Membrane technologies for wastewater treatment

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In most of the applications in wastewater treatment, micro and ultrafiltration membranes are used in conjunction with biological suspended growth treatment processes forming membrane bioreactors (MBR). Membranes are used for the separation of biomass flocs and other suspended and dissolved solids from the clear liquid and thus offer a replacement for final settlement tanks (FST) and sand filters in conventional activated sludge systems. Such membranes are pressure-driven and are termed rejection membranes as they reject particulate and let through soluble components in the filtrate. Other types of membrane applications are extractive and diffusive systems, which are used to either extract or introduce a specific component through a selective membrane. These two applications are still in a research stage and will not be further discussed in this article.

Membrane bioreactors can be configured either as a sidestream process if membranes are placed outside the bioreactor or as a submerged process if membranes are placed inside. Submerged processes are usually equipped with flat sheet (FS) or hollow fibre (HF) membranes, whereas sidestream configurations most often use multi-tube (MT) membranes. The submerged systems operate at lower fluxes therefore requiring more membrane area per flow but are less energy intensive and operate at smaller trans-membrane pressures (TMP). They are usually used in municipal wastewater treatment applications. The sidestream configurations are a bit more energy intensive but operate at higher fluxes and are therefore more compact. They are usually used in industrial applications.

The success of membrane technology in wastewater systems is mainly a result of a superior effluent quality and a much smaller physical footprint compared to conventional activated sludge (CAS) systems. And, as the effluent quality requirements get more stringent, water unit prices get higher making water recycling options more viable. Also membrane unit prices continue to fall, so the technology is becoming more cost-effective against conventional treatment solutions. Recent market figures support these observations and indicate that the market value of MBR technology was approximately $217 million in 2005 and rising at an average annual growth rate of 10.9% – significantly faster than other competitive processes such as aerated filters or sequencing batch reactors (SBR) (S.Judd). According to BCC research, the global market for membrane bioreactor technology is now expected to grow at a compound annual growth rate (CAGR) of 10.5% increasing in value from 296 million in 2008 to 488 million by 2013.

The advantages of MBRs are now widely recognised by both the academic and the engineering community and include:

- Very high quality, completely clarified and largely disinfected effluent achievable in a single process unit. The level of disinfection depends on the average pore size and pore size distribution of a membrane. Microfiltration membranes are capable of removing most of the bacterial cells whereas the ultrafiltration modules can remove bacteria and some viruses.
- Independent control of solids and hydraulic retention times (SRT and HRT, respectively). In CAS processes achievable SRT within the reactor's volume is dependent on sludge separation and thickening efficiency in FSTs. This, in turn, depends on hydraulic conditions inside the FST (i.e. upflow velocity, HRT and RAS flow rate), HRT in the bioreactor (which affects floc size distribution) and sludge morphology, which affects settleability. In MBRs, hydraulic retention times in the bioreactor have almost no effect on sludge separation process and thus the SRT.
- Operation at higher mixed liquor suspended solids (MLSS) concentrations compared to CAS process. MLSS concentrations in conventional processes are limited to a range of 2,000–4,500 mg/L, depending on sludge settleability, as higher sludge concentrations would violate critical permissible mass flux in a FST. MBRs can operate with poor settling, non-flocculent and filamentous sludges up to MLSS concentrations of 8,000–12,000 mg/L, which leads to reduction in bioreactor volume from 200 to 400%. Even higher MLSS concentrations may be used but this would cause an increase in cake build-up on the membrane surface and would lead to reduced oxygen transfer thus increasing aeration costs.
- Reduced surplus sludge production resulting from longer SRTs promoting sludge lysis and stabilisation. Operation at longer SRT also leads to higher and more stable biological oxygen demand (BOD) and ammonia removal rates in the systems leading to better effluent quality.
- A much smaller footprint making it much more attractive for construction in developed urban areas, grey water recycling inside buildings and for decentralised wastewater treatment.

A multi-tube (MT) membrane

These characteristics enabled MBRs to be cost-effective in a variety of applications where either: very high effluent quality is required; treated effluent needs to be treated in a tertiary process or disinfected; or there is land scarcity or treated effluent needs to be reused. MBRs are nowadays less competitive for large municipal wastewater treatment plants (WWTP) where intermediate effluent quality is required and land availability isn't usually an issue. This is mainly due to the following constraints:

- Greater process complexity and requirements for a specialised staff to operate and maintain the membranes.
- Higher CAPEX incurred mainly by the installation and replacements of still costly membrane modules. MBR systems also require better upstream screening systems, usually of 1-3mm spacing to prevent clogging of the membrane flow channels. These capital costs can be often partly offset by lower costs of construction due to smaller process volumes and land requirements.
- Higher OPEX costs due to higher energy demand for aeration and pumping, chemical consumption and manpower costs for periodic membrane cleaning. Higher costs of aeration are due to lower oxygen transfer at elevated MLSS and extra aeration requirements for membrane scouring to prevent cake build-up on the membrane surface (reversible fouling). In sidestream configurations air scouring is replaced by high crossflow velocities introducing shear on the surface of the membrane. Pumping costs originate from the need of forcing the liquid through the membrane and from membrane backwashing. Chemicals are used to periodically clean the membranes from the foulants that cannot be removed by backwashing or air scouring and cross-flow velocity (irreversible fouling).
- Higher risk of foaming due to larger air flows and accumulation of extracellular polymeric substances (EPS) inside the bioreactor.
- Greater sensitivity to shock loads as a consequence of lower HRT.
- Lower sludge dewaterability affecting sludge processing facilities

Most of these deficiencies are related to membrane fouling and membrane channel clogging. Membrane fouling is a reduction of membrane permeability due to occlusion and blocking of membrane pores by suspended solids (so-called reversible fouling) and internal restriction and blocking of pores by soluble components (irreversible fouling). As a consequence of membrane fouling, the membrane resistance increases in time, leading to higher pressure drop across the membrane and thus an increase in pumping costs. Membrane fouling is believed to be affected by several different factors, mostly SMP and bound EPS concentrations in the bulk liquid, membrane type, floc size distribution and sludge morphology and can be controlled by maintaining appropriate hydrodynamic and biological conditions in the bioreactor and application of periodic cleaning procedures (backwashing and chemical cleaning). Channel clogging results from filling of the channels between the membranes with sludge solids restricting the flow of water over the membrane surface. Clogging is prevented by appropriate upstream screening and provision of air scouring.

Due to substantial costs associated with the operation of MBRs and the negative effect of fouling, most of the research on membrane reactors has focussed on minimisation of fouling and developing cost-efficient operation regimes. Selection of optimal operating conditions is however not easy as the same outputs are affected by more than one operational parameter. For example, higher air scouring will increase energy costs for aeration but will decrease fouling and thus decrease the cost for pumping. There is also a compromise between CAPEX and OPEX costs as higher capital investment in bioreactor volume or number of membrane module will decrease MLSS concentrations in the tank, lower the operating flux and thus decrease the reversible and irreversible fouling. Higher SRT in the system will lead to lower SMP and EPS concentrations thus reducing fouling but will lead to higher MLSS concentrations, which will increase cake build-up and therefore will require higher scouring rates. Additionally, an increase in MLSS will lead to a decrease in the oxygen and lead to higher airflow requirements for aeration.

Such a complicated character of MBR operational issues led to large research and development activity focussing on MBR control, selection of the most appropriate flux value, optimisation of MBR operation and cleaning, development of cheaper and less fouling membranes and optimisation of membrane module design. A lot of these activities led to development of mathematical MBR models, which have been applied with various successes in MBR design, control and optimisation. The Water Software Systems Group is currently working on a DTI-funded project looking at the development, calibration and validation of an integrated mechanistic MBR model, including activated sludge biology with SMP and EPS kinetics and a membrane fouling model. This model is will be then used for optimisation and model based control applications.

To summarise, MBR is an intensified activated sludge process, offering superior treatment efficiency in a much smaller reactor volume compared to a CAS process. The apparent benefits of MBRs come at a cost of higher operational and often capital expenses, thus limiting the application of membrane reactors to cases where either superior effluent quality or small footprint are required. The applications of MBRs are many in water-intensive industries where the process water can be recycled back to the process line and thus costs for freshwater intake can be cut down. As the membranes modules get progressively cheaper, requirements for treated effluent quality become more stringent and the scientific and engineering communities increase their knowledge on cost-effective operation of MBRs, the market for MBR application gradually grows in size and membranes become more widely applied also in municipal WWTPs.

Reduction in membrane costs and provision of cheaper membranes introduce opportunities in application of MBRs also in developing countries. One of such opportunities is the application of anaerobic submerged MBRs which can treat effluent at low cost due to lack of oxygen demand, possible energy recovery from biogas and at the same time are able to provide disinfection. Such systems may be feasible e.g. in sub-Saharan African countries where ambient temperatures are more favourable for fermentation processes. Very small footprint of MBR reactors and their modular single reactor design make them very attractive for grey water treatment and reuse applications and decentralised wastewater treatment where instead of constructing large costly sewer infrastructure and a central wastewater treatment plant, the wastewater is treated and discharged at a source.

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