Bioresource Technology 122 (2012) 2–10

Contents lists available at SciVerse ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

A practitioner's perspective on the application and research needs of membrane bioreactors for municipal wastewater treatment

Jeremy T. Kraemer [a,*], Adrienne L. Menniti [b], Zeynep K. Erdal [c], Timothy A. Constantine [a], Bruce R. Johnson [d], Glen T. Daigger [d], George V. Crawford [a]

[a] CH2M HILL Canada Ltd., 245 Consumers Road, Suite 400, Toronto, Ontario, Canada M2J 1R3
[b] CH2M HILL, 2020 South West 4th Avenue, 3rd Floor, Portland, OR, USA
[c] CH2M HILL, 6 Hutton Centre Drive, Suite 700, Santa Ana, CA, USA
[d] CH2M HILL, 9191 South Jamaica Street, Englewood, CO, USA

HIGHLIGHTS

- Review membrane bioreactor design practices for municipal wastewater treatment.
- Five generations covering process design and procurement evolution.
- Accommodating biological nutrient removal and high mixed liquor concentrations.
- Design for operation and maintenance, managing peak flows, and reliability.
- Four knowledge areas identified as important to practitioners meriting research.

ARTICLE INFO

Article history:
Available online 11 May 2012

Keywords:
Membrane bioreactor
Practitioner
Biological nutrient removal
Design
Research needs

ABSTRACT

The application of membrane bioreactors (MBRs) for municipal wastewater treatment has increased dramatically over the last decade. From a practitioner's perspective, design practice has evolved over five "generations" in the areas of biological process optimization, separating process design from equipment supply, and reliability/redundancy thereby facilitating "large" MBRs (e.g. 150,000 m^3/day). MBR advantages and disadvantages, and process design to accommodate biological nutrient removal, high mixed liquor suspended solids concentrations, operation and maintenance, peak flows, and procurement are reviewed from the design practitioner's perspective. Finally, four knowledge areas are identified as important to practitioners meriting further research and development: (i) membrane design and performance such as improving peak flow characteristics and decreasing operating costs; (ii) process design and performance such as managing the fluid properties of the biological solids, disinfection, and microcontaminant removal; (iii) facility design such as equipment standardization and decreasing mechanical complexity; and (iv) sustainability such as anaerobic MBRs.

1. Introduction

This review examines developments in membrane bioreactor (MBR) practice that have evolved over the last 10–15 years, during which time the application of MBRs at full-scale for municipal wastewater treatment has grown exponentially around the world (de Wilde et al., 2007; Judd, 2011; Oppenheimer et al., 2011; Pearce, 2008). The review reflects on the development and application of MBRs for large applications, integration of biological nutrient removal, and how the associated process and facility design challenges were overcome. Finally, the review concludes by proposing areas of research the authors believe will provide meaningful contributions to the science of membrane bioreactors, thereby promoting further full-scale practice.

This review assumes the reader is familiar with membrane technology and MBRs; those readers desiring a greater understanding of the fundamentals are referred to the latest industry reference texts (Brepols, 2010; WEF, 2011; Judd, 2011).

2. Evolution of MBR practice

MBR practice, experience and design capabilities have advanced rapidly in the last 10–15 years, and led to the development of industry best practices. MBRs have become an essential technology in the wastewater practitioner's repertoire with many advantages, although they still have limitations that must be understood for appropriate application.

---

* Corresponding author. Tel.: +1 416 499 9000; fax: +1 416 499 4687.
E-mail address: jeremy.kraemer@ch2m.com (J.T. Kraemer).

0960-8524/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.biortech.2012.05.014

2.1. Emergence of MBRs as an established technology

Even only a decade ago, membrane bioreactors were still an "emerging" technology and relatively novel within the municipal wastewater treatment industry. That the technology was still in development is exemplified by the research conducted at that time by the Dutch Foundation for Applied Water Research (STOWA) (van der Roest et al., 2002) which employed pilot-scale systems directed towards practical application of MBRs for municipal applications. The authors investigated pre-treatment requirements to minimize macro-scale fouling of the membranes from trash and hair, biological system operation impacts on whole plant design, whole system optimization considering biological system and membrane system interactions, the extent of effluent quality benefits with respect to microcontaminant removal and disinfection, and sludge production. MBRs of capacity greater than 1000 m^3/day emerged only in the late 1990's and early 2000's (Stephenson et al., 2000). Prior to this, applications were limited to small size and package plants wholly supplied by the membrane manufacturer. This early era is referred to as the "first-generation" of MBRs (Crawford et al., 2000).

Circa 2000, full biological nutrient removal was still being contemplated for MBRs. Experience prior to this time included some limited application of metal salt addition and of denitrification zones in MBRs; however, various authors (e.g. Stephenson et al., 2000) suggested there should be no reason why biological phosphorus removal could not be applied in MBRs. Hence, the early 21st century reflected the "second generation" of MBRs when expectations of nutrient removal started to become more prevalent (Gnirss et al., 2003). Similarly around this time prospective owners and utilities began to better understand the overall MBR system design, and demanded higher levels of equipment and efficiency optimization such as by reducing the solids retention time and therefore the overall system size and operating cost – this has been referred to as the "third generation" of MBRs. These 2nd and 3rd generation developments were fully realized in Traverse City, Michigan (Crawford and Lewis, 2004). The Traverse City MBR facility, fully operational in 2004, developed many innovations in both plant design and membrane procurement, and illustrated many advancements in practice that were necessary to bring about large capacity MBRs as seen today. MBRs that are now in operation having a design capacity of 150,000 m^3/day continue to utilize some of the innovations and design breakthroughs first employed at Traverse City:

- For the first time, no upstream flow equalization, flow diversion, or bypass provisions were included – the plant was the first MBR that was required to treat all flows received at the plant without interruption or bypass and was the largest in the world based upon peak flow;
- Fine screens were provided downstream of primary clarifiers, possibly for the first time;
- The MBR was designed for a combination of biological and chemical phosphorus removal;
- The facility was designed for automated operation, unstaffed during nights and weekends, with standby power and redundant programmable logic controllers (PLCs) designed for fail-safe control and automatic restart after power failure without requiring operator intervention;
- The membrane manufacturer was selected through a competitive bidding process in early 2002, after the general plant layout and process design had been finalized;
- Some key commitments were made contractually between the membrane manufacturer and the design-builder. The membrane manufacturer committed that the membrane system supplied would exhibit the desired flow and duration relationships, and while doing so would produce an effluent better than 2.5 mg/L total suspended solids (TSS) and turbidity of 0.5 Nephelometric Turbidity Units (NTU). The manufacturer also guaranteed that this membrane performance would be attained continuously without requiring more than four chemical-soaking (recovery) cleanings of the membranes per year, nor more than one chemical backwash (maintenance) cleaning every four days. The design-builder in turn committed to creating an environment for the membranes in the membrane tank that included fine screening pre-treatment, a mixed liquor concentration between 8000 and 10,000 mg/L, a solids retention time of between 10 and 14 days, and a minimum temperature of 13 °C during the maximum month flow and of 10 °C during shorter duration peak flow design conditions.

Industry consensus on MBR design began to emerge by 2006, with publications such as *Membrane Systems for Wastewater Treatment* (WEF, 2006) which reflected North American design practice, whole system integration and operation, and *The MBR Book* (Judd, 2006) which reflected European practice and manufacturer-specific equipment differentiation. This trend towards some level of industry consensus led some groups to contemplate membrane equipment standardization, similar to that available in the external cross-flow membrane module market for drinking water treatment. The European Union financed the project Accelerate Membrane Development for Urban Sewage Purification (AMEDEUS) (de Wilde et al., 2007), which included a mandate to identify the need and viability of standardizing membrane equipment for MBRs. At the outset, many believed it to be possible to mandate the dimensions of membrane cassettes, to develop standardized test methods and performance ratings, and to adopt standardized terminology and units of expression. The latter objective is moving ahead, as is the development of test methods. The efforts to standardize the physical equipment dimensions by regulatory mandate or by collaboration have, however, been abandoned (Frechen, 2009).

The mid- to late-2000's saw the development of the "fourth generation" of MBRs characterized by the emergence of competitive membrane equipment manufacturers offering similar equipment, and a resulting increased definition and separation between the designer's and the membrane equipment manufacturer's respective responsibilities. Improvements were made in the specification and assignment of the associated risk and performance guarantees to each party. The fourth generation also coincided with a dramatic increase in both the number and size of systems (Crawford et al., 2000; Oppenheimer et al., 2011). The evolution of the industry to larger MBRs necessitated complete integration of the MBR within the entire wastewater treatment plant (e.g. management of peak flows), optimization of operating costs over the entire plant and its life cycle (Crawford and Briggs, 2008), and design for phasing/future expansion.

Membrane bioreactors are now an established technology for municipal wastewater treatment. Now in the "fifth generation", current practice recognizes the application of full reliability and redundancy principles in the MBR system design as well as the overall plant, with particular emphasis on redundant control system architecture and standby power systems reliability (Okazaki et al., 2008). These design philosophies ensure that there will be no single point within the control or equipment design that, if it failed, would cause the loss of a significant proportion of the total plant capacity. The redundancy features consider all design components, such as use of a pressure-reducing valve to allow shared redundancy between process aeration blowers and membrane air scour blowers. Meanwhile, this increased consideration of redundancy and reliability is evolving within the context of a membrane equipment market that is maturing as evidenced by the emergence of large corporations as primary suppliers (e.g. Dow, General Electric, Huber, Koch, Ovivo, Pall, Siemens, and Veolia), often through