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Current Conditions and Developing Tendency of Membrane Bioreactor

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Abstract

The classification, technological characteristics, current conditions and developing tendency of membrane bioreactor (MBR) were reviewed in this study. Different classification methods of MBR were introduced firstly. The external MBR and the integrated MBR were discussed in detail subsequently. The advantages and disadvantages of MBR were analyzed compared with conventional activated sludge process (CASP). The history, current conditions and developing tendency of MBR were also summarized.

Keywords: Membrane bioreactor; Classification methods; Advantages and disadvantages; Current conditions; Developing tendency.

1. Introduction

As water shortages are increasing, the need for sustainable water treatment and the reuse of water is essential. Municipal sewage, called “the second water source”, is widely reclaimed and reused to meet the growing city water pressure in all over the world. Membrane bioreactor (MBR), combined with membrane separation technology and biological treatment process, has been much respected among numerous municipal sewage reusing technologies by water treatment researchers. MBR can be divided into different types based on its characters. It has been researched and developed for over half a century, and has a vast development foreground. The classification, technological characteristics, current conditions and developing tendency of MBR were reviewed in this study

2. Classification of MBR

According to the different effects of membrane modules in bioreactors, MBR can be divided into three types (Shown in Fig. 1) of solid/liquid separation MBR (SLSMBR), aeration MBR (AMBR) and extractive MBR (EMBR) [1]. Generally, the MBR called by most people means these three types of MBRs.

SLSMBR uses membrane module to separate solid and liquid. The intercepted sludge is returned to bioreactor and the permeated liquid is reused or is used as the raw water of post-process. Researches and applications about SLSMBR are specially extensive and in-depth [2,3]. As a general rule, MBR usually refers to SLSMBR. AMBR uses breathable membrane and makes bubble-free aeration in the bioreactor, which can significantly increase the contact time and the oxygen transfer efficiency. EMBR uses extractive-membrane to extract priority pollutants in wastewater, and then uses obligate bacteria to

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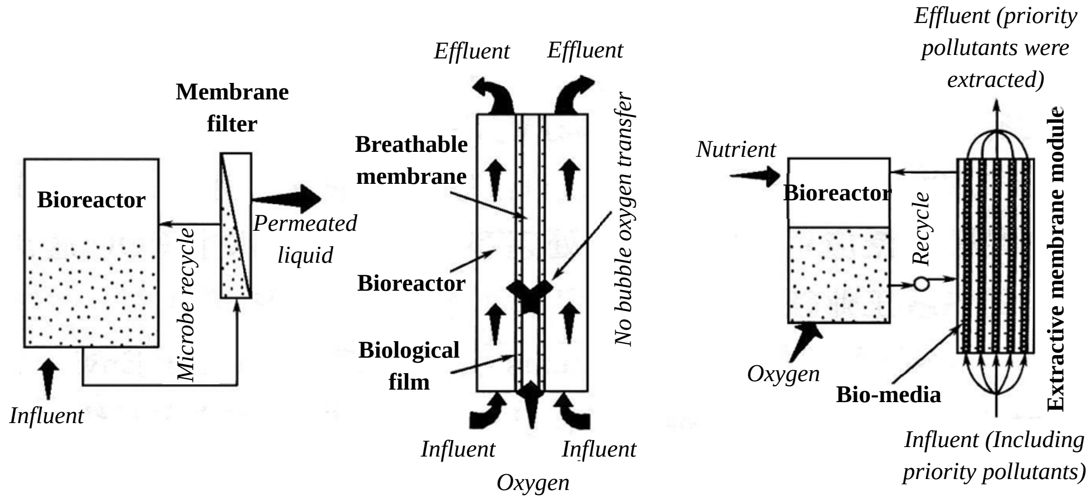
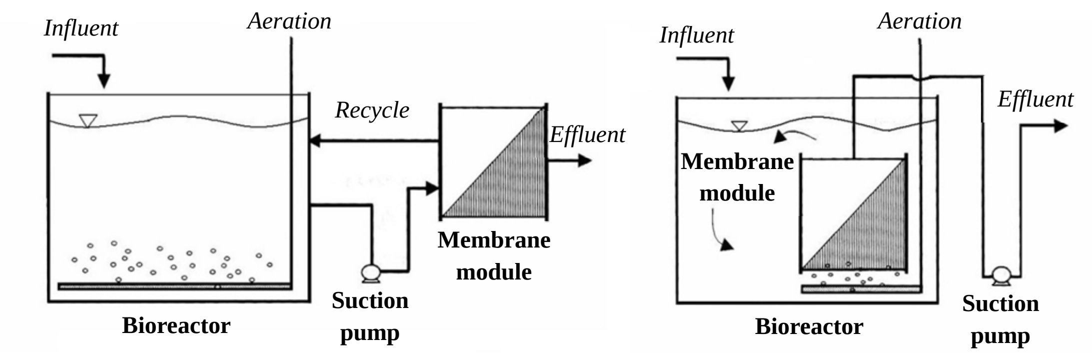
biodegrade the priority pollutants. This process isolates the wastewater and the activated sludge from each other and optimizes the function of the bioreactor [1].

MBR also have other classification methods based on different characteristics. Due to the need of oxygen of microorganism, MBR can be divided into oxic type and anaerobic type. In the aspect of chemical compositions of the membrane materials, MBR can be classified as organic-membrane type and inorganic-membrane type. According to the operation modes, MBR can be classified as sequencing-batch type and continuous type. Based on the pore size of membrane, MBR can be classified as microfiltration membrane type, ultrafiltration membrane type and other types. According to the membrane module forms, MBR can be classified as flat membrane type, tubular membrane type, hollow fiber membrane type and other types. In the aspect of the combination modes of membrane modules and bioreactors, SLSMBR can also be classified as external MBR and integrated MBR [4], which were shown in Fig. 2. Of course, the various categories of MBR as described above are not mutually exclusive or independent. On the contrary, they can be combined into a new biochemical bioreactor if necessary.



(a) SLSMBR (b) AMBR (c) EMBR

Fig. 1 Schematic diagrams of three kinds of MBRs



(a) External MBR (b) Integrated MBR

Fig. 2 Diagram of two kinds of SLSMBRs

External MBR is also known as cross-flow MBR (CMBR). In CMBR, the membrane module is placed outside the bioreactor as showed in Fig. 2 (a). The mixed liquor in CMBR enters into membrane module after been pressurized by a suction pump. Driven by pressure difference, water and small molecules in the mixed liquor go through the membrane and turn into effluent. At the same time, sludge, suspended substance and other macromolecule matter are retained by membrane and return to the bioreactor with concentrated solution. The transmembrane pressure (TMP) range of CMBR is generally from 100 kPa to 400 kPa, and the membrane flux range is from 50 L/(m2·h) to 120 L/(m2·h) [5]. CMBR is in a way of cross-flowing operation through liquid circulating. This type of operation has many advantages, such as less interference between membrane and the bioreactor, stable and reliable operation, larger membrane flux and convenient cleaning, replacement and increase of the membrane. In order to reduce the deposition of contaminants on the membrane surface and to extend the cleaning cycle of the membrane, a suction pump is generally required to provide a higher flow rate on the membrane surface, resulting in an increased quantity of water circulation and an increased power charge [4]. Besides, shear forces caused by the high-speed rotation of the pump would inactivate some microbes [6,7].

Integrated MBR is also called submerged MBR (SMBR). In SMBR, membrane module is placed inside the bioreactor as showed in Fig. 2 (b). Pressure difference is produced in and out of the membrane chamber by the action of suction pump or gravity, thus water and small molecules can be absorbed into the chamber through membrane pores and turn into effluent. TMP of SMBR is typically less than 50 kPa and the membrane flux range is from 15 L/(m2·h) to 50 L/(m2·h) [5]. An aeration system is placed below the membrane module to provide oxygen to microbes, thus can maintain normal metabolic activity of microbes. Besides, the rising mixture provides shear force on the surface of membrane, thus effectively inhibits the deposition of contaminants on the membrane surface [8]. As a result, membrane module can work continuously without frequently cleaning. SMBR is free of mixture circulation, has relative low energy consumption and small space-occupancy. However it is inferior to CMBR in aspects of running stability, water production rate, operations management, cleaning replacement, etc [5].

3. Advantages and disadvantages of MBR

The membrane module in MBR is used to replace the secondary settling tank of conventional activated sludge process (CASP), thus can achieve efficient solid-liquid separation and overcome large fluctuation of the effluent quality and sludge bulking. MBR also has the following advantages [1,3,5,9,10].

(1) Perfect treatment effect and high effluent quality

Membrane and gel layer on the membrane surface have a high efficiency of filtration and interception, thus can strengthen the effect of MBR on wastewater treatment. It includes: a) MBR can achieve the individual control of hydraulic retention time (HRT) and solids retention time (SRT), and then achieving short HRT and long SRT at the same time. Thus can maintain a high mixed liquor suspended solids (MLSS) concentration in bioreactor, reduce sludge loading rate (SLR), accelerate the rate of biochemical reaction and enhance processing capacity. b) The filtration effect of membrane provides favor conditions for slow-proliferated bacteria (e.g. nitrobacteria) and other special microorganisms to enrich themselves, thus can improve the nitrification of systems and the ability of special sewage treatment [4,11]. c) Membrane and gel layer on the membrane surface can efficiently intercept particles, large organic molecules and refractory organics, leaving enough staying time for them and finally removing them [12].

d) Effluent of MBR is almost free of suspended solids (SS) and opacities, as well as bacteria and viruses [4,11,12].

(2) High resistance to shock load and stable effluent quality

High MLSS concentration in MBR can not only greatly improve the volume loading rate (VLR) of the system, but also enhance the ability of the system to resist shock load and hazardous substances, so the system can still keep good removal efficiency and stable effluent quality even in the condition of large impact wave.

(3) Less sludge production and low excess sludge disposal cost

In MBR the MLSS concentration is high and SLR is low. The matrix flowed into MBR is mainly used to maintain the minimum nutritional requirements of microorganisms, so the sludge yield in MBR is far lower than which in CASP [12]. Currently the sludge treatment and disposal cost accounts for 25% to 40% of total operating costs of sewage treatment plants, and some even up to 60% [13]. This item has been one of the constraints of normal operation. Therefore, reducing the production of excess sludge since the source is another valuable advantage of MBR.

(4) A certain effect of denitrification

High MLSS concentration and fast oxygen consumption rate in the MBR make it easy to form a local hypoxia zone or a sludge floc including an aerobic surface and an anoxic internal. Therefore, MBR can achieve simultaneous nitrification and denitrification (SND) in one reactor, having a certain effect of denitrification while removing chemical oxygen demand (COD) [11,12].

(5) Simple structure, easy to modularize, easy to facilitate automated management and easy to upgrading

Few components and compact structure of MBR make it easy to process into complete plant and to achieve modularity and automation. This not only simplifies the transportation and installation of the equipment and shortens the construction period, but is beneficial to upgrade and capacity increase of the original equipment, and achieves automated operation and saves labor costs at the same time.

(6) Small footprint, be suitable for upgrading CASP and decentralized sewage treatment

In the oxic MBR, the range of VLR of COD is generally from 1.2 kg/(m3·d) to 4.2 kg/(m3·d), about 2 to 5 times of CASP [14]. Oxic MBR is free of a secondary settling tank or a sand filter system. That can reduce the reactor volume to 1/5~1/2 of the original, greatly reducing the occupied area. So oxic MBR ideally suited for upgrading the existing sewage treatment plants and decentralized sewage treatment (e.g. wastewater reuse of districts and buildings).

However, MBR also has several disadvantages, mainly in the following respects.

(1) High membrane cost and short lifespan cause a higher MBR infrastructure investment than CASP. But with the advances in membrane manufacturing technology, the cost is expected to gradually decline in the future.

(2) A certain membrane fouling during system operation results in flux decline and reduces water production rate of the system [7,15].

(3) Since the generation of membrane fouling, membrane module must be cleaned or replaced, bringing inconvenience to the operation and management and increasing operating costs [15]. Moreover, post-treatment of the chemical cleaning agents will lead to new environment problems [16].

4. History, current conditions and developing tendency of MBR

The research of MBR which was applied in the field of wastewater treatment began in the 1960s. In 1966 Dorr-Oliver Corp. (USA) first developed the membrane sewage treatment (MST) and used it mainly for marine sewage treatment [17,18]. In 1969 Smith etc. developed a kind of MBR that combined aerobic activated sludge process with the ultrafiltration membrane, and applied it to municipal wastewater treatment. In the same year, Budd etc. developed the external MBR and won a U.S. patent. Since the 1970s, trials on the scale of applying aerobic CMBR for municipal wastewater treatment was further expanded. In 1971 Bemberis etc. did a MBR experiment in the actual sewage treatment plant and achieved satisfactory results. In the meantime, the research of anaerobic MBR also has been started. In 1978 Grethlein etc. treated domestic sewage by a CMBR. In this research, removal rates of biochemical oxygen demand (BOD) and nitrate reached 85% to 95% and 72% respectively [19,20].

Researches between the 1960s and the 1970s showed that MBR has a quality of high MLSS concentration, excellent effluent quality, small covering area, etc. However, due to the high cost of membrane modules, frequent membrane cleaning in MBR and high operating cost of CMBR and other factors, this technology wasn't popular in practice except some small occasions for special requirements [21].

Since the 1980s, MBR got a new opportunity to be developed. For a great need of recycled water, Japan began to pay attention to develop MBR technology for wastewater treatment and water reuse. During 1983 to 1987, there were 13 companies in Japan that used aerobic MBR to treat and recycle wastewater, and the scale of MBR reached 50m3/d to 250 m3/d [19]. In 1989 Yamamoto (Tokyo University, Japan) first put hollow fiber membrane module directly into the aeration tank and invented SMBR [4]. Compared with CMBR in 1980s, SMBR is free of high-speed cross-flow, high energy, and decreased activity of microbes and other disadvantages. This is a milestone in MBR history [4]. In 1990s, Japanese government with many important MBR companies initiated a 6 year's "Aqua Renaissance Programme'90" to develop new technology for water reuse. They did a deep research in the development of new membrane materials, structural design of membrane separation units, MBR operation system, etc., greatly expanding the range and scale of MBR in wastewater treatment. Submerged flat membrane MBR invented by Kubota and hollow fiber membrane MBR invented by Mitsubishi Rayon were the outstanding achievements of this program [22,23]. Driven by Japanese companies, MBR was of rapid development, especially SMBR technology, which have accounted for 55% of the amount of MBR nowadays [14].

Besides, MBR in other countries and regions has also been developed and applied. In the 1980s Zenon Corp. (Canada) successfully developed different kinds of MBR technologies and brought its commercial production into the market in 1982 [18,23]. In the same year, Dorr-Oliver Corp. (USA) launched an external circulation membrane-anaerobic reactor system to treat food wastewater of high concentrations, and the removal rate of COD reached 99%. In South Africa, the anaerobic MBR technology began to enter the market of industrial wastewater treatment in the early 1980s, and in Europe, the aerobic MBR technology also began to appear in the mid-1980s.

From the mid-1990s, MBR entered a rapid-development period and really stepped into the practical stage. This attributed to the increasingly demand for water reuse by water environment and the strongly support for MBR applications and researches by governments. On the other hand, the mature commercialization of MBR technology and the decrease prices of membrane material were also important to drive MBR's success. Fig. 3 shows the price trend of microfiltration membrane from Kubota and Norit.

It has been found that the membrane price was below 50 $/m2 in 2005, approximately a tenth the price in 1992. Such a price has strongly reduced he construction and operating costs of MBR.

With decades of continuous development and mutual merger, there are a number of companies in the world offering membrane modules and MBR equipment, such as GE-Zenon, Kubota, Mitsubishi Rayon, Norit, Siemens, and KMS et al. [2,24,25]. In 2005 the MBR market scale in the world has reached 217 million dollars, while only 10 million dollars in 1995. It has been predicted that the MBR market scale will increase to 363 million dollars by 2010. MBR market in the Europe centers on Germany, Britain, France, Holland, Ireland, Italy and Belgium. This MBR market scale was 57 million Euros in 2004, being expected to more than twice the scale after 7 years. MBR market in North America is growing constantly. Although there has no separate statistics of its market scale, the total market scale of membrane-associated water treatment including water treatment, desalination and wastewater treatment reached 1.3 billion dollars in 2010. Asia, especially East Asia also has an important MBR market. For example, in China, Japan and South Korea, MBR is wildly used in engineering [17,18,26].

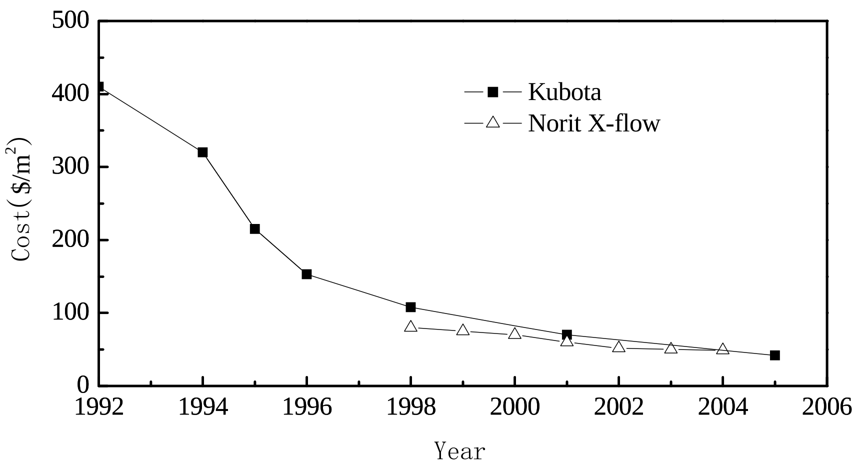


Fig. 3 Changes of Micro-Filtration membranes’ costs with time

By the year of 2004, more than 2,200 plants of MBR were operated all around the world, of which about 70% were used to treat municipal sewage [25]. It had been predicted that in the next five years average 1000 plants of MBR per year would be put into operation [18]. The majority of MBR that treat municipal wastewater has a scale of 103 m3 per day. The MBR scale of 104 m3/d began to appear from about 2000. With rapid development, there are about 40 MBR plants of this size around the world, such as Kaarst, Germany (2004, GE-Zenon, 45000 m3/d), Muscat, Oman (2006, Kubota, 76000 m3/d) and Korea (2008, Mitsubishi Rayon, 30000 m3/d). Dubai is building a scale of 220000 m3/d MBR wastewater treatment system, which is currently the world’s largest MBR construction project and will be the world’s largest MBR plant. MBR applied in the industrial wastewater treatment is more competitive than that used in the municipal sewage treatment. It has been successfully used in food, beer, petrochemicals, slaughterhouse, medicine and landfill and other wastewater treatment. But its scale is smaller, usually between 102 m3/d to 103 m3/d. MBR has also been applied and been generalized in micro-polluted water treatment, groundwater denitrification treatment and other drinking water treatment.

5. History, current conditions and developing tendency of MBR in China

China's research on the MBR began in the mid-1990s, and has been supported by the national scientific and technological projects of "Eight-Five", "Nine-Five", and "Ten-Five", the fund projects by country with provinces and municipalities and the "863" major scientific and technological projects. Over the last ten years, MBR has been wildly studied by Tsinghua University, Tianjin University, Dalian University of Technology, Harbin Institute of Technology, Tongji University and Chinese Academy of Sciences Ecology Center and other units, including domestic sewage treatment, high strength sewage treatment, hardly-degradable industrial wastewater and special industry wastewater treatment, drinking water and micro-polluted water treatment, as well as process feature of MBR (membrane fouling, character and adjustment of sludge mixed liquor, optimization of operating conditions, etc.) [2], among these studies, domestic wastewater reuse and process feature about MBR are particularly important.

In addition to the wild development of scientific research, engineering application of MBR is developing rapidly in China. At present, China has been the world's fastest growing country of MBR projects. Especially, since 2005, the annual growth rate of treatment capacity of new medium and large scale MBR plants is greater than 100% (Fig. 4) [24]. A number of MBR treatment programs have been built up, distributing in Miyun, Beijing (45000 m3/d), Beixiaohe, Beijing (60000 m3/d), Tianjin Airport Industrial Park (30000 m3/d), etc [26].

In China, the main MBR market is carved up by Bishuiyuan (Beijing), Simens (Beijing Saiensite), GE-Zenon and ACEF, among which Bishuiyuan (Beijing) accounts for 60% of the market [24]. Domestic MBR membrane module (including hollow fiber membrane, flat membrane and tubular membrane) has an improving product quality and an expanding market share. Compared with foreign products, it is inexpensive and saves the investment and maintenance costs, but the performance and the mechanical strength of the product should be improved.

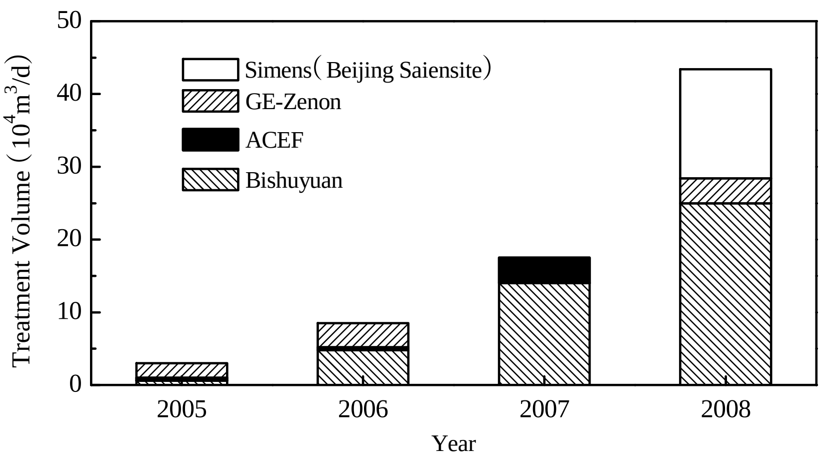


Fig. 4 Capacity of pilot and full scale MBRs in China from 2005

In recent years, a number of novel MBRs are on the rise in China, such as hybrid biofilm MBR, photo catalytic oxidation membrane bioreactor (pMBR) and jet loop MBR and so on. Hybrid biofilm MBR combines an efficient anoxic and oxic biological treatment process with a membrane filtration unit. It can simplify pre-treatment facilities, relieve the loading of the subsequent treatment processes and optimize the whole treatment process [27]. The pMBR is a self-designed MBR added in the photo catalyst TiO2. TiO2 is immobilized on polyurethane foam (PF) cubes. The photo catalytic oxidation zone in MBR tank plays a main role in removing the pollutions and contributes high removal efficiency of COD, BOD5 and color [28]. The jet loop membrane bioreactor (JLMBR) is a homocentric cylindrical vessel, which integrating high performance compact reactor with ultra-filtration membrane, was designed and applied in municipal wastewater treatment of shanghai zhuyuan. JLMBR shows an efficient, reliable process with the advantages of high efficiency of pollutant removal, small area requirement and low sludge yield [29].

6. Conclusions

Along with the rapid development of water recycle and reuse, MBR has been extensively applied in treating municipal wastewater; industrial wastewater; mineral wastewater and oil exploit wastewater. After been researched by several generations of scientists for over half a century, the MBR technology has got mature enough. MBR has many advantages, such as high capability of resistance to shock load, less sludge production, good effect of denitrification, automated management and small footprint. However, MBR also has several disadvantages, like high costs and fouling of the membrane. To be sure, MBR will be more and more popular in the wastewater treatment for its tremendous potential development capability.

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