configuration. They are also affected by environmental conditions such as temperature and feed composition. The filtration parameters, such as aeration intensity and sludge recirculation also influence the feed properties (Drews, 2010; Le-Clech *et al.*, 2006; Meng *et al.*, 2009). Because of the important of feed in determining membrane fouling, the selection of biological and filtration parameters in first instance is to achieve the effluent quality standard, and then to achieve the condition that is favorable for filtration.

Biomass concentration was initially thought to control fouling rate. However, it was proven that the most dominant foulants are the slimy and sticky substances. These are grouped into the terms EPS when they are bound to the flocs or SMP when freely suspended in the supernatant (Drews, 2010; Le-Clech *et al.*, 2006; Meng *et al.*, 2009). They are produced and excreted by biomass, and to a lesser extent come from the MBR influent.

Two mixed liquor components that are the main culprit of membrane fouling are EPS and SMP. EPS mainly consists of carbohydrates and proteins, and the former was found to be more dominant. In some cases, the cake resistance was found proportional to the EPS concentration (Ahmed *et al.*, 2007; Cho *et al.*, 2005). Therefore, both their concentration and their composition are important. However, other studies found no impact of EPS on fouling (Rosenberger & Kraume, 2002) or at least only their loosely bound components to affect the fouling (Ramesh *et al.*, 2006). On the other hand, SMP is expected to more easily accumulate on the membrane surface.

The effect of EPS and SMP and their mechanism on fouling is somehow contradictive. In order to achieve better mixed liquor filterability, extensive reviews have been given elsewhere (Drews, 2010; Le-Clech *et al.*, 2006; Meng *et al.*, 2009). In general, biological parameters have to be adjusted in order to reduce the dominant fouling components, but still being capable of achieving the desired effluent quality and economical limitations (*i.e.*, lowest capex and opex). This can also be achieved by adding a wide variety of foulant reducers, such as powdered activated carbon (Akram & Stuckey, 2008), ferric chloride (Song *et al.*, 2008; Zhang *et al.*, 2008), chitosan (Le Roux *et al.*, 2005), polymeric ferric sulfate (Wu & Huang, 2008), cationic polymer (Yoon & Collins, 2006), etc. The optimum set of parameters and the most effective fouling reducer might be plant specific.

3.5.2. Membrane

Conventional wisdom generally attributes lower fouling to membranes with a smooth surface, having a low foulant affinity and being highly porous with a narrow pore size distribution. Extensive studies investigate the effect of individual membrane properties in order to formulate the ideal membrane for MBRs. However, many discrepancies are found, which limits in capturing general trends because of the diversity of experimental methods applied, varying test durations and the lack of proper membrane characterizations (Drews, 2010; Le-Clech *et al.*, 2006). Nevertheless, a comprehensive study on the effect of membrane properties has been reported elsewhere (van der Marel *et al.*, 2010). They concluded that an asymmetric membrane with an interconnected pore structure, hydrophilic properties, larger pore size and higher surface porosity favors less fouling.

To improve the membrane fouling resistance, several studies have modified membrane properties to render them more hydrophilic. This has been achieved by applying NH^3 or CO^2 plasma treatment (Yu *et al.*, 2003; Yu *et al.*, 2007), addition and coating of TiO^2 nanoparticle into the polymer casting solutions and onto the membrane surfaces, respectively (Bae *et al.*, 2006; Bae & Tak, 2005), coating ferric hydroxide onto the membrane surfaces (Zhang *et al.*, 2008), coating an amphiphilic graft copolymer poly(vinylidene fluoride)-graft-poly(oxyethylene) methacrylate (PVDF-g-POEM) (Asatekin *et al.*, 2006), or grafting polyacrylamide (Yu *et al.*, 2007).

No systematic study has been performed yet to develop and optimize phase inversion membranes for MBR application. Most literature focuses only on investigating an individual effect of membrane properties on filtration performance. Many recent studies report the performance of novel membranes as cheaper alternatives to replace the traditional phase inverted membranes, such as non-wovens (Seo *et al.*, 2003), mesh filters (Fuchs *et al.*, 2005; Wang *et al.*, 2006) or nanofibers (Bilad *et al.*, 2011). However, these new materials are still under development and to date, none of them has been used in a full-scale application. The severe fouling (due to their rough surface and too large pore sizes and wide pore size distributions) still limit their application.

3.5.3. Hydrodynamics

Steering the feed hydrodynamics is the most efficient way to control fouling (Jaffrin, 2008). It is implemented as coarse air bubbles in submerged MBRs and as cross-flow in side stream MBRs. Hydrodynamic homogeneity is among the most important parameters to be managed (Braak *et al.*, 2011). Due to the nature of the module design, homogeneous hydrodynamics are very difficult to be achieved. Along the membrane module, there is an internal pressure drop: TMP is high at the start of the module (suction) where the permeate is withdrawn (**Figure 6**). Therefore, local-flux at this region is higher than at the other end, thus inducing fouling that eventually spreads to the other regions (Chang *et al.*, 2002; Yoon & Collins, 2006; Yu *et al.*, 2003). In the case of hollow fiber modules, an increase in packing density leads to a more heterogeneous permeate profile along the fiber length and also induced membrane fouling (Braak *et al.*, 2011). Furthermore, a filtration cycle including relaxation or backwash induces a high instantaneous flux to compensate for the filtration downtime, which results in the compression of the cake layer (Metzger *et al.*, 2007).

The role of air bubbles in submerged systems is to provide direct shear, to induce a secondary flow of liquid, and to move the membranes (in the case of hollow fibers). This approach has several disadvantages (Genkin *et al.*, 2006). First, the shear-rates experienced by the membrane surfaces are relatively weak. This, only modest fluxes can be used. At a certain air supply, increasing aeration rate will not further increase the cleaning effect (Genkin *et al.*, 2006; Wu *et al.*, 2008). Second, an elevated aeration intensity leads to breakage of sludge flocs and excess production of SMP, and under such condition, the released colloids and solutes could become the major foulants (Rosenberger & Kraume, 2002). Third, increasing the bubble flow reaches a “plateau” in terms of flux improvement and this makes the realization of a higher throughput difficult (Genkin *et al.*, 2006). Finally, it is difficult to achieve an effective bubble distribution and a significant portion of the aeration “energy” will have only small impact. As coarse bubble aeration dominates the operational cost of MBRs, recent studies focus on optimizing this parameter.

The intensity, module configuration and arrangement, bubble size, and sludge viscosity were proven to affect the hydrodynamics (Le-Clech *et al.*, 2006). Furthermore, improving the hydrodynamics can also be performed by applying dynamic membrane systems (Altaee *et al.*, 2009; Beier *et al.*, 2006; Bilad *et al.*, 2012a; Genkin *et al.*, 2006; Jaffrin, 2008).

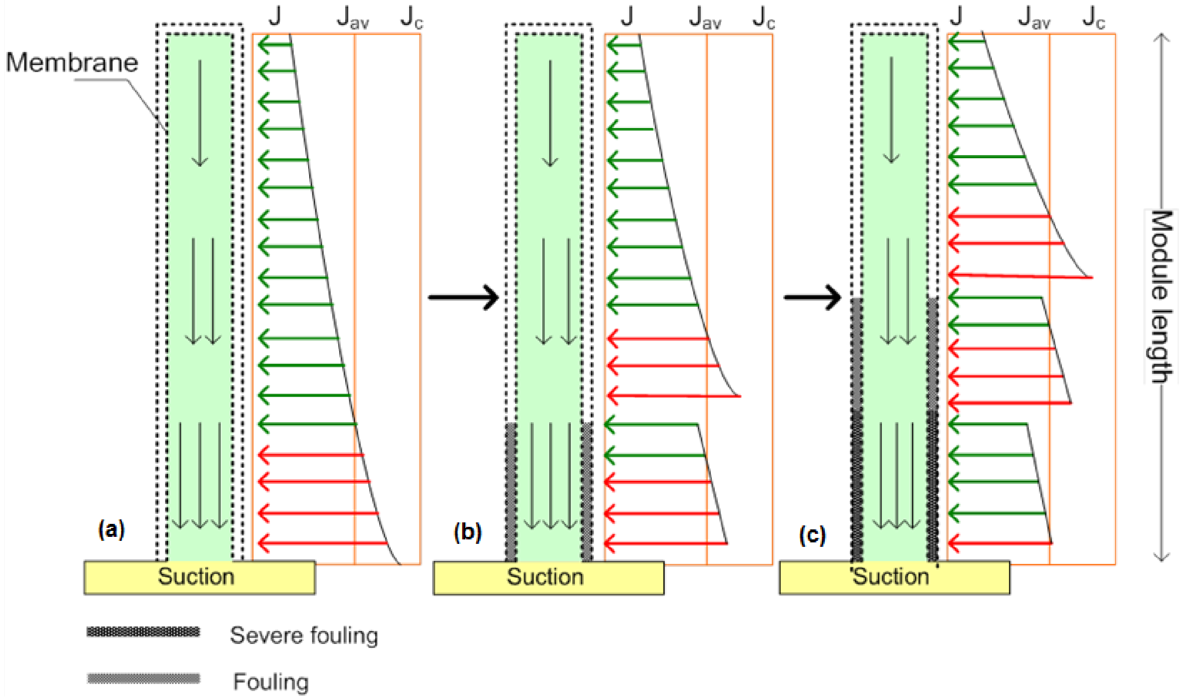


Figure 6. Flux mal-distribution along a membrane module, where J is the local flux, Jav the average flux and JC the critical flux [adapted from Braak *et al.*, 2011). The behavior of the flux distribution over time is illustrated from (a) over (b) to (c).

4. MBR membranes

4.1. Types, materials and configurations

All types of pressure driven membranes have been used in lab-scale MBRs, but only MF and UF membranes are used so far in full-scales (Judd, 2008). The application of NF and RO in MBRs was driven by the motivation to realize a single process for direct water re-use purposes. Such membranes would also exclude internal fouling (Asatekin *et al.*, 2006; Choi *et al.*, 2002; Choi *et al.*, 2005) due to their ability to retain almost everything except water. However, salts accumulated inside the bioreactor and endangered the biological processes. Furthermore, NF and RO membranes operate at very high pressure and low flux, leading to an increased pumping cost and membrane investment, respectively (Judd, 2008; Kraume *et al.*, 2009).

The most common polymers that are used to prepare MBR membranes are polysulfone (PSF), polyvinylidene difluoride (PVDF), polyacrylonitrile (PAN) or derivatives of polyethylene (PE) (Judd, 2008). Although all of these polymers are hydrophobic, they are mostly post-treated to become more hydrophilic (Le-Clech *et al.*, 2006). The membrane materials should have good mechanical strength and high flexibility. This is important to prevent pore collapse and maintain the lateral movement of the fiber (for HF). They must also have good chemical resistance and must tolerate a wide pH range. This is required especially to deal with the chemical cleaning conditions, *i.e.* pH> 11 for base and pH<4 for acid.

An ideal membrane module for MBRs should have a high packing density, allow a high degree of turbulence at the feed side, facilitate cleaning and permit modularization (Judd, 2008; Le-Clech *et al.*, 2006). To meet those requirements, the typical configuration of the module used in MBRs is MT, FS and HF (**Figure 2**). In full-scale, a variety of module configurations is available and no standardization of module design is currently present for MBR membranes. The typical membrane product specifications from different membrane suppliers are summarized in **Table 1**.

4.2. Membrane characteristics

Membrane characteristics provide information about the filtration performances and the physical properties. The performance related characteristics are discussed in **Section 2**. The morphology-related parameters are pore size, pore size distribution, surface porosity, cross section structure, pore shape, and other physical-chemical properties such as hydrophilicity and charge density. It is possible to relate those physical properties to the performance properties, which enables to design the most suitable membrane for a particular application.

Membrane pore size and distribution, surface porosity, hydrophilicity, roughness, materials and configuration are among the membrane characteristics that have been reported to have a direct effect on membrane fouling. (Le-Clech *et al.*, 2006) The effect of the individual membrane characteristics, especially in relation to the membrane fouling are listed below.

Tabel 1. The typical membrane product specifications from different membrane suppliers (adapted from Judd, 2008)).

Supplier	**Country**	**Membrane Configuration**	**Membrane material**	**Pore size(nm)**	**Diameter (d)^1 or separation (δ)^2 (mm)**	**Specific surface area (m^{-1})^3**	**Proprietary name of membrane or module**
Berghof	Germany	MT	PES, PVDF	80	9	110	Hyper-AE, HyperFlux
Brightwater	UK	FS	PSF	120	9	110, 47	MEMBRIGHT
Toray	Japan	FS	PVDF	80	7	135	Toray
Kubota	Japan	FS	PE	400	8	115	Kubota
Colloide	Ireland	FS	PSF	40	10	133	Sub Snake
Huber	Germany	FS	PSF	38	6	160, 90	VRM
Millenniumpore	UK	MT	PSF	100	5.3	180	Millenniumpore
Koch-Puron	USA	HF	PSF	50	2.6 (3.5)	314, 125	Puron
GE	USA	HF	PVDF	40	1.9 (3.0)	314, 125	ZW 500C-D
Norit X-Flow	The Netherlands	MT	PVDF	38	5.2 8	320, 30 290, 27	F4385 F5385
Siemen-Memcor	Germany	HF	PVDF	40	1.3 (2.5)	334	B10R, B30R
Mitsubishi Rayon	Japan	HF	PE PVDF	400 400	0.54 (1.7) 2.8 (2.9)	485, 131 333, 71	SUR SADF^{TM}
Asahi Kasei	Japan	HF	PVDF	100	1.3 (1.3)	710, 66	Microza
Polymem	France	HF	PSF	80	0.7 (1.1)-1.4	800	WW120
Ultraflo	Singapore	HF	PAN	10-100	2.1 (0.7)	1020	SS60
Motimo	China	HF	PVDF	100-200	1.0 (0.9)	1100, 735	Flat Plat

[1] Diameter of hollow fiber

[2] Distance between two flat-sheet membranes in a module

[3] The membrane area divided by the volume of module

4.2.1. Pore size and distribution

The pore size mainly determines which particles or molecules are retained, and which will pass through the membrane. Pore size can refer to an absolute value where every particle of that size or larger is retained, or a nominal value where 95-98% of the particles or molecules of that size or larger are retained. It is obvious that pore size does not clearly define the pore structure and geometry. The pore size and distribution can be determined from electron microscope images, using the bubble point method, or many other methods. Larger pores allow particles smaller than the pore size to clog the pore internally. A narrow pore size distribution prevents an inhomogeneous flow distribution between pores that would lead to preferential deposition and blockage of larger pores (Bilad *et al.*, 2011; van der Marel *et al.*, 2010).

4.2.2. Surface porosity

The surface porosity is defined as the fraction of the membrane surface that is occupied by pores. Together with pore size, distribution and shape, they determine the membrane permeability. It can be determined from electron microscope images of membrane surfaces using image-processing software. (AlMarzooqi *et al.*, 2016) It also has a severe impact on fouling. Membranes with sparse surface porosity can aggravate the effect of adsorption and fouling due to a large build-up of solute near the pores. (Fane & Fell, 1987) Upon increasing surface porosity, the solute accumulation will be spread more evenly, which will also decrease the fouling.

4.2.3. Surface roughness

The effect of surface roughness on the membrane performance is unclear. Roughness not only increases the surface area, but also changes the hydrodynamics near the surface. The former increases the surface porosity, thus reducing the local flux. The latter promotes the effect of concentration polarization and fouling by enhancing the interaction with foulants through preferential accumulation of foulant materials in the valleys of the rough membrane surfaces. As a result, valleys become blocked and fouling becomes more severe. (Elimelech *et al.*, 1997; Vrijenhoek *et al.*, 2001)

4.2.4. Hydrophilicity and charge density

Surface hydrophilicity is normally quantified using contact angle measurement (Rana & Matsuura, 2010). It is usually assumed that fouling decreases with an increase in hydrophilicity of the membrane surface, because most foulants in water are hydrophobic. Depending on their molecular structure, membrane surfaces can contain different types of charged spots. The repulsive forces between the charged surface and the co-ions in the feed solution prevent the solute deposition on the membrane surface. Most membranes are negatively charged, considering the factor that most colloidal particles, such as EPS and SMP, are also negatively charged.

Membrane charges and hydrophilicity directly affect the foulant-membrane interaction. Intuitively, it can be expected that a hydrophilic membrane has a higher affinity to the hydrophilic foulants and that a charged membrane attracts the oppositely charged foulants. Therefore, the fouling propensity of membranes based on foulant-membrane interaction is strongly depending on the nature of mixed liquor. This explains, why in most cases, due to the hydrophobic nature of the activated sludge in the mixed liquor, hydrophobic membranes are more prone to foul. (Rana & Matsuura, 2010) In rare cases, when the mixed liquor is dominated by hydrophilic materials, hydrophobic membranes are superior over the hydrophilic ones(Fang & Shi, 2005).

5. Dynamic Membrane Filtration

5.1. Principles and commercial dynamic filtration systems

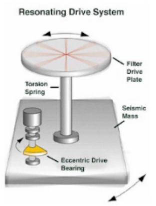
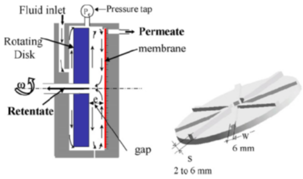
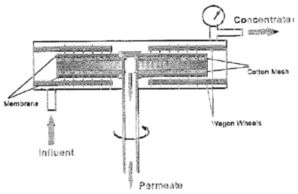
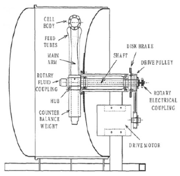
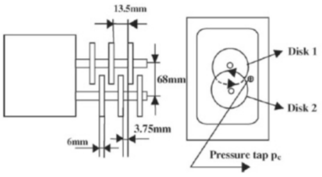
Exposing the membrane surface to a shear is the most efficient way to control membrane fouling. (Jaffrin, 2008) Surface shear is necessary in order to reduce concentration polarization and reduce fouling phenomena such as deposition, pore blocking and cake layer formation. In principle, shear-rates can be induced by creating relative motion between membrane surface and feed liquid.

In traditional systems, shear-rate is provided by coarse bubble aeration and liquid cross flow velocity. In the cross-flow system, high shear-rates at the membrane surface are obtained by increasing the tangential fluid velocity along the membrane and reducing the tube diameter or channel thickness, which generates a large axial pressure gradient. This combination of high velocity and pressure gradient not only requires much energy to drive the pumps, but also causes a decrease of TMP along the membrane, leading to non-optimal membrane utilization. This also occurs along the module length in dead-end filtration (**Figures 6(a), (b), and (c)**).

Another approach to induce surface shear-rate is by moving the membrane surfaces instead of the surrounding fluid or by moving a mass very near to the membrane surface. This type of technique is categorized as dynamic filtration systems (DFSs), also called shear-enhanced filtration. A summary of the existing DFS is given in **Table 2**.

Most DFSs decouple the generation of surface shear-rate from the feed velocity, thus in theory, the mechanical energy is more efficiently directed toward the membrane surface by membrane or fluid mass movement. Therefore, ideally, these systems offer a reduced energy consumption and more effective and efficient fouling minimization. High shear-rates on the membrane surfaces also reduce concentration polarization and cake build-up, allowing the membrane to operate at higher fluxes. Normally the permeate recovery is very high in DSFs, so they do not require large and powerful recirculation pumps. The major part of energy is consumed by rotating or vibrating elements. (Jaffrin, 2008)

Tabel 2. The summary of existing DFSs.

System*	Description	Advantages and disadvantages	Application and commercial system
VSEP	Membrane is oscillated at high frequency (around 60 Hz) in parallel motion relative to the flat-sheet membrane surface. The vibration energy focusses shear waves directly at the membrane surfaces repelling solids and foulant while increasing the permeates rates.		UF, NF, RO (Pall Corp, New Logic)
RD	Filtration module contains a disk, rotating around a horizontal axis, while the flat-sheet membrane is stagnant. The module is sometimes installed with addition of vanes.		MF, UF, NF (Pall Corp)
CR	Filtration module consists of a rotating motor sandwiched between stagnant flat-sheet membranes.		MF, NF (Mesto Papper)
RM	The flat-sheet membrane is mounted onto a rotating hollow disk. The rotation of the disk creates a centrifugal force across the membrane surface.		MF, UF (SpinTek)
CMS	The apparatus consists of membrane head at the end of a rotor arm, containing a plate and frame stack of membranes. It is placed inside a housing.		RO
MSD	The filtration system consists of two parallel hollow shafts rotating at the same speed, each bearing six ceramic membrane disk.		MF (Westfalia Separator)

Only a limited number of reports mentions the weakness of DFS systems. General energy calculations in comparison to the conventional dead-end or the cross-flow system are scarce, making it difficult to verify the claim of energy savings during operation compared to conventional membrane filtration systems. These systems also have other drawbacks, such as apparatus complexity, high tendency of the apparatus to breakdown at the moving parts, and most systems have a very low packing density that leads to very high costs per membrane area. (Beier *et al.*, 2006) Currently, only relatively low numbers of existing DFS are available in the full-scale applications. However, the new generation of commercial DFSs, such as vibratory shear-enhanced processing systems (VSEP) that minimize energy consumption by using the resonance frequency, are expected to present a low specific energy per volume of permeate in a large industrial module, as the power consumption of the vibrating elements is almost independent of the membrane area. (Bilad *et al.*, 2012b)

5.2. DFSs in MBRs

Several DFSs have also been applied in MBRs, such as the vibrating hollow fiber module (VHFM) and VSEP. The VHFM is still under development at lab-scale and only tested in short-terms. The VSEP system was only used to filter an activated sludge solution and showed a low fouling tendency (Low *et al.*, 2009). The VHFM system was tested using a yeast solution (Beier *et al.*, 2006; Genkin *et al.*, 2006) and an activated sludge solution (Altaee *et al.*, 2009) in short-term. Only the HUBER vacuum rotation membrane, Fraunhofer Rotating disk filter and Grundfos BioBooster have been commercialized in the full-scale applications. The schematic illustration or pictures of DSFs in MBRs is given in **Figure 7**.

5.2.1 Vibrating hollow fiber modules (VHFM)

In VHFM, the membrane module consists of hollow fiber membranes placed vertically. The skin layer is located at the outside of the fibers, thus the permeate is sucked from the outside to the inside of the fibers. The membrane modules are vibrated in a vertical motion at different frequencies (0-30 Hz) and different amplitudes (0.2-4 cm) (Altaee *et al.*, 2009; Beier *et al.*, 2006; Genkin *et al.*, 2006). This type of DFS has recently been applied in the lab-scale submerged MBRs. The surface shear rate can periodically be changed and significant improvement of the CF achieved by this system. These improvements were even higher in addition of coagulants and additional vanes (Genkin *et al.*, 2006). The oscillation of the membrane in a VHFM system can also be performed in the transverse direction, which is also proven to maintain a good performance (Kola *et al.*, 2012; Kola *et al.*, 2014).

5.2.2 HUBER vacuum rotation membrane

The HUBER vacuum rotation membrane is commercialized under the trade mark of VRM® Bioreactor, and is basically a submerged MBR. The filtration system consists of a rotating hollow shaft around which 6 or 8 UF flat-sheet modules are fixed with predefined clearance between each module. The modules are rotated at 2.5 rpm and cross-flow is also generated using air bubbles. (Komesli *et al.*, 2007) The rotating motions of the filtration module produce intensive turbulences within the reactor tank, such that no additional circulating units are required.

5.2.3. Grundfos BioBooster

Grundfos BioBooster is provided as an MBR package in a closed system. Unlike most MBRs, the enclosed vessel is pressurized to drive the filtration. The flat-sheet ceramic membranes are fixed while the shear rate is generated from the cycloidal rotating pattern between two disks with different size. These disks also act as a self-cleaning mechanism, thus no chemical cleaning is required. Furthermore, rotating cross-flow impellers between membranes prevent fouling to allow the system to operate at 4-5 times higher MLSS concentration. (Ratkovich *et al.*, 2012)

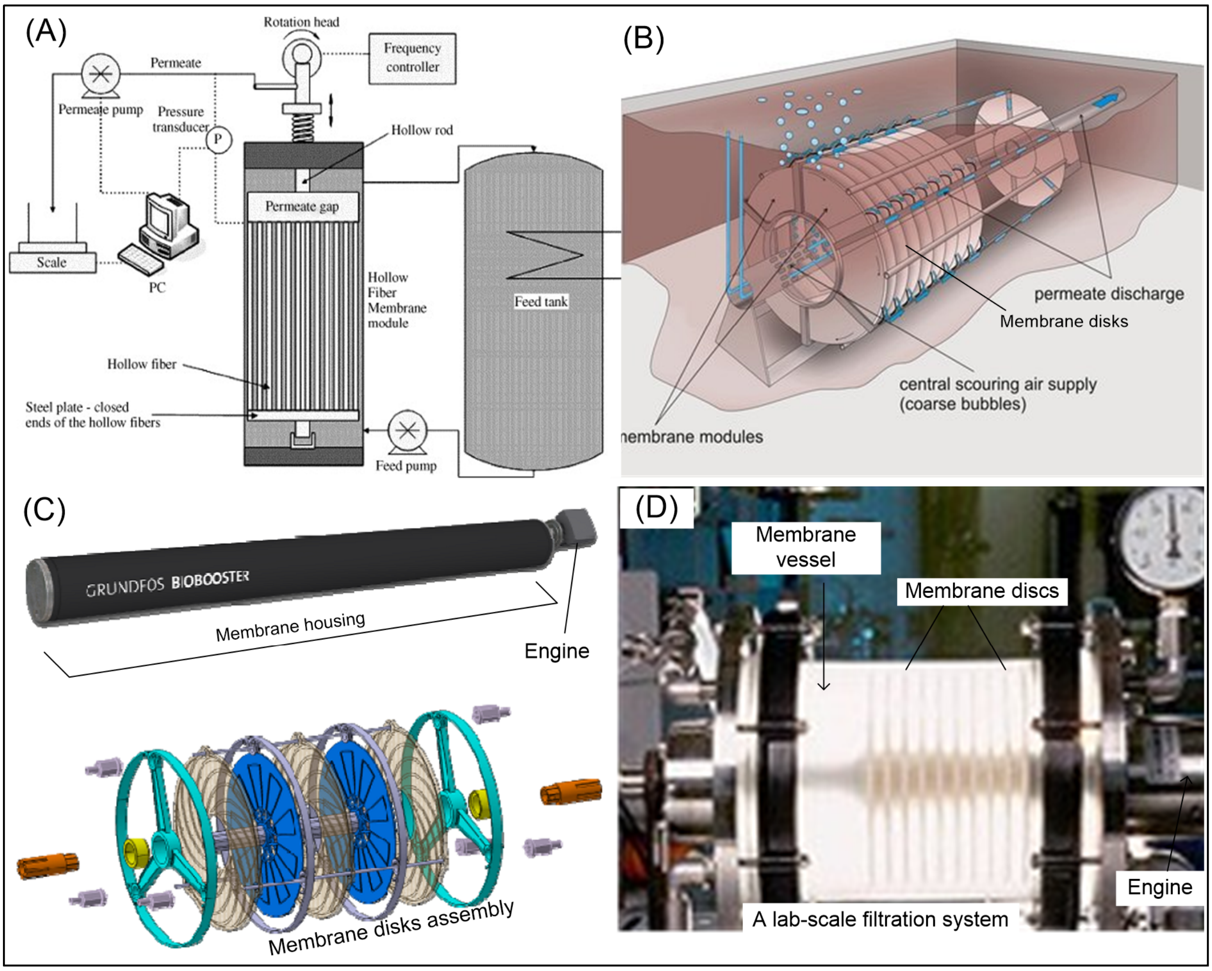


Figure 7. Schematic illustration of (a) VHFM, (b) HUBER vacuum rotation membrane, (c) Grundfos BioBooster MBR, (d) Fraunhofer Rotating disk filter.

4.2.4. Fraunhofer rotating disk filter

Fraunhofer IGB (Germany) developed a rotating disk filter that has also been implemented in decentralized wastewater treatment plants. It is claimed to have the capability of achieving filtration at high flux with a minimum maintenance and low energy consumption. It is composed of a cylindrical housing, containing a stack of ceramic membrane disks on a rotating hollow shaft. The membrane module is placed inside an enclosed pressurized tank of 0.2-1.5 bar. The permeate passes through the separation layer on the membrane disk outside-in and is drawn off via the hollow shaft. The foulants are removed from the membrane surface by means of the centrifugal force field created. This enables the laminar particle layer – adhering on the filter disk and thereby rotating together with the disks – to flow off. Thus, the particle layer is continuously renewed. This technology is manufactured and commercialized and has been implemented on a large scale for the first time in Heidelberg-Neurott in 2005. Another filtration plant is installed for sludge digestion of the wastewater treatment plant of Tauberbischofsheim.

6. CHALLENGES FOR FUTURE MBR RESEARCH

6.1. Dynamic Behavior, Interdisciplinary Field and Multi-Inter-Relationship Parameters

As MBRs involve many different fields, MBR research attracts many research groups from many different disciplines. It results in an outstanding number of publications regarding this topic. State-of-the-art characterization techniques have also been implemented to cover many different aspects, such as morphological visualization, componential characterization, and microbiological identification. (Meng *et al.*, 2010)

It has been discussed earlier that general trends are often hard to catch within the MBRs studies. In the MBR, biological suspensions are characterized by their dynamic behavior and constant changes. The physical and physiological conditions of the biological suspension change in response to the change in environmental conditions. The MBR studies do not only involve the biology, but also chemical and physical aspects. Moreover, no standardization exists in MBRs, allowing a wide variety of different configurations at both full- and lab-scale studies (Drews, 2010). For instance, lab-scale tests are mostly performed in a relatively short period, with a constant synthetic feed composition and temperature, while this is more fluctuating at a full-scale (Kraume *et al.*, 2009). It leads to different characteristics of the mixed liquor, different microbial communities, different levels of SMP concentrations, and different fouling propensity (van der Gast *et al.*, 2006), thus not allowing a fair comparison of both scales. The lab-scale set-up also has a much higher energy input that might lead to more exposure of the activated sludge to shear (Drews, 2010).

6.2. Energy consumption and cost considerations

Both capex and opex for MBRs are still higher than for conventional activated sludge and will remain higher unless possibility of permeate reuse is counted (Judd, 2008). In general, this is associated with the occurrence of membrane fouling which has been discussed widely throughout literature (Braak *et al.*, 2011). Most MBR studies aim at developing or inventing the strategies to control fouling in lab-scale set-ups, or at optimizing the system in full-scale to minimize the costs associated with the coarse bubble aeration which varies from 30-50% of opex (Judd, 2008).

6.3. Research perspectives

Despite the maturity of MBRs, many key areas are being developed to improve the competitiveness of the technology. Forward osmosis has recently been implemented in osmotic MBRs (Wang *et al.*, 2016), which show effectiveness in combating membrane fouling. Novel membrane types that are designed to pose minimum fouling propensity is also effective (Bilad *et al.*, 2015; Kharraz *et al.*, 2015; Marbelia *et al.*, 2016). Performance of MBR can also be further enhanced through process integration, such as with microbial fuel cell (Chen *et al.*, 2014; Ren *et al.*, 2014; Su *et al.*, 2013) or with photobioreactor (Gao *et al.*, 2016; Marbelia *et al.*, 2014). MBR technology also requires an upgrade in order to treat emerging contaminants such as pharmaceutical compounds (Melvin & Leusch, 2016; Prasertkulsak *et al.*, 2016).

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8. AUTHORS' NOTE

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