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Membrane technology for municipal drinking water plants in China: progress and prospect

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ABSTRACT

The quality of drinking water from the conventional treatment process is not satisfactory, due to serious pollution of China's surface water. The improvement of the existing water treatment plants is the key to ensure the quality of drinking water in China. Membrane processes are gaining importance in water applications as a result of the advances in membrane technology and the increasing requirements on water quality. This study presents the results of the thorough survey of membrane technology for municipal drinking water plants in China. The survey consists of surveys of literature, membrane manufacturers, and water plants employing membrane technology. We examined the historic perspective of membrane technology and analyzed the membrane market in China. Performance of membrane plants in producing drinking water is investigated based on the survey as well. The results demonstrate that low pressure membrane technologies are employed extensively in China. Water plants with large capacity account for primary market share and drive the annual revenue growth. China will become a fast growing membrane market in the long run and Taihu basin region will continue to be the greatest market for new membrane equipment due to its enormous population and rapid economic growth.

Keywords: Cost analysis; Membrane technology; Drinking water

1. Introduction

With the accelerating economic development in China, many drinking water sources cannot meet the general requirements under the influence of anthropogenic activities. Generally, a large portion of surface water and groundwater are polluted, especially in the eastern part of China. A great number of water supply source problems are mainly due to organic and ammonia pollution. Some water sources have superfluous bacteria. In China, the majority of large lakes and reservoirs are in a state of eutrophication, characterized by

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frequent algae blooms. Some water sources from rivers are under the threat of eutrophication [1].

According to "Environmental Quality Standards for Surface Water (GB 3838-2002)" in 2002, the quality of surface water is classified into five grades. Only water of Grades I–III is able to be used as drinking water source, while water of Grade V is neither suitable for irritation nor sightseeing. However, up to the present, many water sources do not meet the standards for drinking water quality. In 2011, among the 469 sections of the rivers monitored 61.0% met Grades I–III national surface water quality standard, while 13.7% failed to meet Grade V standard (Fig. 1). Meanwhile, only 42.3% of China's 26 main reservoirs or lakes were in categories I–III [2].

Virtually, most streams, lakes, rivers, and groundwater aquifers in China are used as drinking water sources because of the wide distribution of the population. The improvement of the existing water treatment plants is the key to ensure drinking water quality for protecting public health [3].

The quality of drinking water from the conventional treatment process is not satisfactory. New or advanced treatment technologies have been developed to update water treatment processes to solve the pollution problems of drinking water. Membrane technology has been considered as a substitute for conventional drinking water treatment for effective retention of particulates, bacteria and viruses [4]. Low-pressure membrane technologies such as microfiltration (MF) and ultrafiltration (UF) are recognized as very attractive processes for producing drinking water. Comparing with conventional treatment technologies, membrane process offers several advantages such as little need of chemical agents, good quality of produced water, little production of sludge, compact process, and easy automation.

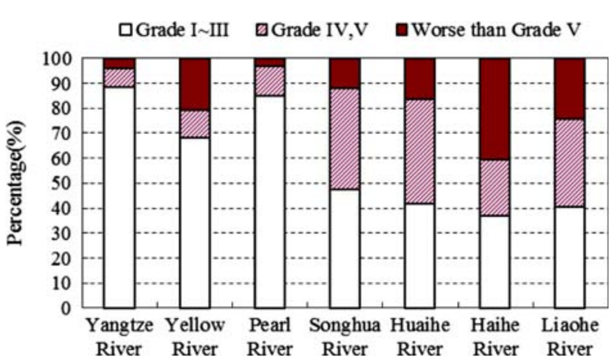

Fig. 1. Water quality grade of seven big rivers in China (2011). Source: Ministry of Environmental Protection of P. R. China (Report on the state of the environment in China 2012).

This paper reviews the development and application of membrane process in China's drinking water treatment. Moreover, an analysis of membrane market was carried out in order to provide useful information for potential customers.

2. Methodology

In order to provide a "snap-shot" of the membrane market in China and evaluate the trends and perspectives, a thorough survey of the municipal membrane market in China has been performed. This survey was carried out by contacting nearly 15 companies who are involved in manufacturing of membranes and 10 universities/institutions which are first class at the frontier of membrane research. The data contained herein comprise the results from 10 companies who returned information based on their installations. The data represent more than 95% of all installed plants.

The survey contains three components: a literature survey, a survey of membrane manufactures, and a survey of plant owners and operators. The data in this paper originating from the vendor survey were confirmed by the survey of plant owners and operators.

2.1. Survey of literature

To consolidate the existing knowledge on membrane systems for drinking water treatment, a survey of literature was conducted. The sources of literature included conference proceedings and journal articles. Elsevier database was used for the search of English papers and China National Knowledge Infrastructure (CNKI) was used for the search of membrane research and application in producing drinking water in China. A total of 127 scientific papers were published in the peer-reviewed journals from January 2000 through May 2012, including 82 Chinese papers and 45 English papers. There are about 30 papers which are related to full-scale or pilot-scale membrane application in drinking water treatment system in China and most of them were published in Chinese.

2.2. Survey of membrane manufactures

The major membrane vendors were contacted to provide responses to a limited number of questions on all of their drinking water and membrane installations. The information requested for each plant included: plant location, start-up date, design hydraulic capacity, source water type, membrane vendor, and membrane type.

2.3. Survey of plant owners and operators

The owners or operators of membrane plants with capacity greater than or equal to 100 m^3/d were surveyed to develop detailed information for the survey. The survey questionnaire included the following sections: plant location and background information; plant design characteristics, including pretreatment; plant operational characteristics; regulatory requirements; costs (capital and operations/maintenance); and lessons learned.

3. Historical perspective in China

The first municipal water treatment with membrane process was in the late 1990s, but it was not extensively employed until the mid 2000s. Three different stages have been observed:

Stage I (from 1997 to 2003): Development prior to 2003 was slow and installations were limited in very specialized islands. About 20 plants whose capacities were equal or less than 2,000 m^3/d were built to produce drinking water. In 1997, the first 144 m^3/d nanofiltration (NF) membrane project was established in Chang Island of Shangdong Province. In the same year, Daqing City started the High-Quality Water Supply Project in order to provide high-quality drinking water to the residents. Membrane systems consisting of preozonation, MF, activated carbon adsorption, UF, and postozonation were installed in various residential districts. The total treatment capacity of the systems was 620 m^3/d [5].

Stage II (from 2004 to 2006): The intermediate level stage was featured by an increase in the number and installed capacities of membrane plants. In 2004, Cixi Hangzhou Bay Hangfeng Water Plant was constructed in Cixi city, which was the first drinking water plant whose capacity was larger than 5,000 m^3/d. The project was based on UF and reverse osmosis (RO) technology, with the capacity of UF 30,000 m^3/d and RO 20,000 m^3/d. In 2005, a large-scale UF system (10,000 m^3/d) integrated with coagulation was applied to treat highly turbid Taihu River in Ducun Waterworks [6]. At this stage, UF was widely used in about 200 rural water supply reformation projects with small capacity ranging from 10 to 1,500 m^3/d, most of which were constructed in Zhejiang, Hainan, Sichuan, Hebei, Jiangxi, Guangxi, and Shandong provinces [7–9].

Stage III (from 2007 to present): Membrane process for drinking water treatment in China underwent a rapid development with a significant increase in the large-scale membrane plants. The new national compulsory drinking water quality standard (GB 5749-2006) [10] urges waterworks to adopt advanced processes to enhance water quality, and the membrane processes could meet the needs. The largest membrane water plant, Hangzhou Qingtai drinking water plant, has a capacity of 150,000 m^3/d for municipal water treatment [11,12]. Now, it has been reported that UF is applied in Zhongqiao Waterworks in Wuxi city with the total capacity of 300,000 m^3/d.

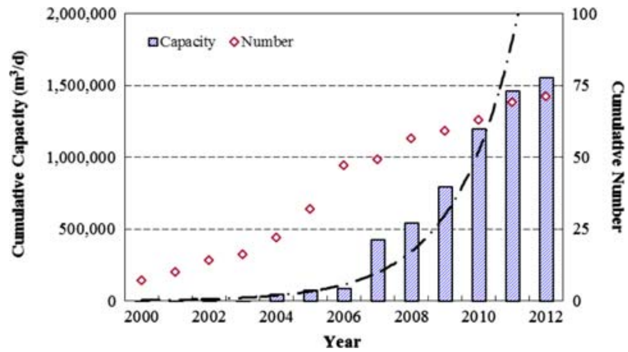

Fig. 2. Cumulative installed capacity and numbers of membrane technology for drinking water in China (>100 m^3/d).

The number of membrane plants (>100 m^3/d) has increased from 7 in 2000 to 69 in 2011. The cumulative distribution of installed capacity over time in China is presented in Fig. 2. This figure shows a dramatic increase in installed capacity. In December 2011, the total capacity online is 1,461,444 m^3/d, and large-scale plants are under construction with the total capacity of 90,000 m^3/d in 2012. Among these plants with the capacity ranging from 100 to 300,000 m^3/d, there are over 25 membrane plants possessing the capacity exceeding 5,000 m^3/d. Newly installed capacities in China display a trend toward larger scale plants as shown in Table 1 [11–19]. Numerous plants with an individual capacity higher than 10,000 m^3/d have been installed since 2007.

As shown in Fig. 3, the larger plants (>50,000 m^3/d), although in small number, represent the primary share of the market and drive the annual revenue growth. The market volume increases and installed membrane surface will be drawn up by the construction of some very large plants (>100,000 m^3/d), which will remain exceptional, and therefore unrepresentative of the market, but will attract much attention. Medium-size plants (1,000–50,000 m^3/d) remained the core of the plants to be constructed in the past 5 years. Small-size plants (<1,000 m^3/d) are always handicapped by relatively high costs and lack of regulation for the scale.

Table 1
Large-scale membrane plants for the production of drinking water in China

Location	Capacity (m^3/d)	Supplier	Start-up year
Hanzhou Qingtai drinking water plant, Zhejiang	300,000	Microza	2010
Kaohsiung Kaotan waterworks, Taiwan	300,000	Litree	2007
Wuxi Zhongqiao waterworks, Jiangsu	150,000	Siemens	2009
Ordos Dalate waterworks, Neimenggu	100,000	Omexell/DOW	2011
Dongying Nanjiao drinking waterworks, Shangdong	100,000	Litree, Zhongshuiyuan	2009
Beijing 9th waterworks	70,000	Litree	2010
Dashuitang drinking water plant, Macao	60,000	ZeeWeed	2008
Tianjin Nangang waterworks	50,000	Motian	2012
Jintan 3rd waterworks, Jiangsu	50,000	Motian	2011
Sha Tau Kok municipal water treatment system, Hongkong	40,000	Omexell/DOW	2012
Zhangqiu waterworks, Shandong	40,000	Omexell/DOW	2007
Shangyu SYZ drinking water plant, Zhejiang	30,000	Litree	2011
Xujing drinking water plant, Shanghai	30,000	Litree	2011
Mianyang Xinyong waterworks, Sichuan	30,000	Memstar	2011
Cixi Hangzhou Bay Hangfeng water Plant, Zhejiang	30,000	Koch	2004
Dongying 2nd waterworks, Shandong	25,000	Motian	2011
Nantong Ruting drinking water plant, Jiangsu	25,000	Litree	2010
Tongsheng water group, Shanghai	20,000	Litree	2008
Cidong waterworks, Zhejiang	20,000	Norit	2008
Dingxi Brackish water desalination project	10,000	Bluestar	2008
Ducun waterworks, Jiangsu	10,000	Litree	2005

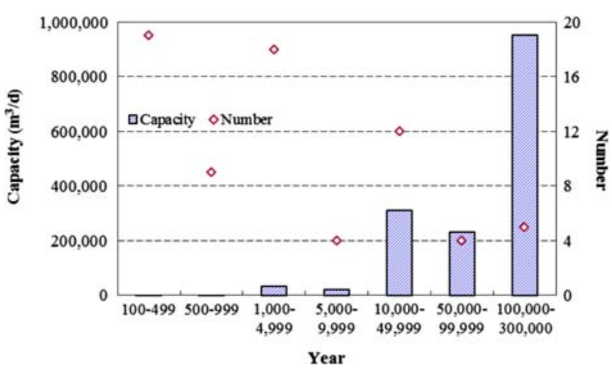

Fig. 3. Scale distribution of membrane plants in China (>100 m^3/d).

The geographic distribution of membrane plants is shown in Fig. 4. It should be noted that this survey is based on installed capacity and only plants with a capacity of at least 100 m^3/d were considered. Most membrane plants have been installed in the east of China, especially in Zhejiang, Jiangsu province, where the overall capacity may continue to increase in the next years. This distribution is related to water pollution in Taihu Lake. In May 2007, a drinking water crisis took place in Wuxi City in Zhejiang Province, following a massive bloom of the toxin producing cyanobacteria Microcystis sp. in Taihu Lake, leaving approximately two million people lack of tap water for at least a week. The impact of Wuxi water crisis clearly resulted in rapid growth of membrane plants. Zhejiang and Jiangsu region has grown rapidly, and this growth was represented by a few very large membrane plants. Taihu basin region will become a fast growing market in the long run, due to its enormous population and rapid economic growth that is most likely to lead to water demand that cannot be satisfied with conventional water sources.

4. Suppliers repartition

Fig. 5 shows the market repartition according to the suppliers of membrane plants. For the sake of clarity, only the main membrane suppliers are presented in Fig. 5. Chinese manufacturers are not included except Litree, Motion, and Zhongshuiyuan. Litree polyvinyl chloride (PVC) UF membrane occupies the majority of the membrane market in drinking water in China, whereas Omexell, now owned by Dow Chemical, has a larger number of installations in the southeast of China. The early development of UF in China by Litree and Omexell/Dow was characterized by a large number of pilot plant and small systems. As expected in a developing industry, the first company

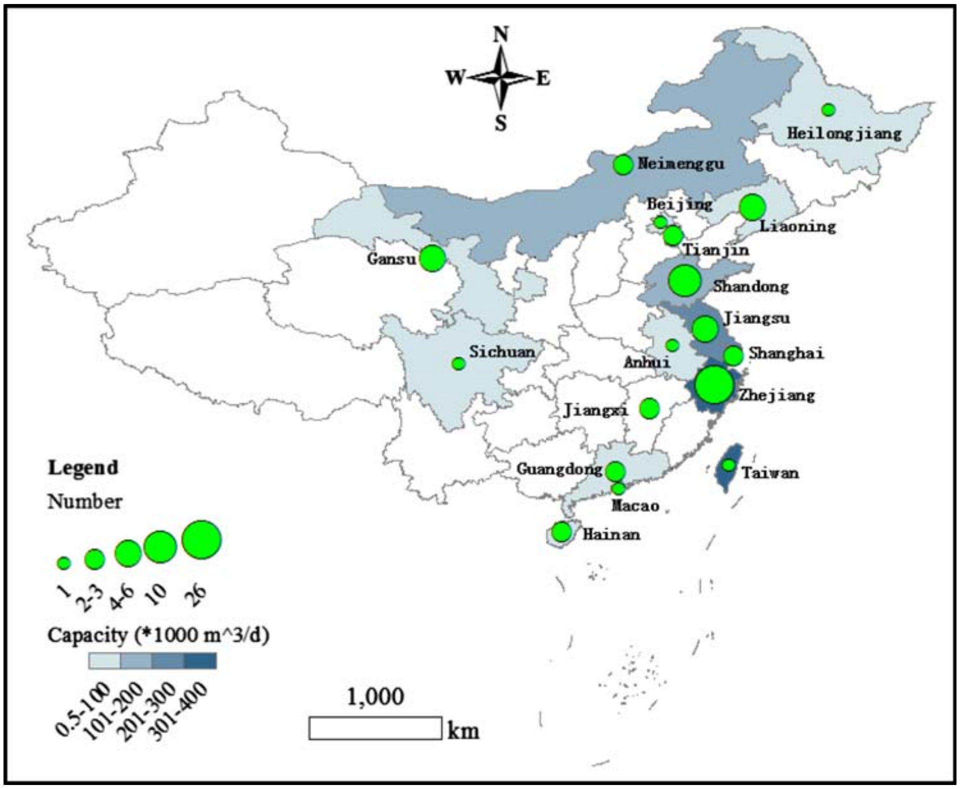

Fig. 4. Geographic distribution of membrane plants in China (>100 m^3/d).

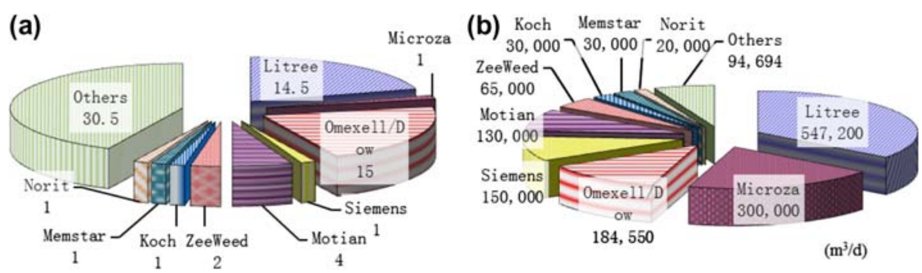

Fig. 5. Market repartition of membrane suppliers (>100 m^3/d) (a) distribution of numbers of plants and (b) distribution of installed capacities.

with a viable, economic product has an early and significant effect on market leadership. There has been a trend to gain market share through the acquisition of established companies and businesses. At the time of this survey, 35.3% of the installed capacity was provided by Litree and it continues to capture a large percentage of drinking water treatment plant installations since 2007. The Omexell/Dow appears to be successful in the small capacity range (<500 m^3/d) and the Litree product in the larger capacity range (>1,000 m^3/d). Even though Omexell/Dow was the first to develop and apply membrane technology in rural areas, their primary market is in wastewater treatment, instead of drinking water by now. After acquisition by Dow Chemical, Omexell business appears to have abandoned low pressure membranes in drinking water market.

Other membrane suppliers in China are Siemens, Microza, Zeeweed, Koch, Memstar, Norit, etc. Due to serious pollution of surface water and stringent national standard for drinking water, it is expected that a significant increase in membrane plant capacity and widening of application areas will occur in the future. The relatively low pressure membrane plants shown by several companies were typical for products in commercial development. It is anticipated that their

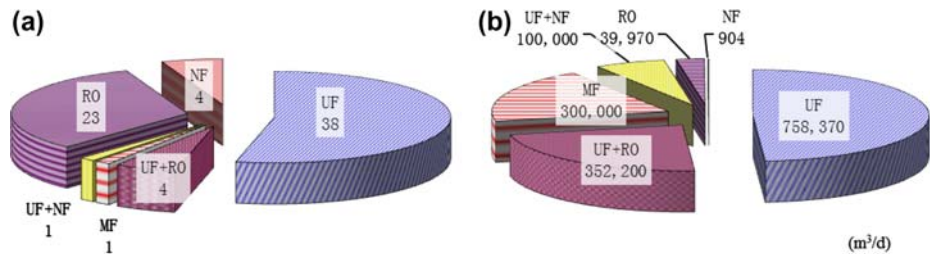

Fig. 6. Market repartition of membrane processes (>100 m^3/d) (a) distribution of numbers of plants and (b) distribution of installed capacities.

future growth will be substantial, judging from their investments in manufacturing.

Low pressure membranes, including MF and UF, have been used for treating various water sources (groundwater or surface water, including river, reservoir, and lake source waters.). As shown in Fig. 6, UF applications represent about 78.0% of the total installed capacity, of which 37.4% is used as pretreatment for RO or NF. MF is the second most applied membrane process, which occupies 19.3% of installed capacity. The largest plants recorded for UF and MF applications are Kaohsiung advanced drinking water plant (300,000 m^3/d, UF + RO) in Taiwan and Qingtai drinking water plant (300,000 m^3/d) in Hangzhou, respectively. The proportion of NF is the lowest and it only accounts for 0.06% of installed capacity in drinking water and the largest installed capacity is 500 m^3/d.

UF/MF membrane products employed are summarized as follows. All membrane products have pore sizes of 0.01–0.2 micrometers (μm) and are hollow fiber (HF) membranes. More than 95% of installed capacity provided by HF membranes is from polyvinylidene difluoride (PVDF) and PVC materials, where the PVDF membranes are produced mainly by Microza, Omexell/Dow, Siemens, Motian, ZeeWeed, Koch, and Memstar (providing 859,550 m^3/d installed capacity) and the PVC is mainly by Litree (providing 547,200 m^3/d installed capacity).

5. Performance of membrane plants in producing drinking water

Membrane technologies have been considered as a substitute or enhancement for conventional water treatment for effective removal of particulates, algae, bacteria, and viruses [4,20–24]. In particular, low pressure membranes, including MF and UF, are receiving increasing attention due to their low energy consumption and easy and economic operation. MF/UF can be used on its own for treating drinking water where the feed water concentration is not too high in terms of organic contents [25,26]. However, where the source water is of lower quality, the low level of organic matter removal achieved with UF may not ensure that the treated water will comply with standards (disinfection by-products (DBPs) formation). Minimization of natural organic matter (NOM) has emerged as a critical issue in treating the surface water for drinking purposes because NOM can result in the formation of DBPs such as trihalomethanes, which are harmful to people's health [27]. In order to improve the removal of NOM in a MF or UF process, MF can be combined with other unit processes, such as coagulation and adsorption, and improved results have been demonstrated [28–36]. Thus for surface waters with high organic contents, MF/UF alone is not sufficient enough to guarantee the required water quality. To broaden the application of low pressure membrane, different types of treatment combination (adsorption, coagulation, and oxidation) with UF can ensure the treated water quality which meet regulations for various source water [37–42,54–55]. Coupled with PAC or coagulant, UF can be used well to treat surface water contaminated by micropollutants such as pesticides or surface water with a high organic load.

Many practices have proved that UF technology had a good capability to reduce turbidity and remove a wide range of micro-organisms, resulting in an effluent free from pathogenic micro-organisms [6,11,12,43–46]. From Table 2, it is clear that after UF treatment, more than 90% turbidity, NH_3–N, and total coliforms were removed and it is given in Table 2. The effluent turbidity in most cases was less than 0.1 NTU (Nephelometric turbidity unit), with a few exceptions of less than 0.2 NTU. The NH_3–N concentration and total coliforms in the effluent were lower than 0.11 mg/L and 3 CFU/L, respectively.

It is noteworthy that dissolvable pollutants like NH_3–N, dissolved organics, and ions cannot be removed by UF directly. However, the combination with conventional treatments (adsorption, coagulation, and oxidation) can greatly broaden the scope of UF applications and meet the quality criteria of produced

Table 2
Performances of UF plants for drinking water in China

Plants	Jishan village waterworks [43]		Hangzhou Bay Hangfeng waterworks [12]		Ducun waterworks [6]		New Urban waterworks [52]		Kaotan waterworks [51]		Yangliuqing waterworks [46,53]	
Location	Huzhou city, Zhejiang province		Cixi city, Zhejiang province		Suzhou city, Jiangsu province		Foshan city, Guangdong province		Kaohsiung city, Taiwan province		Tianjin city	
Source water	River water		Reservoir water		Taihu river		Tap water		River water		River water	
	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent
Turbidity (NTU)	83.7	0.2	15	<0.01	10–150	<0.01	0.326	0.096	16–230	<0.1	1.08–21.70	<0.1
COD_{Mn} (mg/L)	10.0	4.50	10–20	1–4	2–8	<3	1.29	0.71			2.70–4.90	<3
NH_3–H (mg/L)	0.60	0.11	3	<0.01	<0.2	<0.1			0.15–0.2		0.02–0.25	<0.05
Total bacteria (PFU/mL)		<1	500	<1	500–2,200	<1	15	<1	1,000,000	Not detected		<1
Total coliform (PFU/L)	>16,000	<3	>150	Not detected	100–2,100	–	0	0	1,000,000/L	Not detected		<3
Fe (mg/L)	2.75	<0.20	0.3		0.3–2.7		<0.04	<0.04	0.1–1.96	0.05		
Mn (mg/L)	1.27	<0.10					0.01	0.01	0.03–0.19	0.1		
F (mg/L)	1.22	0.62					0.22	0.22				

Note: – represents no bacteria detected.

water. Moreover, comparing with that of conventional process, effluent water quality of UF is superior in safety against biological risk with little by-products from disinfection and coagulation. One way to fight against these biological risks is to apply UF to insure the turbidity is below 0.2 or even 0.1 NTU. It has been found that turbidity is more than a sensory index: virus and bacteria always adheres to particulates in the water, so as long as the turbidity is low, the biological risks are minimal [47].

5.1. *PAC adsorption combined with UF*

For removing trace organic compounds, the process of powdered activated carbon (PAC)-UF combination is a viable alternative to more conventional methods like PAC and ozonation [48–50]. The membrane provides a physical barrier preventing the passage of the PAC, and therefore retaining the organic compounds adsorbed on the PAC, which otherwise would not be trapped by the membrane [45]. These compounds include organic matter, pesticides, compounds responsible for taste and odor, precursors of DBPs, etc. The process combines the advantages of UF and of PAC adsorption. The UF recirculation loop here serves as a reactor for mixing water and PAC.

The process has been in operation at full-scale plants, with various types of source water and in treatment systems of varying complexity. Several large-scale plants now demonstrate the success of this process for large drinking water production plants: Shanghai Tongsheng Drinking Water Plant (20,000 m^3/d), Dongying Nanjiao Drinking Water Plant (100,000 m^3/d) and Foshan New Urban Waterworks (5,000 m^3/d).

5.1.1. *Case 1: Nanjiao drinking water plant (100,000 m^3/d), Shangdong*

Application of UF as the key technology of water quality improving project in Nanjiao Waterworks with a water supply capacity of $10 \times 10^4\ m^3/d$ has been run for 1 year. The practical operation indicated that the effluent water quality was largely improved by UF combination process and the effluent turbidity of UF was kept below 0.02 NTU. The average removal rates of COD_{Mn}, UV_{254}, and TOC by UF combination process were 44.96, 43.22, and 20.10%, respectively, which were improved 8.99, 10.23, and 7.81% comparing with sand filtration process. Meanwhile, the removal efficiencies of algae and pathogenic micro-organism were prominent. It could effectively ensure the stability of UF membrane operation in a sustainable flux. The domestic UF membrane had satisfied water production efficiency and anticontamination ability. The water cleaning could control the increase of transmembrane pressure (TMP) effectively, and extend the recoverable chemical cleaning period. The actual investment and operational cost of the UF combination process were lower than the estimated value.

5.1.2. *Case 2: Zhongqiao drinking water plant (150,000 m^3/d), Jiangsu*

In Zhongqiao Drinking Water Plant (150,000 m^3/d), Taihu River water was treated by UF with ozone pretreatment. The following treatment process illustrated in Fig. 7 was chosen to produce drinking water, which consists of sand filters into PAC filters preceded by oxidation. Oxidation can effectively reduce taste and odors, improve disinfection, reduce trace organic contaminants, and increase dissolved organic carbon (DOC) biodegradability. The biological PAC filters can effectively remove some algae toxins, ammonia, biodegradable organic carbon, and many trace organic contaminants.

Each module contains 38 m^2 of Memcor L20 V HF membrane operating in dead end mode with the flow from outside to inside. The membrane material is related with a nominal pore size of 0.04 μm and fabricated into individual membrane units with a height of 1,800 mm and an outside diameter of 119 mm. The membranes are operated at an average flux of 86 L/m^2 h (LMH) and a maximal TMP of 0.08 MPa. Membrane fouling is controlled through air backwash. Automatic air backwash is conducted every 45 min. In addition, each stream is chemically cleaned with HCl and NaClO every three months.

5.2. *Coagulation/sedimentation step prior to the UF process*

This treatment combination can be considered for surface waters containing fairly high levels of organic matter, especially since UF membranes cannot efficiently remove dissolved organics. This combination should also be considered when upgrading conventional treatment plants in order to meet regulations on turbidity, *Cryptosporidium* removal, and DBPs forma-

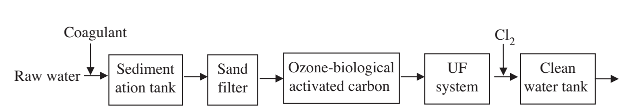

Fig. 7. Flow diagram of Zhongqiao drinking water plant (150,000 m^3/d).

tion control. This process combination has been chosen for a project in Ducun drinking water plant. The facility has a 10,000 m^3/d production capacity and has been in operation since 2005. Phase 2 of the facility that will lead to double its capacity is under consideration. The process includes pretreatment with a Superpulsator using coagulation (ferric sulfate) prior to the UF membrane. Several large-scale plants demonstrate the success of this process for large drinking water production plants: Yangliuqing Drinking Water Plant (5,000 m^3/d), Jiangxinzhou Waterworks in Anhui Province (5,000 m^3/d), Nantong Ruting drinking water plant (25,000 m^3/d) and Zhongqiao Drinking Water Plant (150,000 m^3/d).

5.2.1. Case 3: Ducun drinking water plant (10,000 m³/d), Jiangsu

The raw water of Ducun Drinking Water Plant was taken from Taihu River, which varies significantly in turbidity, DOC, bacteria levels, among other parameters. The raw water quality is presented in Table 2. The system integrated with coagulation ($FeCl_3$) was applied to produce drinking water from the highly turbid Taihu River [6]. This UF installation could produce 10,000 m^3 drinking water per day. The treatment process was as shown in Fig. 8.

Fig. 8 shows a process flow diagram of the system which consisted of a HF membrane module and a prefilter (the prefilter was 150 μm filter screen and was used to remove suspensions and large-size particles to protect the UF). Filtration was performed in a dead-end mode. The water flux was fixed at 100 LMH (25℃). The UF operation cycle was set at 25 min and membrane cleaning was periodically performed under automatic control. Physical cleaning included flushing with raw water for 10 s and backwashing with filtrate (flux, 250–320 LMH) for 20 s; chemical cleaning comprised immersing the UF membrane in citric acid for 2 h and then washing with 0.2% alkaline (mixture of sodium hydroxide (80%) and sodium hypochlorite (20%)) for 20 min at ambient temperature.

The practical operation shown that UF system combined with coagulation removes 26–50% COD_{Mn}, and for the permeate quality, the concentration of COD_{Mn} is less than 3 mg/L. There was a high, stable turbidity removal in the operation period and its value was not affected by changes of operation parameters, such as raw water fluctuation, operation cycle, and chemical cleaning, and remained below 0.01 NTU. The NH_4^+–N concentration in the raw water exhibited sharp variation with season in the range of 0.2–0.02 mg/L. By the treatment of the coagulation/UF process, most of NH_4^+–N in the raw water could be removed, and its level was always maintained below 0.1 mg/L, and most of time being 0.01 mg/L. This coagulation/UF system also removed most of the coliform bacteria and total bacteria from the raw water, but the removal was not affected by the operational parameter. Total bacteria are less than 1 count/mL. With the pretreatment of $FeCl_3$ at 6 mg/L, this UF installation operated steadily for six months by retaining high specific flux, 180 L/m^2 h·bar.

5.2.2. Case 4: Nantong Ruting drinking water plant (25,000 m³/d), Jiangsu

Ruting drinking water plant in Nantong City was applied with the traditional treatment process before 2010 [18,19]. The source water was from Yangtze River. In order to meet the latest Standards for drinking water quality (GB 5749-2006), a shortened process integrated inline coagulation with UF membrane filtration after the upgrading reconstruction in 2010. In this process, a new route to combine the coagulation, settling, UF, concentrated water reclaiming, sludge thickening, and sludge drainage into a structure was found. After coagulation with a dosage of 10–15 mg/L of polymeric ferric sulfate, the water was treated with the UF membrane modules without sedimentation. The plant was equipped with the hollow-fiber UF membrane modules made of PVC, which had a filtration area of 36,400 m^2 with a nominal pore size of 0.01 μm. Filtration was carried out in a dead-end mode with outside-in flow pattern. The designed flux was more than 30 L/m^2 h (LMH) under around 4 m hydraulic pressure. The running cycle was 23 h filtration. The running cycle was 23 h filtration. Hydraulic backwash was performed 30 s/h with a flux of 60 LMH (inside-out) and air bubble intensity of

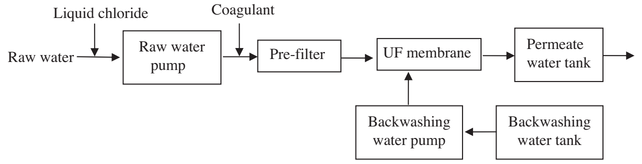

Fig. 8. Flow diagram of Ducun drinking water plant (10,000 m^3/d).

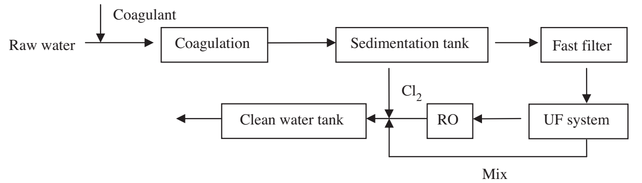

Fig. 9. Flow diagram of Kaotan Waterworks (300,000 m^3/d).

Table 3
Applications of UF plants for drinking water in China

Plants	Jishan village waterworks [43]	Hangzhou Bay Hangfeng waterworks [12]	Ducun waterworks [6]	New Urban waterworks [52]	Kaotan waterworks [51]	Yangliuqing waterworks [46,53]	Zhongqiao waterworks [14]
Location	Huzhou city, Zhejiang province	Cixi city, Zhejiang province	Suzhou city, Jiangsu province	Foshan city, Guangdong province	Kaohsiung city, Taiwan province	Tianjin city	Wuxi city, Jiangsu
Source water	River water	Reservoir water	Taihu river	Tap water	River water	River water	Taihu river
Commissioned	2004–2012	2005–2002	2005–2005	2006–2002	2007–2003	2008–2005	2009–2012
Capacity (m^3/d)	150	50,000	10,000	5,000	300,000	5,000	150,000
Source water	River water	Reservoir water	River water	Tap water	River water	River water	River water
Membrane flux (L/m^2 h)		92.7	100	57.5	115	37.5	86
Supplier	Dow (Omexell)	Koch	Litree	GE	Litree	Litree	Siemens
Membrane type	OMEXELL SFD—26	V1072-35-PMC	LH3 1060 V	ZeeWeed 1000		LH3 1060 V	Memcor L20 V
Membrane material	PVDF	PS	PVC	PVDF	PVC	PVC	PVDF
Membrane pore (μm)	0.03	100,000*	0.005–0.007	0.02	0.01		0.04
Operation pressure (MPa)		0.25	0.02–0.06		0.05–0.08	<0.15	0.05–0.08
Backwash period (min)	45	30	25	40–50	45	20–30	45
Backwash time (second)		60	20	240	40	60–90	
Recovery (%)	>90	90		92–95	95	98	98

*Molecular weight cut-off.
Note: PVDF: poly vinyldene fluoride; PS: Polysulfone; and PVC: polyvinylchloride.

$90\,m^3/m^2/h$. The hydraulic retention time and sludge retention time were about 0.768 and 3 h, respectively. An additional maintenance cleaning with sodium hypochlorite (NaClO, 200 ppm) was carried out every two weeks in order to keep a continuous operation.

The facility was operated very stably in terms of water quality. The coliform bacteria did not exist in the filtration permeate and the turbidity removal efficiency was more than 99%. In general, the low-pressure PVC UF membrane performed successfully in a long-term operation. Coagulation could remove a large part of particles and had a limited effect on eliminating organic foulants.

During the whole filtration process in 2010, the temperature of source water variated largely from 3 to 31.5℃. It was found that total resistance (Rt) substantially increased from 2.11×10^{12} to $3.26 \times 10^{12}\,m^{-1}$. The changes could be divided into three stages according to the variation of permeate flux. From January to April, flux was around 31 LMH, indicating a good start-up of the facility. After April, the flux dropped marginally. The flux was increased and reached the maximum flux at 34.3 LMH in July with a lower viscosity. The final stage was from August to December. The flux decreased sharply from 33.98 to 23.28 LMH, only 75.13% of initial flux.

5.3. UF pretreatment to RO

As neither MF nor UF can ensure high quality of treated water for high organic content surface source waters, MF/UF could be combined with RO in order to achieve the water quality objectives. Current pretreatment perspectives to RO include the use of UF especially for surface water treatment. Several large-scale plants demonstrate the success of this process for large drinking water production plants: Kaohsiung Drinking Water Plant (30,000 m^3/d), Cixi Hangzhou Bay Hangfeng Water Plant (30,000 m^3/d) and Cidong Drinking Water Plant (20,000 m^3/d).

Raw water of Kaohsiung deteriorated rapidly because of the pollution caused by industrial waste water. The existing water treatment plant could not assure the drinking water safety. The utility was faced with the serious water quality challenges, including turbidity, hardness, micro-organisms, TDS, and so on. To improve the drinking water quality, the local authority developed the "drinking water quality improvement plan" and decided to build a new plant. The design capacity of the new plant was 300,000 m^3/d.

The treatment process shown in Fig. 9 was chosen for Kaohsiung Advanced Drinking Water Plant. Alloyed PVC UF membrane manufactured by Litree was chosen over other kinds of UF membrane in the project, because it has good quality of permeate, good performance, high antifouling, and low cost. The quality of permeate from UF membrane system is listed in Table 2.

The practical operation situation for almost 2 years since its start-up is given in Table 3. The turbidity of treated water of alloyed PVC UF system maintains less than 0.1 NTU, and the TMP ranges from 0.05 MPa

Table 4
Capital costs of different membrane plants

Plants	Capacity (m^3/d)	Initial Capital (RMB)	Unit capital costs (RMB/m^3 d)	People served
Jishan village waterworks [9,43]	150	250,000	1,667	1,500
Salan town waterworks [44]	220	305,000	1,386	1,200
Simingshan town waterworks [44]	350	352,000	1,006	2,000
Yuanma village waterworks [44]	440	455,000	1,034	4,000

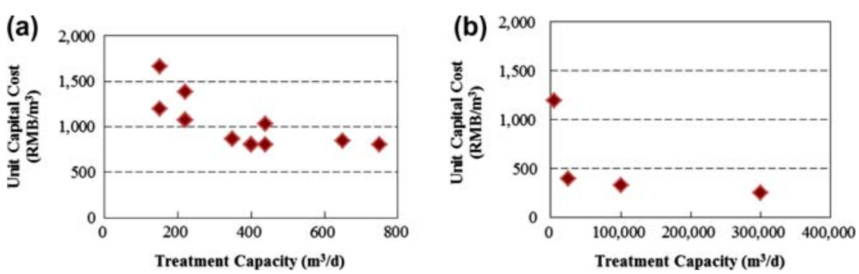

Fig. 10. Unit capital costs for a range of plant sizes (a) Omexell/Dow and (b) Litree.

Table 5
Operating costs of different scale of membrane plants

Plants	Jishan Village Waterwork [43]	Simingshan Town Waterworks [44]	Yangliuqing Waterworks [46,53]	Dongying Nanjiao drinking water plant [13]	Zhongqiao Waterworks [14]	Kaotan Waterworks [51]
Capacity (m^3/d)	150	350	5,000	100,000	150,000	300,000
Membrane manufacturer	Omexell/Dow	Omexell/Dow	Litree	Litree, Zhongshuiyuan	Siemens	Litree
Nonmembrane life expectancy (year)	20	20		25	20	
Membrane life expectancy (year)	5	5	4	5	8	5
Energy price (RMB/kWh)	0.7	0.7	0.67	0.78	0.65	0.5
Unit energy consumption (kWh/m^3)	0.75	0.33	0.106		0.071	0.1
Operating costs						
Depreciation of assets (RMB/m^3)	0.267	0.121	0.25	0.063	0.10	
Membrane replacement cost (RMB/m^3)	0.090	0.121		0.060		0.0482
Unit energy cost (RMB/m^3)	0.522	0.234	0.13	0.020	0.046	0.05
Labor cost (RMB/m^3)	0.081	0.146	0.049			
Chemical agent cost (RMB/m^3)	0.090	0.073	0.035	0.025	0.005	0.008
Others (RMB/m^3)	0.271	0.144	0.005	0.017	0.018	
Total costs (RMB/m^3)	1.32	0.85	0.49	0.185	0.17	0.099

to 0.08 MPa at a flux of about 100 L/m^2/h with the four months chemical cleaning period.

6. Economic aspects

Table 4 shows initial capital costs and unit capital costs (costs per m^3) of different membrane plants. Although the capital costs per m^3 of membrane module (unit membrane capital costs) will not change with plant size, the capital costs per m^3 of nonmembrane (unit nonmembrane capital costs) correspondingly declines with increasing facility scales. As far as the membrane plant using the same membrane module is concerned, unit capital costs decreases when the capacity of membrane plant increases. For example, when capacities of membrane plants using membrane modules of Omexell/Dow are set at 150 m^3/d and 750 m^3/d, respectively, a big difference between their unit capital costs can be observed (1,667 RMB/m^3 and 800 RMB/m^3) [43,44] (Fig. 10(a)). Comparing membrane plants with Litree modules, the unit capital of Yangliuqing Waterworks (5,000 m^3/d) is 1,195.2 RMB/m^3/d [46], while that of Kaohsiung Kaotan Waterworks (300,000 m^3/d) is only 250 RMB/m^3/d [51] (Fig. 10(b)).

Another way to show the cost economies of scale is to consider the unit operating costs (costs per m^3 treated wastewater). For membrane plants ranging from 150 to 350 m^3/d, the difference in the unit operating costs is quite significant as shown in Table 5. As the capacities of the membrane plant increases, the unit operating costs decreases. For instance, when the capacity of membrane plants using membrane modules from Omexell/Dow increases from 150 to 350 m^3/d, their unit operating costs decrease from 1.32 to 0.85 RMB/m^3.

7. Conclusions

This study presents the results of the survey of membrane technology for municipal drinking water in China based on information collected from 15 companies involved in the manufacturing of membranes, representing more than 95% of all installed plants. Major findings include:

- Low pressure membrane has become a significant unit operation in the water treatment business. UF applications represent about 72.1% of the total installed capacity and approximately 28.8% of UF is used as the pretreatment unit for RO. The largest installed capacity provided by UF membranes is from PVC, followed by PVDF.
- The large plants (>50,000 m^3/d), although in small number, represent the primary share of the market and drive the annual revenue growth. Membrane suppliers are dominated by seven companies, accounting for >96% of sales. Litree PVC UF membrane occupies the biggest part of the membrane market, whereas Omexel /Dow has a large number of installations in the southeast of China. Other membrane suppliers in China are Microza, Siemens, Koch, Zenom/GE, Norit, etc.
- Coupled with PAC or coagulant, low pressure membranes can be used well to treat surface water contaminated by micropollutants such as pesticides or surface water with a high organic load.
- As the price has been decreasing the requirement for operation conditions, low pressure membrane technologies are no longer deemed as "magical but expensive and delicate technology." This results in a significant growth of its applications in the drinking water sector, with many new water treatment plants planning to apply low pressure membrane instead of conventional treatment.
- Taihu basin region will become a fast growing market in the long run, due to its enormous population and economic growth that is most likely to lead to water demand that cannot be satisfied with conventional water sources.

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