The Future Challenges of Anaerobic Membrane Bioreactor (AnMBR) for High Strength Wastewater

S. Salaeh, W. Khongnakorn* & W. Chaipetch

Centre of Excellence in Membrane Science and Technology, Department of Civil and Environmental Engineering, Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla, 90110, Thailand

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ABSTRACT

This article is to present a review of anaerobic membrane bioreactor (AnMBR), process, operational condition, fouling mechanism and future challenge for high strength wastewater. Since 1969s, membrane filtration technology has been used and continuously developed for wastewater treatment and recovery. AnMBR has proposed for the economic feasibility owing to the low footprint, high yield production under the relatively low energy consumption. Continuous stirred tank reactor (CSTR) configuration is the widely used couple with a flat sheet or hollow fibre modules. The various factors of operating condition are influence on the performance such as hydraulic retention time (HRT= 6 – 12 d), solid retention time (SRT > 100 d) and operating temperature (T = 10 - 56°C). In addition, the increase in temperature is related to high methanogenic activity and high COD removal efficiency (85% - 99%). However, the limitation of this process is fouling that occurs from the soluble microbial product (SMP), exopolymer substance (EPS) and biopolymer cluster (BPC). Almost of appropriate operating conditions for high performance, anti-fouling, the majority of effective microorganisms and energy balance are discussed in detail. For the challenge work, improvement of the prevention membrane fouling and high energy recovery in the hybrid/combination system with forward osmosis (FO), membrane distillation (MD) and powder activated carbon (PAC)-AnMBR.

Keywords: Anaerobic membrane bioreactor (AnMBR), operating condition, removal efficiency, anti-fouling; hybrid process

1.0 INTRODUCTION

Anaerobic membrane bioreactor (AnMBR) is focused and developed for high strength or hardly biodegradable wastewater treatment to obtain the high-water quality and renewable energy as methane-rich biogas from wastewater. Previous researches are studied the application of leachate [1, 2] and industrial wastewater (such as brewery wastewater [3], kraft evaporator condensate [4], etc). The purpose of this article is to present the challenge of the anaerobic membrane bioreactor process, operational condition, fouling mechanism, and hybrid process for the future challenge.

2.0 AnMBR SYSTEMS

2.1 Membrane Characteristics, Module and Their Configuration

Several authors have explored with the commercial MF and UF polymer membranes which made from polyvinylidene fluoride (PVDF) [5-6],

* Corresponding to: W. Khongnakorn (email: watsa.k@psu.ac.th)
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polytetrafluoroethylene (PTFE) [7], polysulfone (PS)/ polyethersulfone (PES) family, cellulose acetate (CA) [8], polypropylene (PP) [9] and polyethylene (PE). The modules are often fabricated in flat sheet, hollow fiber, and tubular modules [5, 9, 10]. In addition, ceramic membranes are used and effectively provide for a high resistance for corrosion, anti-fouling, and concentration polarization (CP) control. The ceramic membrane is also tolerant for chemical oxidation and high temperature. The configuration of AnMBR is divided into 2 types: external/side-stream configuration and submerged/immersed configuration as shown in Figure 1. Almost flat sheet module is employed in submerge configuration. Tubular module is employed in side stream configuration. Nowadays, hollow fiber are developed to operate under high flux because of their high packing density and large pore size [11-12]. Table 1 presents the summary of AnMBR performance under the different membranes. The COD removal in the system is higher than 90% with a high organic loading rate (OLR>10 kg COD/m³.day) [3-4, 13]. The completely stirred tank reactor (CSTR) configuration is a typical reactor which use for lab-scale at the low loading [14]. Moreover, gas-lift anaerobic membrane bioreactor (GL-AnMBR), completely mixed digester (CMD), anaerobic dynamic membrane bioreactor (AnDMBR) configurations were conducted to enhance flux and reduce fouling in the systems [3, 15]. The micro-pollutants (such as pharmaceutical products, high strength wastewater, etc) are high removal performance with dynamic technology or submerged anaerobic dynamic membrane bioreactor (AnDMBR) [9].

Figure 1 Configuration of AnMBRs for (a) external and (b) submerged AnMBR (adapted from [16])

2.2 Effects of Operating Condition

Many researches [4, 6, 12, 13] were focused on operating conditions in AnMBR that affect its performance. The performance in AnMBR is focusing on water permeate quality, flux obtained, and methane yield. The mainly significant parameters of operational condition are discussed as follows:

Sludge Retention Time (SRT) and Hydraulic Retention Time (HRT)

SRT is a major important factor that indicates the footprint of the system, biomass concentration, biomass production, and especially the quantity of biopolymer cluster product (BCP) such as soluble microbial product (SMP) and exo-polymer substance (EPS).
Table 1 Summary of AnMBR performance under the different membrane characteristics, membrane module and configuration

| Reactor type/module configuration/ membrane configuration | Type of waste water                  | Membrane type | Material | Pore size (µm) | Filtration area (m²) | Flux (L/m² h) | TMP (kPa) | Reference |
|----------------------------------------------------------|--------------------------------------|---------------|----------|---------------|----------------------|--------------|-----------|-----------|
| Jet flow anaerobic bioreactor /Cross-flow                | Landfill leachate                    | UF            | -        | -             | 1                    | -            | 100       | [1]       |
| UASB/Flat sheet/AnDMBR                                   | Landfill leachate                    | -             | -        | 40            | -                    | 6            | 40        | [2]       |
| Gas-lift anaerobic membrane bioreactor (Gl-              | Synthetic sewage,                    | UF            | PVDF     | 0.03          | 0.013                | 18           | -         | [5]       |
| AnMBR)/Tubular                                           | Mimicking household wastewater       | -             | PVDF     | 0.002         | 0.07                 | 15-35        | 35-90     | [6]       |
| UASB/Hollow-fiber                                        | Bamboo industry wastewater           | -             | PVDF     | 0.5           | 0.2                  | -            | -         | [8]       |
| Upflow sludge contact bioreactor /Hollow fiber            | Synthetic wastewater                 | -             | PES      | 0.7           | 0.022                | 2.7-6.9      | 8         | [47]      |
| AnHMBR/Aerobic membrane bioreactor and fixed-bed biofilm reactor | Synthetic wastewater                 | -             | -        | 0.7           | 0.022                | 2.7-6.9      | 8         |           |
| UASB/Completely mixed glass reactor/                     | High strength wastewaters           | -             | Polypropylene | 10           | 0.018                | 2.6          | -         | [9]       |
| Submerged flat sheet/rectangular                         |                                     |               |          |               |                      |              |           |           |
| Completely mixed digester (CMD)/Tubular                   | Dairy manure                         | UF            | PVDF     | 0.03          | 0.079                | -            | -         | [12]      |
| Completely mixed digester (CMD)/Tubular                   | Textile wastewater                   | MF            | -        | 0.4           | -                    | 1.8-14.4     | -         | [40]      |
| CSTR/Submerged Hollow fiber                              |                                     |               |          |               |                      |              |           |           |
| CSTR/Submerged /Flat sheet                                | Whey/Sucrose                         | -             | -        | 0.4           | -                    | 2-5          | -         | [45]      |
| Submerged AnMBR/Hollow-fiber                             | Pre-screened wastewater from the     | -             | PVDF     | 0.4           | 2                    | 3.5-14.4     | -         | [46]      |
| Submerged/Flat sheet                                      | Synthetic raw sewage                 | MF            | PVDF     | 0.45          | 0.05                 | -            | -         | [48]      |
Practically, long SRT (> 100 d) is an effect on performance and removal efficiency than HRT. The concentration of SMP increases at elevated SRT that causing a decreasing fouling potential [14, 17-20]. The typical HRT is between 6-12 d. Almost of publications conclude that a higher HRT is necessary for biodegradation of complex wastewater and reduction of volatile fatty acids (VFAs) accumulation in the reactor. The accumulation of VFA could reduce the performance efficiency and induce fouling. In the contrast, long SRT makes a larger footprint and lower OLR, and thus induces the reduction of the permeate fluxes [14, 21].

**Temperature**

The operation under thermophilic conditions (>45 °C) obtained higher methane yields due to the high-rate metabolite. Actually, the limitation of high temperature induces more release of SMP and ESP were caused by the high fouling potential [20]. The operation temperature in the mesophilic range under higher organic loading rates (> 10 g COD/L.d) found no significant different yields when compared with the thermophilic conditions. In the contrast, thermophilic conditions obtain the yields rate more than 5 times in mesophilic conditions especially in the hydrolysis process [22].

**Microorganism in the System**

Hydrolytic and fermentative bacteria are included *Clostridium spp, Peptococcus anaerobes, Lactobacillus, Bifidobacterium spp, Desulphovibrio spp, Corynebacterium spp, Actinomyces, Staphylococcus, and Escharichia Coli* [22]. Methane yield production depends on the activity of methanogenic populations that are major influenced by temperature. Methanogenic microorganisms identified in mesophilic conditions include the rods (*Methanobacterium, Methanobasillus*) and spheres (*Methanococcus, Methanothrix, and Methanocarnia*). Bakonyi et al. [21] were concluded that high methanogenic activity and can be diverted when operating under high SRT and high temperature (60 - 65°C).

The summary of operating conditions was the effect on performance is presented in Table 2 and can be concluded as follows:

- The thermophilic temperature increases the biogas production performance according to increasing the microorganism activity.
- The high HRT induced better biodegradation and reduce the VFA accumulation. It will be enhanced methane production.
- The high SRT induces the SMP and EPS production that lower fouling rate in AnMBR.

### 3.0 FOULING AND PREVENTION

The disadvantage of AnMBR is fouling, especially, biofouling such as soluble microbial product (SMP) and exo-polymer substance (EPS), etc. The operational condition is a main influence to produce biofouling as present above [23-25]. Many researchers studied fouling prevention by increasing cross-flow velocity (CFV), sparging internal recirculation, and vibratory shear process to enhance the shear rate at the membrane surface [26-28]. The ultra-sonication had used to control cake formation and enhance the membrane filtration without the anaerobic bacteria activity inhibition and membrane damage.
Table 2 Summary of AnMBR performance under the different operating condition

| Type of waste water                  | OLR (kg COD/m³ day) | HRT (d) | SRT (d) | Temp (°C) | COD removal (%) | Reference |
|--------------------------------------|---------------------|---------|---------|-----------|-----------------|-----------|
| Landfill leachate                    | 6.27                | 7       | -       | 37        | 90              | [1]       |
| Landfill leachate                    | 6.27                | 7       | -       | 37        | 90.7            | [1]       |
| Landfill leachate                    | 1–6.27              | 7       | -       | 37        | >92             | [1]       |
| Landfill leachate                    | 4.87                | -       | -       | -         | -               | [2]       |
| Brewery wastewater                   | 12                  | -       | -       | 30        | 90              | [3]       |
| Brewery wastewater                   | 12                  | -       | -       | 30        | 99              | [3]       |
| Kraft evaporator condensate          | 22.5                | -       | -       | 36-38     | 93-99           | [4]       |
| Kraft evaporator condensate          | 1-24                | -       | -       | 36-38     | 99              | [4]       |
| Synthetic sewage, Mimicking household wastewater | -    | -       | -       | -         | 98              | [5]       |
| Bamboo industry wastewater           | 4.4                 | ≥5      | -       | 28-30     | 85-90           | [6]       |
| Synthetic wastewater                 | 1.5(±0.20)          | 0.125   | -       | 37        | 98 (±0.7)       | [8]       |
| Synthetic wastewater                 | 5                   | 1       | 50      | 30        | 96              | [10]      |
| High strength wastewaters            | 2                   | -       | -       | 35.7-0.1 | 99              | [9]       |
| Landfill leachate                    | 8-11.8              | 11-19   | 30-300  | 10-35     | >95             | [13]      |
| Palm oil mill effluent (POME)        | 7.66±0.40           | 6       | 30      | 45        | 72-78           | [42]      |
| Synthetic raw sewage                 | -                   | 0.35-0.49 | -       | 30-32     | 94±0.5          | [48]      |
| Molasses-based                       | 5–12.2              | -       | -       | 27–33     | -               | [49]      |
| Organic waste mixture                | -                   | 2–20    | -       | 35        | 99              | [50]      |
| Organic waste mixture                | -                   | 0.083   | -       | 35        | 99              | [50]      |
In addition, Quorum quenching (QQ) was reported for the mitigation and biodegradation of microbial and microbial production which affect fouling [29-30]. Moreover, entrapped cells or/and encapsulation cells had been studied to reduce fouling and enhance the performance of the microbial communities [31-33]. The membrane fabrication and modification with the incorporation by nanoparticles (such as silver (Ag), gold (Au), etc.) were developed for reducing biofouling [34].

4.0 NEW CHALLENGE AND PROSPECTIVE IN HYBRID ANMBR

In the last 10 years, many researchers attempted to develop the system without energy supply or obtain more energy and also less fouling. Many researchers [9, 17, 35] had reported maximum net energy used approximately at 0.04 kWh/m³ for sulfate-rich urban wastewater removed under high ambient temperature and/or high SRT conditions. The average energy production obtained at 2.02 kWh/kg COD removed. Hence, the hybrid/combination system was proposed to reduce energy consumption such as the combine system with forward osmosis (FO) [15, 36], anaerobic membrane bi-electrochemical reactor (AnMBER) [37], granular activated carbon (GAC)-fluidized AnMBR [36], AnMBR-membrane distillation (MD) [39], anaerobic dynamic membrane bioreactor (AnDMBR) [24], entrapped cell- based AnMBR [31], granular or PAC AnMBR [38, 40-42] etc. In addition, adapted microbial fuel cell (MFC) in anaerobic membrane bi-electrochemical reactor (AnMBER) for wastewater treatment with nitrification and denitrification process obtained high performance and less fouling. The energy obtained about 1.16 W/m³ net cathodic chamber (NCC) [37]. The hybrid technology can be summarized in Table 3. While the couple with FO presented high performance but the external concentration polarization (ECP) by protein was a majority of fouling in this system [36]. Increasing of granule (G-AnMBR) and PAC (PAC-AnMBR) in the system increased performance especially the small particle size due to enhanced hydrodynamic mixing, reduced gas sparging demand [41, 42-44].

Hence, it can be concluded that the development of study is focused as follows:

- Firstly, the study is focused on fouling prevention by hydrodynamic force (i.e. increasing of shear rate at the membrane surface) and biofouling prevention by SMP and EPS limited (i.e. operational condition control).
- Secondly, the study is focused on energy consumption and production by the biogas and methane yield and the biogas recirculation in the system, and,
- The last study is focused on water effluent quality, especially from high strength wastewater (i.e. industrial wastewater or hard biodegradable wastewater).

5.0 CONCLUSION

AnMBR is a well-known process for high-strength wastewater treatment. The efficiency of the system is depending on the membrane properties, design performance, and operational condition. The main advantage is positive net energy obtain and high removal.
### Table 3: The summary of energy recovery in hybrid AnMBR

| Type of hybrid AnMBR | Membrane                  | Type of wastewater                      | OLR (kg COD/m³ day) | HRT (d) | SRT (d) | COD removal (%) | Energy recovery (kWh/m³) | Reference |
|----------------------|---------------------------|------------------------------------------|---------------------|---------|---------|----------------|-------------------------|-----------|
| GAC-fluidized AnMBR  | PVDF-UF membrane          | Domestic Wastewater                     | 1.4±0.5             | 0.2     | 11±5    | 86-90          | 0.27                    | [38]      |
| AnMBR-MD             | MF                        | Synthetic domestic wastewater           | -                   | 4       | 215     | 98.4 ± 0.4     | 0.3–0.5 L-biogas/g COD_added | [39]      |
| MEC-AnMBR            | PVDF-UF membrane with     | Synthetic wastewater                   | 5                   | 1.5     | -       | 70.6           | 0.6 V (DC)supply         | [51]      |
| MFC- AnMBR           | MF                        | Synthetic wastewater                   | -                   | -       | -       | 58.7           | 1.16                    | [37]      |
However, the limitation of AnMBR is fouling. Hence, the hybrid process such as dynamics process (AnDMBR), osmotic pressure process (FO-AnMBR), porous material addition (PAC-AnMBR; G-AnMBR), electrochemical process (AnMBER), and microorganism improvement have been proposed and developed to achieve high performance and high energy recovery.

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