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Development Strategy of Hollow Fiber Membrane Technology and Industry in China

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Abstract: Hollow fiber membrane (HFM) technology is a common and crucial technology for solving major challenges, including water and energy crises, as well as environmental pollution. HFM technology is also a crucial strategy for achieving high-quality developments in the industry, as characterized by energy conservation, clean production, and improvement in system efficiencies and product quality. Here, the strategic demand, development status, and development trend of HFM technology and industry are analyzed. Further, the major challenges and innovation of HFM subfields in China, as well as the development goals for 2025 and 2031, are discussed. Moreover, the following four key components are proposed: the hollow fiber ultrafiltration /microfiltration membrane, high-quality hydrophobic membrane, new membrane technologies, and waste membrane recycling. Furthermore, measures and strategies were proposed toward personnel management, innovation investment, industry standards, and international cooperation to avail a reference for the high-quality development of HFM technology and industry in China.

Keywords: hollow fiber membrane; membrane material; membrane application; sustainable development

1 Introduction

Hollow fiber membrane (HFM) is a new product of membrane technology, which is formed via the intersection of functional fiber material and separation membrane technologies. It is associated with advantages, such as high filling density per unit volume, a large filtration area, a small footprint, and relative inexpensiveness. Therefore, HFM has emerged as the fastest developing product of membrane technology on the largest scale with the highest output value in the field of separation membranes. HFM technology has become a key technology in environmental protection, resource recovery, new energy, and other fields; it is also an essential strategy for upgrading traditional industries (Fig. 1). HFM technology has been listed as a key development strategy by developed countries and is also a key component of China's emerging strategic industries, as well as scientific and technological innovation. For example, high-performance separation membrane technology has been included in the key projects of *China Manufacturing 2025*. Here, the development statuses of HFM technology and industry in China and abroad were studied from the perspectives of the membrane materials, application technologies, etc. The key challenges, as well as technical and policy bottlenecks that confronted the development of HFM technology and industry in China, were analyzed, after which the key tasks, measures, and proposals for developing the HFM technology and industry were clarified. By summarizing and analyzing the development trend of HFM technology and industry in China, scientific proposals were presented for the high-quality

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development of HFM and related technologies and industries in China.

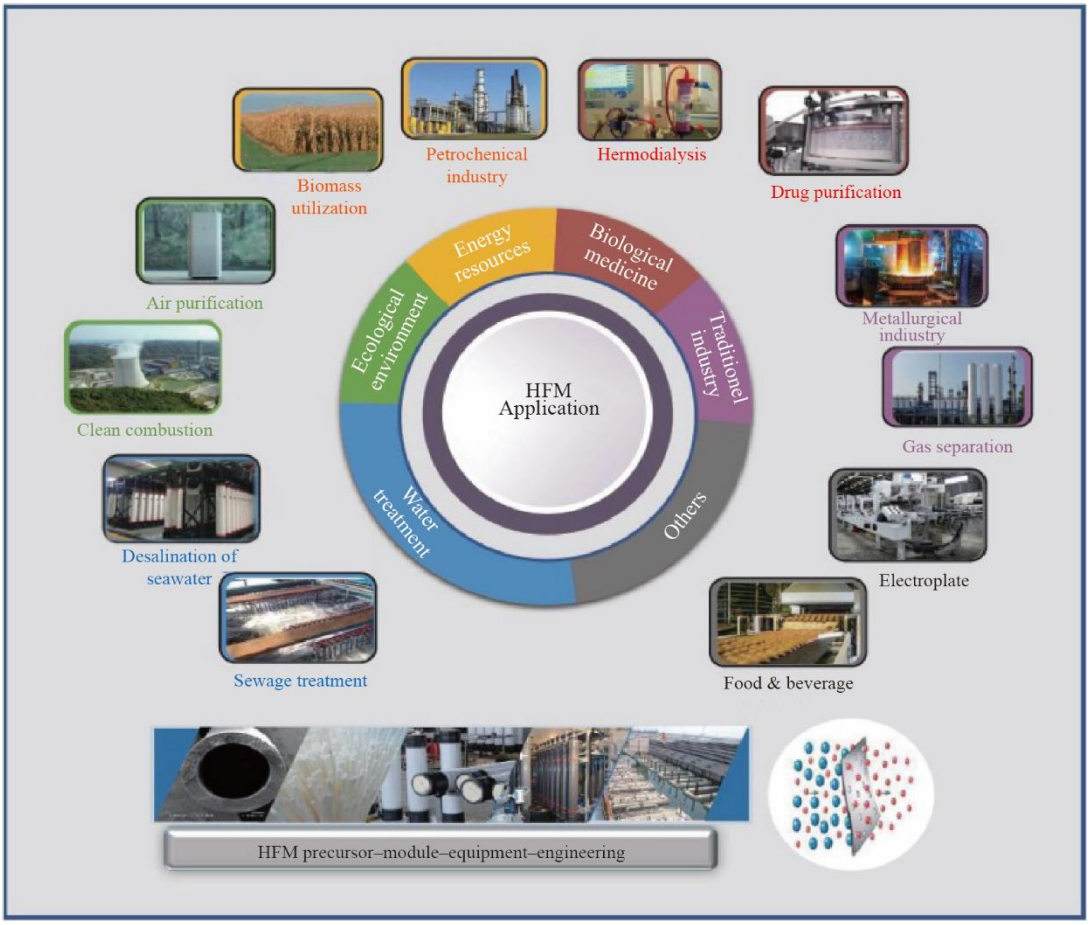

Fig. 1. HFM technology and its application fields.

2 Analyses on the demand for HFM technology and industry in China

2.1 HFM technology as a crucial measure for ensuring water safety in China

Shortage of water resources and water pollution have become bottlenecks that restrict social progress and economic development. More than two-thirds of the major cities in China suffer from water scarcity (the total annual water shortage exceeds 4×10^{10} t). Moreover, $>7.5 \times 10^{10}$ t of sewage is discharged annually in China [1], and only <15% of them are effectively treated and reused, corresponding to serious water wastage and water pollution. Membrane separation technology has been considered the most effective technical strategy for recycling sewages and ensuring the safety of drinking water. In recent years, the improvement of the sanitary standard of drinking water and the continuous improvement of the effluents of urban sewage and industrial wastewater in China have ensured the rapid upgrading and reconstruction of waterworks and sewage/wastewater treatment plants, thereby availing new opportunities and requirements for developing the HFM technology and industry.

2.2 HFM technology as an essential tool for upgrading traditional industries and developing emerging ones

With its expanding applications in recent years, HFM technology is widely employed in water treatment, as well as petrochemical, medical, biological, food, electronics, energy, air pollution control, aerospace, military, and other industries. Additionally, HFM technology has gradually replaced traditional separation technologies, such as distillation, extraction, and adsorption, and has become an essential tool for technically upgrading traditional industries and developing emerging industries, thereby availing innovative technical supports for energy conservation, emission reduction, clean production, and improving product quality and system efficiency. Therefore, the development of HFM technology is a strategic requirement to achieve high-quality development in many industries.

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2.3 Innovative developments of high-end technology and industry for HFM are becoming increasingly urgent

After more than 50 years of development, China has established relatively complete R&D and industrial systems regarding membrane materials, modules, and equipment, including reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), and microfiltration (MF); the systems have a relatively strong international reputation and competitiveness. However, there is still a gap between Chinese and international top-level technologies with respect to fundamental and applied research of membrane science especially regarding high-precision, high-performance, and special separation membrane products. Thus, the large high-end membrane market is still monopolized by foreign enterprises. With the ongoing disadvantageous situation involving the blockade or protection of key high-techs in developed countries, it is increasingly urgent to promote the innovation and development of HFM technology and industry in China.

3 Analyses on the development of the HFM technology and industry in China and abroad

Regarding the production capacity and market scale, China is a major producer and utilizer of HFM. In 2018, the global HFM market scale reached 110 billion CNY and continued to grow rapidly with a compound annual growth rate of 11% [1]; thus, it is projected to reach 245.1 billion CNY by 2025. Based on the regional distribution of the market, the global HFM market is concentrated in Asia, North America, and Europe. Major foreign manufacturers of HFM include Suez Environment, Koch, DuPont, Asahi Kasei Corporation, Mitsubishi Rayon, TOYOBO, and Siemens AG. These well-known companies account for >95% of the shares of the global high-end membrane separation market owing to their brands and technological advantages. China's HFM market is growing steadily, reaching 11 and 30 billion CNY in 2015 and 2020, respectively, accounting for 20.7% and 50.1% of the global and Asian markets, respectively [1]. Further, it is projected to reach 60 billion CNY by 2025. Until 2020, there were approximately 200 enterprises that were engaged in the R&D, design, and production of HFM in China with a total production capacity of ~1×10^8 m^2/a. However, there were only more than 10 enterprises that boasted of an annual output value of over 100 million CNY, and this still leaves a significant gap between their output values and technical strengths and those of foreign enterprises. In the following section, the development status and subsequent R&D focus of HFM will be analyzed from the subdivision points of HFM materials and membrane applications.

3.1 Analyses on the development of HFM materials

3.1.1 UF/MF HFM

UF/MF HFM is associated with the largest output, most advanced development, and strongest market competitiveness among other membranes in China. The global UF/MF HFM markets were worth ~ 93.5 and 123.2 billion CNY in 2018 and 2020, respectively. The market scales in China were approximately 19.6 and 26.79 billion CNY in 2018 and 2020, respectively [1]. The global production technology for UF/MF HMF is relatively advanced, generating a market pattern with stable demand and full competition in the industry. The United States, Japan, and other developed countries/regions are leading producers of high-performance UF/MF HFMs, exhibiting technological innovations [2]. Traditional leading UF/MF HFM enterprises in China include Beijing Origin Water Technology Co., Ltd. (BOW), Tianjin MOTIMO Membrane Technology Co., Ltd., Hainan Litree Purifying Technology Co., Ltd., Yancheng Hyperon Membrane Technology Co., Ltd., Beijing Scinor Membrane Technology Co., Ltd., and Shandong Zhaojin Motian Co., Ltd. Through original innovation and technological integration, new technologies, processes, and products with different characteristics have been introduced and widely employed in large-scale water treatment projects in China and abroad. In the future, China must continuously strengthen its industrial and technological advantages in the field of UF/MF HFM and focus on advancing the research on the green preparation technology and new membrane materials for special separation purposes, high-performance UF/MF HFM modules, as well as their integration technology, thus promoting the digital transformation of the UF/MF HFM industry.

3.1.2 NF HFM

Owing to the complexity of preparing high-performance NF HFM, it is yet to be industrialized. Foreign membrane enterprises that have been long associated with developing NF HFMs include Koch Industries (the

United States), Evonik Industries AG (Germany), and Blue Ocean (International) Mechanical Parts Co., Ltd. (Singapore). Universities and research institutes in China are the main R&D units of NF HFMs. For example, Tiangong University and Tianjin MOTIMO Membrane Technology Co., Ltd., as well as other units, have combined to explore the industrialization of NF HFM. They built an experimental production line with an annual production capacity of 4×10^5 m^2, thus achieving the continuous and stable production of the membranes via interfacial polymerization. In the future, China must continue to accelerate the industrialization of NF HFMs, focus on the R&D of high-precision, one-step continuous preparation technology and equipment for NF HFM, and strive to dominate the global large-scale production of NF HFM.

3.1.3 RO HFM

China's RO HFMs still lag behind similar foreign products regarding the research depths and application scopes. RO membrane separation has become the mainstream technology for desalinating seawater and brackish water, as well as producing pure and ultrapure waters. The RO proportions of the global desalination markets for seawater and brackish water are >70% [3]. In 2019, the global output value of the RO membrane exceeded 6 billion USD. China is the world's largest consumer of RO membranes, accounting for 26% of the total global consumption [4]. TOYOBO (Japan) is the only present supplier of RO HFM (cellulose acetate) globally. However, Tianjin MOTIMO Membrane Technology Co., Ltd., has developed an experimental RO HFM production line exhibiting an annual production capacity of 4×10^5 m^2, although the separation performance of the product still required improvement. In the future, China must continue to improve basic research on the synthesis and control of the structures of special polymer materials for RO HFM, as well as the key technologies for continuously preparing high-performance RO HFM, and the theory of high-efficiency module-filling processes.

3.1.4 Hydrophobic HFM

Hydrophobic membrane technology has emerged as an essential strategy for separating and purifying chemicals in the fields of the resource recovery, environment, new energy, as well as traditional industries. It exhibits a strong development momentum in the field of biological medicine. The corresponding application market scale is presently worth 10 billion USD [5]. Foreign countries exhibit significant technical advantages in the hydrophobic HFM industry. There are many hydrophobic HFM manufacturers; they include Sumitomo Electric Industries and Mitsubishi Rayon (Japan) and Minnesota Mining and Manufacturing Company (3M), Merck Millipore, and Gore (the United States). Several developed countries have developed strong research and industrial layouts, including the preparation and microstructural control of hydrophobic and superhydrophobic membranes. These have ensured the development of new membrane contactor and process design, as well as process strengthening methods [6]. Although China's hydrophobic HFM industry emerged late, it is already gradually establishing the technology and industrial chain from hydrophobic HFM research to process design and industrial application, even assuming a leading advantage in some aspects of superhydrophobic membrane technology. In the future, China must continuously improve the research on key technologies for preparing high-performance hydrophobic HFM materials, modules, processes, strengthening methods, and equipment-integrated systems; and key application technologies, especially the special R&D of hydrophobic HFM in biomedical fields, such as the design of artificial lungs.

3.1.5 Inorganic HFM

The large-scale productions of inorganic MF, UF, and NF HFMs have been achieved by foreign countries. In 2016, the global market scale of ceramic HFM was 99 million USD, which is projected to reach 200 million USD by 2025 [7,8]. The industrialized inorganic HFM in foreign countries is mainly Al_2O_3 ceramic and stainless-steel HFMs, and the production and R&D enterprises are mainly located in the United States, Japan, as well as Europe. Presently, the inorganic membranes in China are mainly tubular, and their core preparation technology and production equipment have not been independently mastered. There are presently no commercial domestic inorganic HFM products in China, revealing a significant gap in high-performance inorganic HFMs in China and other countries. In the future, China must strengthen the research on preparing technology and equipment for inorganic HFM, the new products of high-performance inorganic HFM and their high-level applications.

3.2 Analyses on the development of HFM applications

3.2.1 Application in water treatment

China accounts for the largest HFM water-treatment market globally. The world water-treatment market scale

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has exceeded 1 trillion USD [9], and the Chinese sewage-treatment market scale reached 1.39 trillion CNY during the 13th Five-Year Plan period. The market share of membrane-based water treatments is rapidly growing. The HFM-based separation technology occupies an absolute leading position in the membrane-based water treatment market globally; it exhibits a rapid growth trend. Owing to the continuous decline in the cost of membrane material and the continuous improvement in the stability of the process, Canada, Singapore, the United Kingdom, Australia, Israel, and other countries have successively built UF water-treatment plants of different scales. Further, the membrane biological reactor technology comprising UF-lined membranes has been widely employed in the extensive treatment and reuse of municipal sewage and industrial wastewater because of its good effluent quality, small occupancy area, and convenient operation and control, amongst other advantages. Subsequently, in order to satisfy the requirements for high-quality development of the environment and resources, China must strengthen the research on membrane fouling theory and fouling-control strategy based on the interface process, develop new water-treatment technologies for sewage reutilization from the perspective of resource and energy and for healthy drinking water, and explore high-efficiency modular-membrane equipment to build a "smart water affairs" system.

3.2.2 Application in the petrochemical industry

Internationally, HFM has been widely employed in the petrochemical industry. It accounts for a large market in the refinement of petroleum, treatments of oilfield-produced water and petrochemical wastewater, production of petrochemical products and their derivatives, pervaporation separation, preparation of high-purity gases, etc. In China's petrochemical industry, HFM is majorly applied to treat oilfield-produced water and petrochemical wastewater, purify and recover volatile organic compounds in gas separation, etc. The domestic enterprises of HFM for gas separation in the petrochemical industry mainly include Tianbang National Engineering Research Center of Membrane Technology Co., Ltd. in Dalian and Dalian Eurofilm Industrial Ltd., although their annual output values are small. In the future, the research on HFM materials for special separation purposes, separation technology, and process strengthening must be improved in China to achieve the extensive treatment of petrochemical wastewater and gas separation and develop membrane modules, equipment, and products to achieve resource utilization of petrochemical wastewater, gas separation, as well as the separation and purification of organic gas–liquid substances.

3.2.3 Application in biological medicine

HFM is widely employed in biomedical fields, such as the designs of artificial kidneys (hemodialysis), artificial lungs (oxygenation membranes), separation of blood components, and the separation and purification of Chinese and Western medicines [10]. The global market scale of hemodialysis reached 80 billion USD in 2019, and it is projected to reach 101.5 billion USD in 2025. In 2018, the market scale of hemodialysis in China was 33.5 billion CNY, which is projected to reach 112.5 billion CNY by 2025 [11]. The internationally renowned suppliers of hemodialysis HFMs include Fresenius AG (Germany), Baxter International and DaVita HealthCare Partners Inc. (the United States), Asahi Kasei Corporation (Japan), and MEMBRANA (Germany). Chinese producers of hemodialysis HFMs include WEGO (Shandong), Bai'en Medical Equipment (Guangzhou) Co., Ltd., Guangdong Biolight Meditech Co., Ltd. Domestic products account for ~40% of the market share of hemodialysis HFMs in China, although the core technologies and raw materials are still imported. Extracorporeal membrane oxygenation (ECMO), a well-known critical equipment for treating the cardiopulmonary system during the outbreak of the coronavirus disease 2019, has been researched, developed, and produced only by <10 manufacturers, such as Maquet Company (Germany), Medtronic Inc. (the United States), and Sorin Company (the United Kingdom). There are still technical gaps, which must be urgently bridged, between China and the developed countries in the related fields. In the future, China must improve the research on the raw materials and membrane surface-treatment technology for blood-compatible hemodialysis HFMs and support the scientific and technological innovations of the oxygenation HFM technology and industry, as well as the innovation of the HFM technology for drug separation, purification, and precise separation.

3.2.4 Application in food and beverages

In recent decades, the application of HFM in food and beverages to improve the product qualities and production efficiencies of fruit juices and beverages, dairy products, bean products, wine, etc., has developed rapidly. It involves emission reduction in wastewater and the recovery of resources in the food and beverage industry, as well as other fields [12,13]. The applications of HFM technology in the food and beverage industries in China and abroad are generally synchronous. Large-scale beverage enterprises, such as Mengniu Dairy (Group)

Co., Ltd., Yili Group, Bright Dairy & Food Co., Ltd., as well as Beijing Huiyuan Food and Beverage Co., Ltd., have employed membrane technology to improve the qualities of their products. Compared with similar products abroad, the UF/MF HFMs, which were independently developed in China, exhibit wider membrane pore-size distributions and relatively low separation precision and antifouling performances. The markets, such as that of food and beverages, for high-end UF/MF HFMs with high value, are mostly dominated by foreign products. In the future, China must improve the research on food-grade special HFM materials and their green preparation technologies, high-precision and antifouling HFM products, membrane coupling integration, and separation technology for grading.

3.3 Analysis on the overall scientific research of the HFM technology

Regarding the number of research papers and patents, China is the leading country in the research on HFM globally. Between 2008 and 2019, China accounted for 1476 (corresponding to 34.22%) of the 4314 SCI papers that were published globally with respect to the HFM technology [14]. However, regarding the total citation frequency, the National University of Singapore ranks first, followed by Nanyang Technological University. Zhejiang University, Tiangong University, and the Chinese Academy of Sciences rank fifth, sixth, and seventh, respectively, indicating the need to improve the quality of the innovation of HFM technology in China. Globally, there are 6525 patent applications regarding HFM technology, and 3093 of them were applied by the top 20 institutions, accounting for 47.4% of the total patents. Among these institutions, the top five are from Japan. And Japan accounts for eight enterprises among the top 20. Moreover, only Sinopec Group (sixth) and Tiangong University (seventh) made the ranks from China. Although there are 3150 patent applications from China in the field of HFM (48.28% of the total global applications), the patentees are majorly foreign enterprises. Therefore, the proportion of patents from domestic institutions is low [14,15].

4 Limitations of the HFM technology and industry in China

After more than 50 years of development, the membrane technology and industry in China has greatly progressed. Moreover, a theoretical framework was established for the design and preparation of membrane materials, thus availing a series of high-performance membrane products with independent intellectual property right, as well as developing a series of membrane integration technologies and equipment. However, compared with developed countries and regions with advanced membrane industries, China's HFM technology and industry is still lagging [15,16], as manifested by the following four points:

4.1 Rate of localizing raw materials for membrane preparation is low, and the quality of separation membrane still requires improvement

The raw materials, including polyvinylidene fluoride (PVDF), polyethersulfone (PES), polysulfone (PSF), cellulose triacetate (CTA), and polymethylpentene (PMP), for preparing MF, UF, RO, and gas separation membranes are mainly imported from the developed countries, indicating a large gap between domestic and foreign raw materials in terms of their molecular weights and distribution index control, as well as other aspects. Moreover, these foreign countries have placed embargoes on some of these materials. Following analyses, inadequacies were observed in the collaborative innovation between China's membrane technology industry and the upstream raw material industry, and the investment in the development of special polymer materials, as well as the tackling of key scientific and technological limitations, are insufficient. Therefore, China must urgently implement a multidisciplinary collaborative innovation for developing polymer materials, controlling polymerization reactions, and preparing separation membranes to achieve a major breakthrough in the raw materials of key separation membranes and membrane products.

4.2 Classification of separation membranes is relatively simple, and there are gaps in key membrane products

There are few types of domestic membranes, which are mostly UF/MF HFMs, and their products are mostly employed in middle- and low-end fields with low-added values. Compared with similar foreign products, Chinese products exhibit several limitations, such as low stability, low precision for membrane separation, and poor antifouling performance. China's membrane technology and product markets, such as blood oxygenation and special separation membranes, are still monopolized by foreign enterprises, and this is a bottleneck that must be

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urgently overcome. Following analyses, it was observed China's investments in the development of medical hydrophobic membrane and new membrane technologies, as well as other aspects, are insufficient, and the collaboration of the production, education, research, and application is lacking, while the transformation of innovative technologies is lagging. Therefore, based on the key applications and national strategic demands, China must flexibly set up a collaborative technology and industry innovation team that integrates production, education, research, and application, and focus on promptly tackling key scientific and technological limitations to achieve breakthroughs in science and industry.

4.3 Desire for independent innovation is not strong; the vitality and ability of the innovation are insufficient, causing the lagging of the iteration of the technology and products

Many products have been mainly developed by domestic enterprises, although there are only a few products with independent innovation. The number of patents obtained is relatively low. The insufficient protection of intellectual property rights weakens the desires of enterprises to exhibit independent innovation, further lowering the market competitiveness of domestic membrane materials and resulting in extremely low shares in high-end markets. Additionally, the cooperation mechanism between production, education, research, and application is not perfect. Thus, the R&D cannot satisfy the industrial demand, thus causing obstacles in the transfer and transformation of technological achievements. Following analyses, it was observed that the national guidance and supportive policies for enterprises to invest in scientific and technological R&D, as well as collaborative innovation, are still insufficient. Further, the promotion and protection policies for the transformation of scientific and technological achievements must be improved.

4.4 Market-normalized management and standardization must be improved

There are evident shortcomings in the overall development, planning, and standardization of the industrialization of the HFM in China. The development of technical standards for the HFM industry still lags, and the implementation of industrial standards is still lacking. The protection and maintenance mechanisms of intellectual property rights are still imperfect. These limitations account for the serious homogenization of domestic products in the market, and most of these being confined to low-tech products. The uneven quality of products, as well as the lack of investment in the innovation of enterprises, have seriously affected the high-quality development of the HFM technology and industry.

5 Development goals and main tasks of the HFM technology and industry

The following are the major tasks of the HFM field: overcoming a series of bottlenecks and developing forward-looking technologies, supporting original research and products R&D, promoting the industrialization of new membrane technologies with application potentials, promoting the upgrading of traditional industries via membrane technologies and expanding their applications in emerging industries, and promoting the structural reform of the supply side and implementing high-end manufacturing strategies.

The focus of 2025 would be to solve a series of bottlenecks in HFM technology to establish international competitiveness in the raw materials for membrane preparation, manufacturing and application of high-end separation membranes, and other aspects. The UF/MF HFM industry would attain the international leading level. New membranes and special biomedical membranes would continue breakthrough. Additionally, significant improvements will be made in the self-sufficiency rate of the raw materials of traditional membranes; novel membrane materials including polymers of intrinsic microporosities (PIMs), organic framework (MOF/COF) materials, polymethylpentene (PMP), molecular-sieve membrane materials, polyarylene sulfide, and other special separation membrane materials would be developed; corresponding technologies for preparing membranes and equipment must be significantly improved.

By 2030, a series of forward-looking novel HFM technologies would be developed to achieve the wide application of membrane technologies in emerging industries. The NF and inorganic HFMs would attain the international advanced level, and the special HFM technology for the gas separation, biological medicine, and food and beverage industries would approach the international leading level. The digital transformation of the HFM industry would also be realized, and a perfect waste membrane recycling and reusing technology system would be established.

Therefore, research in the following four directions must be emphasized to support the development and industrial application of the related membrane technologies.

5.1 Conducting the green manufacturing and industrial digital transformation of high-performance UF/MF HFM

The persisting unfavorable situation in which the raw materials for preparing membranes are imported must be gradually changed. And a green, large-scale, and stable synthesis process must be developed to prepare the raw materials for membranes. An effective process for producing UF/MF HFMs must be developed via establishing the automation, intelligence, and standardization of the manufacturing process, thus achieving the precise regulation and control of the structure of the membrane. The digital transformation of the industry must be promoted. And energy-saving modular treatment systems with a 10 000-t scale must be developed, building an effective control platform of membrane operation that depends on the perception of the information of the whole process, intelligent decision-making, automatic control, and precise management, thereby gradually achieving the "smart water affairs."

5.2 Developing and industrializing high-quality hydrophobic HFM

New superhydrophobic-polymer-based raw materials must be developed. The precise regulation and control in the surface/interface and pore structures of hydrophobic HFM must be researched to industrialize hydrophobic HFM to achieve uniform pore size, good hydrophobic stability, and high mass-transfer efficiency. The ECMO membranes and other high-end hydrophobic HFM products were broken through. The methods for constructing superhydrophobic and double-hydrophobic HFMs must be researched to achieve their continuous and controllable preparations. The development of hydrophobic HFM modules, equipment, process-intensification methods, and integrated systems must be enhanced for engineering applications. And the innovative application of hydrophobic HFM in resource extraction, new energy, biomedical science, and technology, as well as other fields, must be promoted.

5.3 Developing new HFM technologies and performing engineering demonstrations

It is necessary to accurately grasp the direction of international frontier research on separation membranes, accelerate the development of industrialization of HFM technologies, such as NF, RO, and inorganic HFMs; And improve the innovative research of HFMs in forward osmosis, intelligent response, catalytic separation, affinity and dynamic transmission, energy storage, chromatographic membrane, as well as other technologies. Moreover, the methods for developing and improving green and efficient membrane processes and multiprocess coupling must be explored to improve efficiency. The large-scale preparation and engineering demonstration of new key membrane products would be implemented.

5.4 Studying the recycling and reusing technology of waste membranes

The failure mechanism and the evolution model of membrane materials must be studied. The evaluation method of composition and chem-physical indexes of the waste membranes must be established. Further, new technologies must be developed to prolong the lives of membrane materials and to remanufactur them to maximize the utilization of waste membrane materials. The matching technologies between remanufactured membrane materials and the application process must be explored to form a complete set of technologies for the efficient recovery and high-value reuse of waste composite membrane materials. Research must be conducted on the technologies for identifying and recognizing membrane materials. Furthermore, technologies for sorting membrane materials must be developed. And a professional technical-service platform must be established to achieve the reutilization of waste membrane products and overcome the limitations of large amounts of solid waste and wastage of resources caused by the decommissioning of tens of millions of square meters of membrane modules annually.

6 Countermeasures and suggestions

6.1 Developing a talent management model to stimulate the innovative power of industrial science and technology

The HFM technology involves many fields, such as textiles, materials, chemistry, environments, machinery, and control. However, there is a great shortage of versatile professionals with interdisciplinary knowledge. Thus, a very flexible and open talent training mechanism is proposed to promote the cultivation of high-end specialized multidisciplinary personnel in separation membranes. Some high-performance membrane-material innovation

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centers must be established with industry-leading enterprises, membrane-related state key laboratories, and national engineering centers as the main bodies to promote multi-disciplinary exchanges, cooperation, and innovation to improve the training of through-type skilled teams in the membrane field. Additionally, it is advisable to integrate the whole chain of raw material resources for membrane preparation (upstream), membrane-preparing equipment and technology (midstream), and membrane application (downstream) to vertically establish industrial alliances and stimulate the innovative power of industrial science and technology to continuously improve the technical level of China's membrane industry.

6.2 Increasing resource input to promote the innovative research of membrane materials

The comprehensive utilization of financial investment, preferential tax, preferential financing, and personnel policies can be implemented. The market mechanism could be utilized to encourage and guide social capital into the membrane industry. Industrial investment funds, venture capital funds, and other investment methods of facilitating state investment must be explored. Further, all kinds of financial institutions can be encouraged to financially support the rapid development of the membrane industry. Additionally, national research projects in basic fields must be increased for basic and applied research on raw materials for preparing membranes. Moreover, social capital could be encouraged into intervening in the innovation chain and extend to the front end of the innovation chain, thus improving the effectiveness, timeliness, and transformation efficiency of the technology development by employing market sensitivity and the entrepreneurial spirit of the social capital.

6.3 Improving industrial norms to consequently improve intellectual property right protection and standardization

The implementation of a strict intellectual property rights protection system is proposed, as well as the improvement of the systems for safeguarding intellectual property rights. Policies and measures for reducing the cost of protecting and safeguarding intellectual property rights for small- and medium-sized enterprises must be evaluated and formulated. Further, the utilization of intellectual property rights must be improved. Enterprises must be encouraged and supported to implement intellectual property rights to compete in the market, following the guidance of orderly competition. Energy efficiency standards, water efficiency standards, and the norms for membrane technology in different fields must be implemented. Standardization of the recycling and reusing of waste membranes must also be promoted. The mutual recognition of standards with major trading countries must be promoted in China. China must strive to jointly conduct international standards research and formulation based on the engineering demonstration and application of membranes abroad.

6.4 Strengthening international cooperation to explore international markets

Combining the top-level layout of the Belt and Road initiative, China can employ membrane technology as a link to improve scientific and technological exchanges, thus establishing joint laboratories with foreign countries and building an international development, cooperation, and service platform for the HFM industry. China must improve brand internationalization and avail technical, informative, and policy supports for HFM enterprises to "go global". The transfer of water-treatment technologies must be promoted in China to satisfy the environmental protection needs of the countries along the Belt and Road.

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References

[1] GEP Research. Development report of hollow hiber membrane industry [R]. Beijing: GEP Research, 2019. Chinese.

[2] National Advisory Committee on New Materials Industry Development Strategy. 2018 annual report on China new materials technology development [M]. Beijing: Chemical Industry Press, 2019. Chinese.

[3] Saadat A H M, Islam M S, Parvin F, et al. Desalination technologies for developing countries: A review [J]. Journal of Scientific Research, 2018, 10 (1): 77–97.

[4] Ismaila A F, Khulbe K C, Matsuura T. Recent progress in reverse osmosis (RO) science and technology [J]. Journal of

Applied Membrane Science & Technology, 2017, 21: 1–10.

[5] Xu Y, Goh K, Wang R, et al. A review on polymer-based membranes for gas-liquid membrane contacting processes: Current challenges and future direction [J]. Separation and Purification Technology, 2019: 115791.

[6] Zhao S, Feron P H M, Deng L, et al. Status and progress of membrane contactors in post-combustion carbon capture: A state of the art review of new developments [J]. Journal of Membrane Science, 2016, 511: 180–206.

[7] Athayde D D, Souza D F, Silva A M A, et al. Review of perovskite ceramic synthesis and membrane preparation methods [J]. Ceramics International, 2016, 42(6): 6555–6571.

[8] Transparency Market Research. Hollow fiber ceramic membrane market (ultrafiltration, microfiltration, nanofiltration)—Global industry analysis, size, share, growth, trends, and forecast 2016—2025 [R]. Albany NY: Transparency Market Research, 2018.

[9] Markets and Markets Research. Membrane bioreactor market by membrane type (hollow fiber, flat sheet, multi-tubular), system configuration (submerged, external), application (municipal wastewater treatment and industrial wastewater treatment), Region—Global Forecast to 2024 [R]. Illinois: Markets and Markets Research Private Ltd., 2019.

[10] Zhao C S, Zhao W F, Zhang X, et al. Research framework and anticipated results of novel blood purification materials and wearable artificial kidney [J]. Advanced Engineering Science, 2018, 50(1): 1–8. Chinese.

[11] Qianzhan Industry Research Institute. China hemodialysis industry development prospect forecast and investment strategic planning analysis report from 2021 to 2026 [R]. Shenzhen: Qianzhan Industry Research Institute, 2020. Chinese.

[12] Castro-Muñoz R, Conidi C, Cassano A. Membrane-based technologies for meeting the recovery of biologically active compounds from foods and their by-products [J]. Critical reviews in food science and nutrition, 2019, 59(18): 2927–2948.

[13] Castro-Muñoz R, Boczkaj G, Gontarek E, et al. Membrane technologies assisting plant-based and agro-food by-products processing: A comprehensive review [J]. Trends in Food Science & Technology, 2020, 95: 219–232.

[14] Xu H F. Research and development situation analysis report of hollow fiber membrane technology [R]. Beijing: National Science Library, Chinese Academy of Sciences, 2019. Chinese.

[15] Zheng X, Wei Y S, Wang Z W. Report for sustainable development strategy of China water treatment industry: Membrane industry Ⅲ [M]. Beijing: China Renmin University Press, 2019. Chinese.

[16] Membrane Industry Association of China. Outline of the 13th Five-Year Plan for the development of China's membrane industry [R]. Beijing: Membrane Industry Association of China, 2015. Chinese.