ADVANCED WASTEWATER RECYCLING

Anaerobic membrane bioreactors are on the cusp of revolutionising wastewater treatment. **Angela Bywater** explains how they work and the dramatic environmental benefits they promise.

Traditional wastewater treatment methods are energy intensive, with an estimated energy use of between 1% to 3% of **global energy output** https://tinyurl.com/4383xwm4. Driven by climate change imperatives, increasingly stringent discharge standards and circular economy principles, which regard wastes as resources, many wastewater treatment companies are introducing challenging net zero targets that require fundamental changes to the way they treat sewage and recycle water.

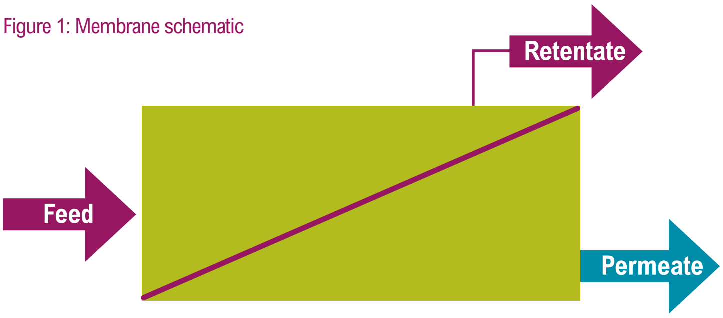
Anaerobic digestion is a core technology which can help fulfil these aims, due to its ability to degrade organic matter, reduce pathogens and produce renewable energy that can be used in the treatment process. Nevertheless, a slightly different approach is required in order to remove the maximum quantity of biodegradable biomass and produce quality water for re-use. This is where membranes come in.

In its broadest sense, a membrane reactor (MBR) is a membrane combined with a biological reaction; if air is removed from the system, making it anaerobic, the biology is modified accordingly, and the system is known as an anaerobic membrane bioreactor (AnMBR).

Capturing contaminants

The largest use of membrane bioreactors is in wastewater treatment systems, but the technology has been applied in a number of sectors, including food and beverage, petroleum, pharmaceuticals, pulp and paper and textiles. Membranes are materials that selectively allow some physical or chemical components of a given organic feed to pass through (known as permeate) whilst leaving others behind as retentate. Membranes vary in their pore size. Water, for example, can be filtered through increasingly smaller pores: micro-, ultra- and nano-pore membranes. As the pores become smaller, more pumping energy (pressure) is required. Companies such as **Biothane** https://tinyurl.com/ys9xr7md use **Pentair's** ultrafiltration (UF) membranes in their AnMBR systems. https://tinyurl.com/nherca9k

Figure 1: Membrane schematic



The two most important things about membrane systems are that (a) they retain biomass and (b) they create a very low-solids effluent. The former is powerful in terms of biology and is particularly useful for the degradation of low solids feedstocks, whereas the latter is advantageous in terms of further effluent treatment options. This method of biomass retention is also a particularly fascinating example of the interface between engineering and biology: by not washing away the biomass, the biology which needs to adapt more slowly to digest the retained biomass is allowed the time to do so.

Additionally, the biology can be manipulated in order to improve degradation and to optimise the performance of the membrane. If the biomass is allowed to grow too thickly and densely on the membrane, for example, the membrane will no longer operate, so biomass retention is both a powerful benefit and a drawback of these systems.

There are many different types of membranes, but in the applications described here, membranes are typically made of a suitable polymer which may be designed in a system with one or more flat sheets or as a bundle of hollow fibres (see the Pentair link left).

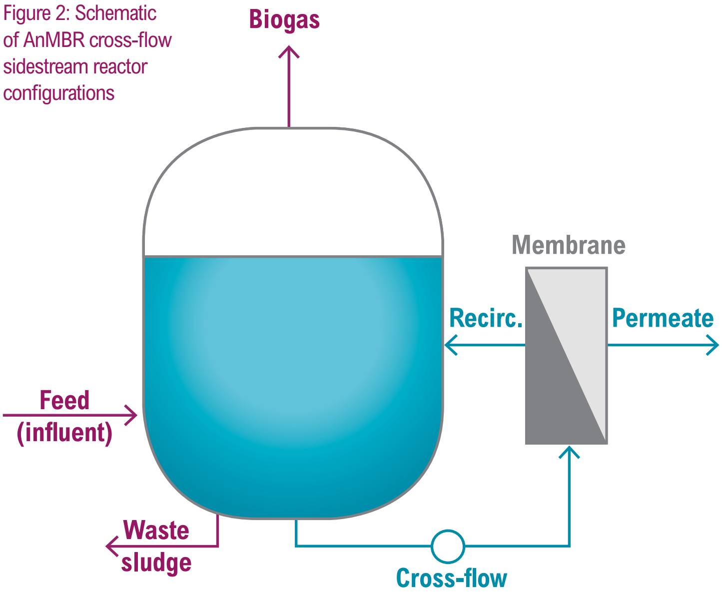
In a membrane system, the contaminants remaining in the retentate tend to accumulate on the membrane surface (known as fouling) which leads to a reduction in the flow (flux) through the membrane. If the system tries to maintain the flux at a certain rate, then the transmembrane pressure (TMP) increases. Thus, the permeability of the membrane is the ratio of flux to TMP.

There are many physicochemical and biological mechanisms which can cause fouling. Biofilm formation on a membrane is an example of biological fouling.

Configurations and cleaning options

There are many AnMBR configurations, but they fall into two broad categories: the membrane is submerged in the bioreactor (and have low shear forces on the membrane) or, more typically, the membrane is external to the bioreactor (also known as a sidestream system). These crossflow sidestream systems will typically have higher velocities/shear forces across the membrane (Figure 2).

Figure 2: Schematic of AnMBR cross-flow sidestream reactor configurations



In a conventional, pressure-driven membrane process, the retentate can flow continuously past the membrane (Figure 2 above) which means that for a given passage of feed across the membrane, only a proportion flows through the membrane, as the flow is tangential to the membrane. The speed of this flow (expressed as m/sec) is known as the cross-flow velocity (CFV) and its shearing effect on the surface of the membrane reduces fouling. Conversely, if the flow is perpendicular to the membrane surface and the retentate is not recirculated past the membrane, the shear forces are less, larger particles build up as a cake layer, accelerating the fouling effect.

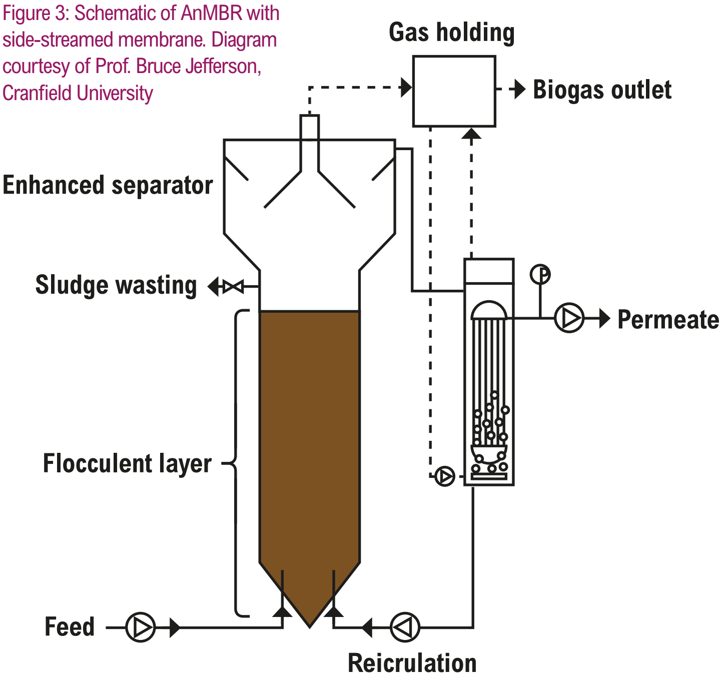
Researchers have also trialled many chemical and physical approaches to reduce membrane fouling so that the TMP is not too high at a given flux.

In a recent Environmental Biotechnology Network webinar (recording available here: https://ebnet.ac.uk/ebnet-rc22-anmbr/), Professor Jules van Lier from TU Delft described the successful use of Adifloc KD451 (a cationic polymer) to mitigate fouling in AnMBRs treating black water (sewage direct from toilets). Because the sludge is mainly negatively charged, the addition of the cationic polymer improved the sludge filterability, making larger particles and a more open structure on the accumulating membrane cake layer. This approach is highly dependant upon the characteristics of the feed to the AnMBR, but under these conditions, filtration was improved long-term, with 'no significant adverse effects on permeate quality or COD removal' https://tinyurl.com/2p924rms. At commercial scale, however, the cost of the polymer would have to be taken into account.

In the same EBNet webinar, Professor Bruce Jefferson from Cranfield University described their AnMBR system operating at ambient temperature which can be as low as 5-6 degrees on average in winter and not much higher than 20 degrees in summer. In order to ensure that the system could be energy positive, their approach to fouling was to clean the membranes through intermittent biogas sparging with the membrane in a 'relaxed' state, i.e. the membrane flow was briefly turned off and therefore not permeating.

Because the solid flux is one of the main factors that determined membrane fouling, the Cranfield approach was to send as much of the settled solids as possible to conventional AD prior to treating the remainder through the AnMBR. The AnMBR system consisted of an upflow anaerobic sludge blanket (UASB) reactor, coupled with an external membrane reactor (see below).

Figure 3: Schematic of AnMBR with side-streamed membrane. Diagram courtesy of Prof. Bruce Jefferson, Cranfield University



As the reactor temperature drops, the solubility of methane goes up (as it does for all gases), so 50%-88% of the methane could be in the liquid phase. Thus, the majority of the gas in this AnMBR could be dissolved in the liquid phase, so it would need to be degassed - an area which needs further development.

AnMBR in action

AnMBR reactors are edging into commercial reality. Severn Trent has a large demonstrator treating 500 m^3/day – the largest AnMBR in the world treating settled sewage. Another system designed by Cranfield University for Melbourne Water's Innovation Challenge reduced GHG emissions by 90%, was net energy positive (133%), provided enhanced water reuse and recovered ammonia, which is valuable as a fuel, platform chemical and more.

Dr Santiago Pacheco-Ruiz, Biothane's Director of Technology, Engineering and Innovation, said that they have seen a gradual but steady increase in the use of AnMBR technology for industrial effluents over the last decade. He noted that, compared to traditional high-rate treatment systems (e.g. anaerobic granular biomass), AnMBR systems are ideal for the direct treatment (i.e. with no pre-treatment) of industrial effluents with high total suspended solids (TSS), high total chemical oxygen demand (TCOD) and fats, oils and grease (FOG), as there is no risk of biomass loss. Furthermore, many industries are trying to minimise process water use, which has the effect of pushing TSS and FOG concentrations in the process effluents even higher. There is also an increased requirement for water re-use.

Additionally, AnMBR systems are well-suited to such applications because they have complete biomass retention, enable decoupling of the solids and hydraulic retention times, and produce a premium quality effluent and can demonstrate a very high TCOD removal, typically > 98%, depending upon the substrate biodegradability (Figure 4).

Figure 4: Permeates from AnMBR and reverse osmosis (RO) systems

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Nevertheless, with more than 10 commercial plants in operation, Biothane's experience has shown that trying to biologically or chemically control the morphology in AnMBRs to improve filterability (membrane performance) is not currently feasible in full-scale industrial effluent treatment applications because of the associated added expense and/or reactor stability issues. Instead, they have found that optimisation of the membrane skid configuration and its control/automation results in a much more manageable and cost-efficient fouling control and thus in the best outcomes in terms of operational flexibility and capex/opex.

Dr Pacheo-Ruiz believes that improvements in membrane technologies and configurations over the past 6-8 years has significantly contributed to the full-scale commercial application AnMBR's, but that it will not become the main solution for industrial effluents until membrane prices drop considerably which is unlikely to be in the near future. Nevertheless, he adds that industrial deployment will continue to grow for the sorts of niche applications which typically have one or more of the following operating conditions: a requirement for water reuse, a highly concentrated waste stream (in terms of salinity, fats or solids), the necessity for a low footprint or where capex/opex is not a limiting factor.

The commercial use of these systems is, nevertheless, another exciting application which demonstrates the versatility of microbial systems.