Separation Science and Technology

Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713708471

The Commercial Status of Membrane Bioreactors for Municipal Wastewater

A. Santos[a]; S. Judd[a]
[a] Centre for Water Science, Cranfield University, UK

Online publication date: 23 April 2010

Separation Science and Technology, 45: 850–857, 2010

ISSN: 0149-6395 print/1520-5754 online
DOI: 10.1080/01496391003662337

The Commercial Status of Membrane Bioreactors for Municipal Wastewater

A. Santos and S. Judd
Centre for Water Science, Cranfield University, UK

The status of membrane products for membrane bioreactors is reviewed with specific reference to the municipal wastewater market. Products are identified according to their geographical location and characteristics. The latter are appraised with reference to the membrane configuration, polymeric material type, pore size and, for the hollow fiber (HF) products, the filament diameter. The market penetration of 11 of the suppliers is also assessed.

Keywords membrane bioreactor; immersed commercial; pore size; material

INTRODUCTION

It is revealed that the time taken between the launch of a product and the installation of a large membrane plant (>10,000 $m^3 d^{-1}$ capacity) based on that product has decreased significantly over the past 10 years, appearing to reflect on a growing acceptance of and confidence in the technology. While the market continues to be dominated by the two most established suppliers, a number of new providers are emerging, in particular from Korea and China. The preferred polymeric membrane materials are polyvinylidene difluoride (PVDF) and polyethersulfone (PES), which account for around 75% of the total products on the market including 9 out of the 11 most commercially important products. There appears to be rather more diversity of material types and membrane element size in the HF products than in the flat sheet (FS) ones, notwithstanding the emergence of new non-rigid FS panels and the existence of FS rotating modules.

THE MARKET AND THE COMMERCIAL TECHNOLOGIES

The advantages offered by membrane bioreactors (MBRs) have been widely recognized for almost 50 years (1), and by the early 1970s the first commercial technology was available (Dorr Oliver) with the Rhone Poulenc technology introduced subsequently. However, it is only since the introduction of the immersed configuration (iMBR) – some two decades after the original sidestream technology – that a rapid growth in its implementation and subsequent significant penetration of the substantial municipal has taken place (2). The MBR market value doubled in the five years between 2000 and 2005 to reach $217 and is expected to increase its market value from $296 million in 2008 to $488 million in 2013 (3). Even with the slowing of growth brought about by the global financial crisis, the prospects for the technology appear auspicious.

It is therefore unsurprising that the number of available proprietary MBR membrane products has dramatically increased since the first iMBR technology was commercialized in 1990 (the Kubota ES flat sheet panel), followed by the second (the GE Zenon "Zeeweed®" hollow fiber module) in 1993 (Table 1). These two technologies retain their dominance of the global municipal MBR market today (Fig. 1), with Kubota providing 39% of the total number of MBR installations for the top 11 MBR membrane providers (with respect to installed capacity) and GE Zenon around 46% of the total global installed capacity for MBR treatment; Mitsubishi Rayon Engineering (MRE) have almost as many installations as Kubota, but their activities are largely limited to the Far East. However, newer MBR membrane products are increasing in number and also in market share. As recently as 2003, the most established three players of Kubota, MRE, and GE Zenon had 85–90% of the municipal MBR market, with around 800 installations between them (4). By mid-2009 this number had risen to over 3500 of the total of approaching 5000 municipal installations, with more than 20 other membrane suppliers with MBR reference sites for municipal wastewater treatment. Of the suppliers listed in Table 1, only a handful of them pre-date the year 2000 with regard to their original product launch. Table 1 lists membrane suppliers according to membrane configuration with a few suppliers (e.g., Mitsubishi Rayon and Huber) providing more than one membrane product of a single configuration, and one or two more (e.g., Orelis Environment and Ecologix) providing more than one membrane configuration.

Received 1 November 2009; accepted 31 December 2009.
Address correspondence to S. Judd, Centre for Water Science, Cranfield University, UK. E-mail: s.j.judd@cranfield.ac.uk

TABLE 1
Total MBR technologies reviewed

Immersed (iMBR)		Sidestream (sMBR)
Flat sheet	*Hollow fibre*	*Multitube/multichannel*
A3–*MaxFlow*$^{\mathrm{DE}}$	Asahi Kasei–*Microzoa*®$^{\mathrm{JP}}$	Berghof–*HyPerm-AE; HyPerflux*$^{\mathrm{DE}}$
Alfa Laval$^{\mathrm{SE}}$	Beijing Origin Water Technology Co.$^{\mathrm{CN}}$	Norit X-Flow–*Norit Airlift*$^{\mathrm{TMNL}}$
Brightwater–*Membright*®$^{\mathrm{IRL}}$	*Ecologix–EcoFlon*™, *EcoFil*$^{\mathrm{CN}}$	Orelis Environment–*Kerasep*®$^{\mathrm{FR}}$
Colloide–*Sub snake*$^{\mathrm{NIR}}$	ENE Co., Ltd.–*SuperMAK*$^{\mathrm{KR}}$	MEMOS Membranes Modules Systems GmbH$^{\mathrm{DE}}$
Ecologix–*Ecoplate*™, *EcoSepro*$^{\mathrm{CN}}$	GE Zenon–*ZeeWeed*®$^{\mathrm{US}}$	
Huber–*VRM*®; *VUM*®/ *GreyUse*$^{\mathrm{DE}}$	Hangzhou H-Filtration Membrane Technology Engineering Co., Ltd.–*MR*$^{\mathrm{CN}}$	
Jiangsu Lantian Peier Memb. Co. Ltd.$^{\mathrm{CN}}$	Koch Membrane Systems–*Puron*®$^{\mathrm{US}}$	*Hollow fibre*
KOReD–*Neofil*$^{\mathrm{KR}}$	Korean Membrane Systems–*KSMBR*®$^{\mathrm{KR}}$	Ultraflo–*Ultraflo*®$^{\mathrm{SG}}$
Kubota–ES/EK$^{\mathrm{JP}}$	Litree–*LH3*$^{\mathrm{CN}}$	Polymem–*Immem*$^{\mathrm{TMFR}}$
Microdyn-Nadir–*BioCel*®$^{\mathrm{DE}}$	Memstar–SMM$^{\mathrm{SG}}$	
Pure Envitech Co., Ltd.– *ENVIS*$^{\mathrm{KR}}$	Mitsubishi Rayon–*Sterapore SUR*®; *Sterapore SADF*®$^{\mathrm{JP}}$	*Flat disc ceramic*
Shanghai Megavision Memb. Tech.$^{\mathrm{CN}}$	Philos$^{\mathrm{KR}}$	KERAFOL Keramische Folien GmbH$^{\mathrm{DE}}$
Shanghai SINAP Membrane Science & Technology Co., Ltd.$^{\mathrm{CN}}$	Porous Fibers S.L.–*Micronet*®$^{\mathrm{SP}}$	Grundfos–*Biobooster*$^{\mathrm{DK}}$
Toray–*TRM*$^{\mathrm{JP}}$	SENUO Filtration Technology Co., Ltd.– *SENUOFIL*$^{\mathrm{CN}}$	
Vina Filter–*Vinap*$^{\mathrm{CN}}$	Shanghai Dehong Biology Medicine Science & Tech. Development Co., Ltd.$^{\mathrm{CN}}$	
Weise–*MicroClear*®$^{\mathrm{DE}}$	Siemens Water Tech.–*Memjet*$^{\mathrm{TM\ DE}}$	
	Sumitomo–*PoreFlon*®$^{\mathrm{JP}}$	
	Superstring MBR Tech. Corp.–*SuperUF*$^{\mathrm{CN}}$	
	Tianjin Motimo–*FP AIV*$^{\mathrm{CN}}$	
	Vina Filter–*F08*$^{\mathrm{CN}}$	
	Zena Membranes–*P5*$^{\mathrm{CZ}}$	

CN: China/Taiwan; CZ: Czech Republic; DE: Germany; DK: Denmark; FR: France; IRL: Southern Ireland; JP: Japan; KR: Korea; NIR: Northern Ireland; NL: Netherlands; SE: Sweden; SG: Singapore; SP: Spain; US: United States.

A review of the geographical location of the listed providers (Fig. 2) reveals them to derive primarily from East Asia, with China, Korea, Japan, and Singapore and providing over half of the technologies identified, and the EU, and principally Germany, providing most of the remainder. Moreover, there are a number of other MBR membrane products either currently close to being commercialized or already commercially available but not visible through the usual routes of internet search engines, international trade shows, or articles/advertizement in trade magazines. Having said this, it is not always possible to distinguish between the original membrane or the membrane module manufacturers (i.e., original equipment suppliers, or OEMs) and those which simply acquire these products and rebrand them for sale.

Some technologies have evolved over a number of years, with significant modification of the designs yielding different products. The original submerged iMBR membrane module produced by GE Zenon, for example, was the Zeeweed® 145, containing 145 square feet of membrane area and in which the fibers were looped over a raised section of the frame. This design was subsequently superseded first by the ZW150 and then by the more familiar ZW500 module, for which there have been three generations with a fourth due shortly. The Kubota 510 membrane panel, on the other hand, has remained unchanged since its

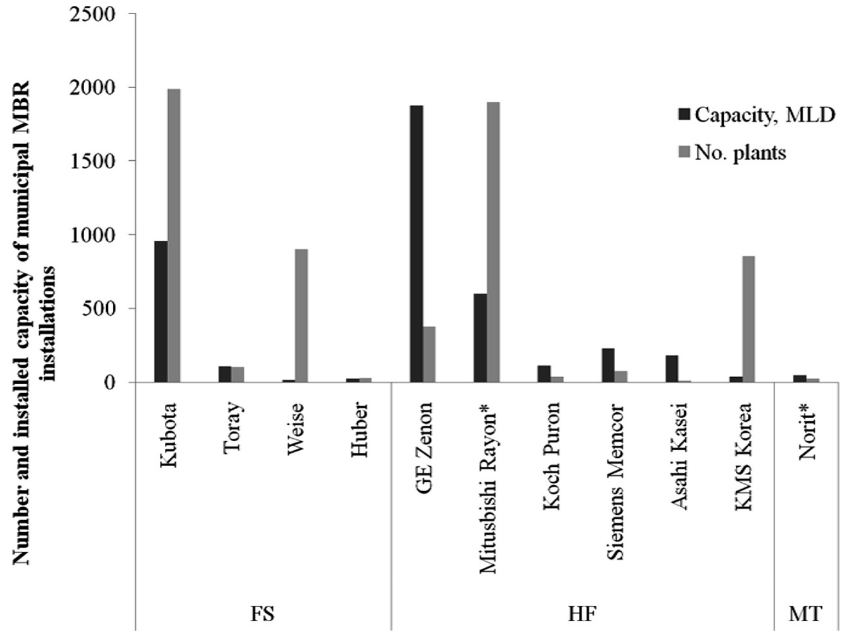

FIG. 1. MBR municipal market; *estimated figures from available information.

introduction in 1990 and was only supplemented by the larger 515 panel in 2008. MRE similarly introduced its SADF membrane module in 2004, a product significantly different in design to the original SUN module and which now forms the basis of all large municipal MBRs based on MRE technology.

Of the other technology suppliers, Huber (and also Maffin Systems AG) both provide both classical rectangular panels and a more novel rotating FS configuration membrane. Some suppliers (e.g., Koch, Microdyn-Nadir and Orelis Environment) provide membranes of different configurations, though in such cases it appears that only one configuration is actually marketed for MBR duty. A few vendors, particularly in China and Korea, provide a number of different dedicated MBR membrane configurations. For example, the company Ecologix in Taiwan provides HF membrane modules of two different membrane materials (PVDF and PTFE) and two distinct FS panels (a rigid and non-rigid variety, apparently available in PVDF, PES, and PAN). Such extraordinary diversity from a single supplier, however, and the products are too recent to have achieved substantial market penetration.

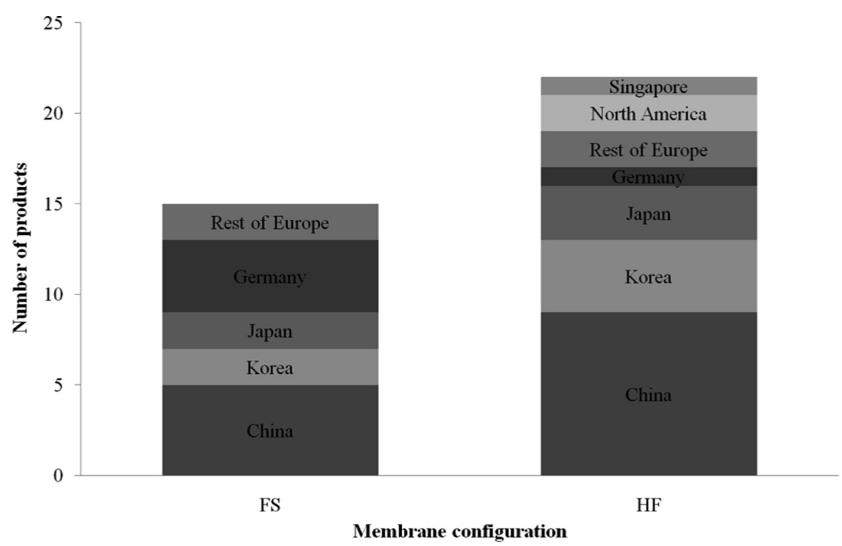

FIG. 2. Global distribution of flat sheet (FS) and hollow fiber (HF) membrane suppliers.

Finally, there are some new ceramic products (Kerafol and the highly unusual Grundfos *Biobooster*) which may come into use for industrial effluent treatment in the future.

It should be noted that some MBR technology suppliers employ other membrane products. This is particularly evident with the sidestream technologies of process suppliers such as Aquabio in the UK, Parkson in the US, and Wehrle in Germany, all of whom employ multitube (MT) membrane products for their technology, and primarily Norit but also Berghof and others. Such diversity of suppliers is made possible by the standardization of MT membrane modules, which are thus of a set diameter and length regardless of the membrane material and pore size. Hitachi and Busse similarly employ proprietary flat sheet panel products in their technologies, both of them achieving success through specializing in package plants for specific applications. These examples reflect the wider issue of the importance of the design of the overall MBR technology, and not just that of the membrane module.

Recent reviews in the EU market (5,6) have revealed rapid growth in this region, which reflects growth encountered elsewhere in the world. These reviews have shown the EU in particular to be dominated by the two leading suppliers, in that as at the end of 2008 all of the large MBRs (>10 megalitres per day, or MLD, in capacity) were either Kubota or GE Zenon. There were also noted regional differences, with all such large MBR installations in Italy (4 off), and the Netherlands, Switzerland, Belgium, Cyprus, and Hungary (one each) being GE Zenon. A more equal distribution (of the 32 installations in total across the EU) between Kubota and GE Zenon was reported for Germany, Spain, and the UK. However, other technologies have a presence in the EU, and the Netherlands in particular has a well-established national programme for demonstrating a range of MBR technologies at reasonable scales.

Globally, there is also a pronounced upward trend in plant size, reflecting noted trends reported for the EU by Lesjean et al. (5,6), as unsurprisingly dominated by GE Zenon (Table 2) who provide 15 of the 20 largest plant (as of end 2009); in terms of the average flow capacity the company still accounts 13 of the top 20. However, a unsurprisingly dominated by GE Zenon (Table 2) who provide 15 of the 20 largest plants (as of end 2009); in terms of the average flow capacity the company still accounts for 13 of the top 20. However, a review of the largest installations, including those in planning or construction and due before 2011, for individual technologies (Table 3) reveals that some Far Eastern suppliers, with products launched only

TABLE 2
Top 20 largest MBR installations globally

Project, Country or US State	Supplier	Date	PDF, MLD	ADF, MLD
Wenyuhe, China	Asahi Kasei BOW	2007	100	100
Johns Creek, Georgia	GE Zenon	2009	94	41
Beixiaohe, China	Siemens Water Tech	2008	78	60
Al Ansab, Muscat, Oman	Kubota	2009	78	56
Peoria, Arizona	GE Zenon	2008	76	38
Cleveland Bay, Australia	GE Zenon	2007	75	29
Lusail, Qatar	GE Zenon	2008	60	60
Cairns North, Australia	GE Zenon	2009	58	19
Cairns South, Australia	GE Zenon	2009	58	19
Sabadell, Spain	Kubota	2009	55	35
San Pedro del Pinatar, Spain	GE Zenon	2007	48	20
Syndial, Italy	GE Zenon	2005	47	38
Broad Run WRF, Virginia	GE Zenon	2008	47	38
Beijing Miyun, China	Mitsubishi Rayon	2006	45	30
Nordkanal, Germany	GE Zenon	2004	45	17
Tempe Kyrene, Arizona	GE Zenon	2006	44	34
Brescia, Italy	GE Zenon	2002	42	42
Traverse City, Michigan	GE Zenon	2004	39	27
Linwood, Georgia	GE Zenon	2007	38	17
North Kent Sewer Authority, Michigan	GE Zenon	2008	35	23

PDF – Peak daily (design) flow; ADF – Average daily (design) flow.
BOW – Beijing Origin Water.

TABLE 3
Largest installations, operational by 2010, for individual technology providers; plants >10 MLD capacity

Location	Supplier	Date	Capacity, MLD
Jumeirah Golf Estates, UAE	GE Zenon	2010	189
Wenyuhe, China	Asahi Kasei BOW	2007	135
Guangzhou, China	Memstar	2010	100
Beixiaohe, China	Siemens Water Technology	2008	78
Al Ansab, Muscat, Oman	Kubota	2009	78
Najran, Saudi Arabia	Toray	2010	60
Beijing Miyun, China	Mitsubishi Rayon*	2006	45
Tianjin Industry, China	Tianjin Motimo	2007	30
Griffith, Australia	KMS Puron	2010	30
Daegu Dalsung, Korea	Korea Membrane Separation	2008	25
Ji'an, China	Microdyn-Nadir	2010	20
Palm Jumeirah, UAE	Norit	2009	17

*SADF technology, introduced in 2004.

within the past few years, have been able to secure contracts for very large projects, particularly in China and the Middle East.

The historical development of the technology is intriguing. For example, at the end of the last millennium, the largest MBR plant in the world was the plant at Swanage in the UK, with a design capacity of around 13 MLD. It was around that time that Norit first started developing their novel air-lift sidestream configuration for municipal wastewater applications, at a pilot plant in Vienna, before launching it as a commercial product in 2002. There are now around 30 plants worldwide based on this technology, with the largest of these being the 17 MLD plant at Palm Jumeirah in the UAE (Table 4), compared with the 237 Kubota plants in 1999 when Swanage was being commissioned. This means that, in less than a decade, a technology based on a novel configuration (i.e., air-lift sidestream) has grown to the point where the largest installation based on that technology exceeds the capacity of that of the largest installation ten years ago.

This would seem to reflect a more general trend in increasing acceptability of comparatively new technologies. Of the 12 technologies listed in Table 3, only two pre-date 2000 and many have less than 50 reference sites (Fig. 1). Notwithstanding this, some very large installations, the smallest being the Palm Jumeirah plant, are planned based on these technologies despite some of them being no more than 1–7 years old. This provides further evidence of the change in perception of MBRs as a "new" or high-risk technology: it appears that fewer reference sites are now required for a technology to be considered commercially acceptable at a large scale. Indeed, a correlation of the time taken for a technology to achieve the first 10 MLD capacity plant provides a stark illustration of this, with the gestation time sharply decreasing since the turn of the millennium (Fig. 3).

THE MEMBRANES

The membranes used in MBRs can be categorized according to their configuration (primarily their geometry and flow direction), material type, and physical size (2). All MBR membrane technologies are either flat sheet (FS), hollow fiber (HF), or multitube (MT), with the immersed process technologies exclusively comprising HF or FS membranes and the sidestream technologies being mainly MT, and they are almost exclusively polymeric: none of the ceramic membrane-based technologies are in general use for MBRs. With regard to physical size, it is primarily the separation of membrane panels and the fiber (or filament) outside diameter which constitute the key dimension for the FS and HF configurations respectively, whereas it is the internal diameter for the MT products. Only the iMBR products are considered in the analysis below. Apart from the standardized MT products (Norit and Berghof), the other sMBR systems are varied, currently have little market penetration and are subject to different design criteria.

In the case of the FS configuration, all products for which information is available have a membrane separation between 6 and 10 mm. Almost all of the immersed systems apart from the two rotating membrane products (the Huber VRM and the Martin Systems siClaro DM) are rectangular panels around 0.5 m wide and 1–1.5 m deep. Purely in terms of the physical dimension of the panels, they are thus all quite similar. However, some of the newer products, specifically those from Alfa Laval, Colloide, Microdyn-Nadir, and the new AGFA-Vito

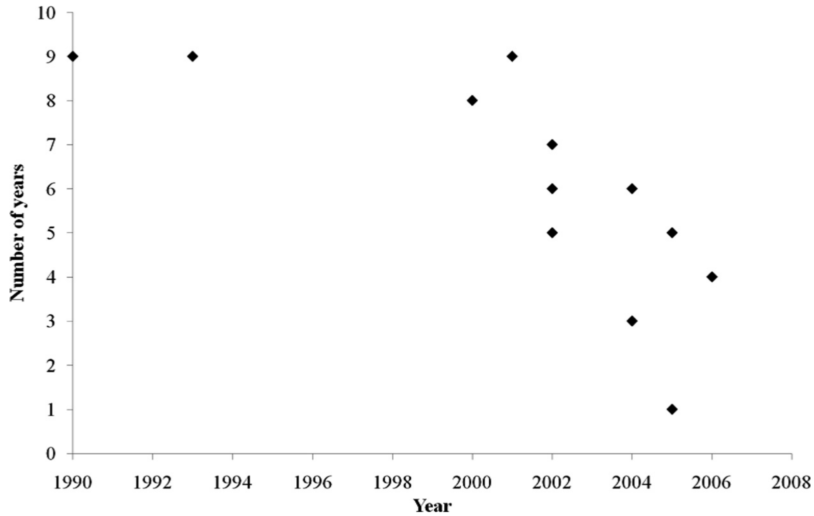

FIG. 3. Time taken between product launch and installation of first plant of more than 10 MLD capacity for 12 MBR membrane products.

membrane (still under development but close to commercialization (7)), are based on non-rigid, composite membrane panels which do not rely on a rigid plastic substrate of, for example, acrylonitrile butadiene styrene (ABS) plastic in the case of Kubota, for mechanical integrity. A slimmer membrane panel permits a higher packing density and potentially reduced production costs if the complete double-sided composite membrane can be produced continuously. Moreover, unlike the rigid FS panels but like HF membranes, these materials are backflushable. On the other hand, since these are new products their robustness over the long-term use is currently unknown, whereas there are reference sites based on both Kubota and GE Zenon membranes which demonstrate membrane life of up to 11 years.

Polymer materials used for MBR membranes are largely limited to two fluorinated polymers (polyvinylidene difluoride, PVDF, and polytetrafluoroethylene, PTFE), two sulphonated polymers (polyethersulfone, PES, and polysulphone, PS), and two polyolefinic membranes (polypropylene, PP, and polyethylene, PE), with a pore size ranging from 0.01 to 0.4 μm (Fig. 4). PES/PS membranes are mostly in the ultrafiltration pore size range and make up 20% of the iMBR membrane materials listed. The PTFE and polyolefinic membranes, on the other hand, are all in the microfiltration range (0.8–0.4 μm). However,

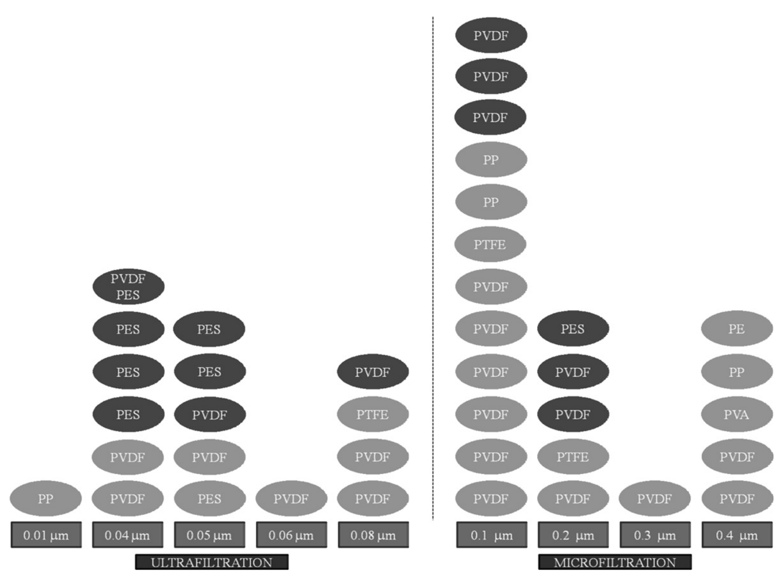

FIG. 4. Membrane pore size *vs.* membrane material (light shadow: HF; dark shadow: FS), immersed systems.

polyvinylidene difluoride (PVDF) membranes dominate, making up 55% of the total iMBR membrane technologies considered and cover almost the entire pore size range (between 0.04 and 0.4 μm). The only other polymeric membrane material employed are polyacrylonitrile (PAN), employed in one sidestream HF product, and polyvinyl alcohol (PVA) in an immersed FS technology. There is a greater diversity of materials used for HF membranes than for FS ones, with those used for FS panels currently being largely limited to PES, PVDF, through the market leader (Kubota) employs a chemically modified PE material.

A review of the facets of the different polymeric materials used for MBR membranes is beyond the scope of this paper, and both a comprehensive review (8) and an excellent precis (9) are available elsewhere. However, the most salient properties of the membrane material properties relate to their surface and bulk properties. The surface properties comprise the pore size distribution and the hydrophilicity, and the important bulk properties have chemical, thermal, and mechanical integrity. All the membrane materials are naturally hydrophobic and have to be made hydrophilic either by blending with hydrophilic copolymers (as applies to PES/PS products), oxidative chemical post-treatment (possible for PE), or wetting out, normally using a reagent such as polyvinyl alcohol (PVA). The membrane materials are also thermo-tolerant beyond the 40°C limit imposed by many of the membrane suppliers, but this threshold is determined by other constituents of the membrane module (specifically the potting compound).

Polyolefinic HF membranes are generally produced by the relatively simple process of dry spinning, which produces slit-like pores, therefore having a wider pores, size distribution. This, along with the relatively low pore density, tends to make the membrane more susceptible to fouling and thus necessitates lower-flux operation than that of other membrane materials. This can be countered to some extent by producing modules of higher packing density and thus smaller diameter filaments (Fig. 5), and this is reflected in the commercial trends. However, the limitations of this material have meant that it has been largely superseded by the other polymeric materials.

The combination of good chemical resistance and surface structure (the latter due to the wet-spinning pore formation process) has meant that the sulphonated and fluorinated polymers, and PES and PVDF in particular, dominate in modern MBR membranes. PS and PES have the widest chemical resistance, tolerating pH levels as low as 1.5 and as high as 13, as well as moderate chlorine resistance. PDVF is less tolerant of alkaline conditions, with an upper pH limit of 11, but has a very high tolerance to chlorine, which is the most widely used cleaning reagent in MBRs, and is less brittle than PES. Its chemical resistance increases with crystallinity, such that highly crystalline PVDF membranes such as the Asahi Kasei *Microza*® product have extremely high chemical resistance combined with good mechanical properties. The use of PAN and PTFE for hollow fibers is a relatively recent development, though the Orelis Pleiade® FS membrane, one of the original sidestream MBR membranes, is based on PAN.

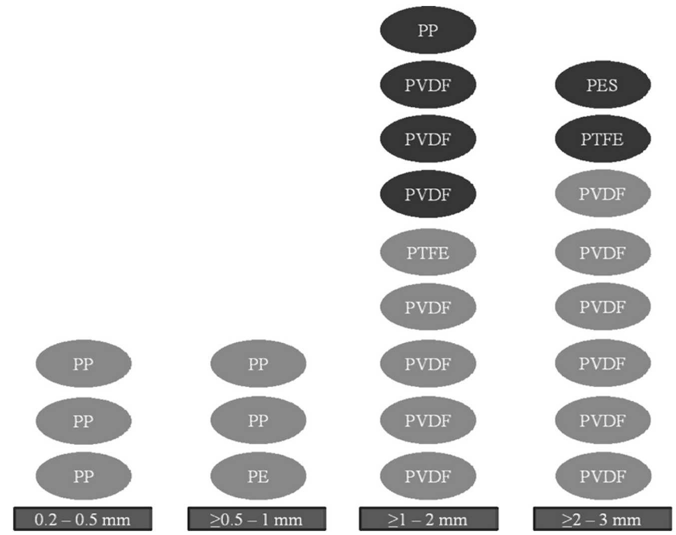

FIG. 5. HF membrane diameters *vs.* membrane material (light shadow: MF; dark shadow: UF), immersed systems.

The data for the range of fiber diameters (Fig. 5) show that the HF MBR membranes currently range in size from 0.2 up to 3 mm. Data indicate that the polyolefinic membranes are predominantly used for smaller fiber diameter, all but one being <1 mm in fiber diameter, and are largely in the MF pore size range. For the larger-diameter fibers (>1 mm), PVDF seems to predominate.

CONCLUSIONS

The most recent available information on commercial MBR membrane technologies indicates that:

- There are approximately 43 MBR membrane product suppliers, with possibly more given that further products are close to commercialization, 35 of them supplying immersed (iMBR) membrane modules. Given that some suppliers produce more than one product, the total number of discrete products exceeds 50, although perhaps no more than half of these have irrefutably been demonstrated at full scale.
- The vast majority of the iMBR products are less than 10 years old: only the Mitsubishi Rayon Engineering *SUR*®, the GE Zenon *Zeeweed*®, and the Kubota *ES* unquestionably pre-date the year 2000. Notwithstanding the immaturity of

these products, there are an increasing number of ever larger plants based on them which would appear to reflect a growing confidence in the technology per se, with the lead time from the introduction of the technology to implementation of a large-scale plant decreasing markedly since commercialization of the original MBR membrane products in the early 1990s.

- Around 75% of the available iMBR membrane products are either polyvinylidene difluoride (PVDF) or polyethersulfone (PES), the remainder being polysulphone (PS), polyacrylonitrile (PAN), polytetrafluoroethylene (PTFE), polypropylene (PP) or polyethylene (PE). The latter two materials are predominantly microfilters ($>0.1\,\mu m$ pore size) and of relatively small filament diameter (<1 mm) if configured as hollow fibers. The predominance of PVDF and PES reflect the desirable pore structure and chemical resistance properties of these materials.

REFERENCES

1. Bemberis, L.; Hubbard, P.J.; Leonard, F.B. (1971) Membrane sewage treatment systems – Potential for complete wastewater treatment. *American Society of Agricultural Engineers Winter Meeting*, 71–878: 1–28.
2. Judd, S. (2006) The status of membrane bioreactor technology. *Trends in Biotechnology*, 26 (2): 109–116.
3. Hanft, S. (2008) Membrane bioreactors: global markets (MST047B). BCC Research.
4. Pearce, G. (2008) Introduction to membranes – MBRs: Manufacturers' comparison: Part 1, *Filtration and Separation* 45 (1–2):32–35.
5. Lesjean, B.; Huisjes, E.H. (2008) Survey of European MBR market, trends and perspectives. *Desalination*, 231: 71–81.
6. Lesjean, B.; Ferre, V.; Vonghia, E.; Moeslang, H. (2009) Market and design considerations of the 37 larger MBR plants in Europe. *Desalination and Water Treatment*, 6: 227–233.
7. Doyen, W.; Mues, W.; Molenberghs, B.; Cobben, B. (2010) Spacer fabric supported flat-sheet membranes: A new era of flat-sheet membrane technology. *Desalination*, 250: 1078–1082.
8. Meng, F.; Chae, S.-R.; Drews, A.; Kraume, M.; Shin, H.-S.; Yang, F. (2009) Recent advances in membrane bioreactors (MBRs): Membrane fouling and membrane material. *Water Research*, 43 (6): 1489–1512.
9. Pearce, G. (2007) Introduction to membranes – Membrane selection, *Filtration and Separation*, 44 (3): 35–37.