Membrane bioreactors (MBRs): Activated sludge filterability and full-scale MBR functioning

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Sammendrag

Membran-bioreaktorer (MBRs): Aktivslammets filtrerbarhet og fullskala MBR-funksjon

Til tross for at det har vært en kontinuerlig forbedring av MBR-teknologien, er det fortsatt store utfordringer knyttet til membrangjentetting (fouling) og medfølgende høyt energiforbruk og kostnadsnivå. Effektiviteten til filtreringsprosessen i en MBR er styrt av aktivslammets filtrerbarhet, som fortsatt er lite klarlagt men bestemt av samspillet mellom biomassen, avløpsvannets sammensetning og prosessforhold. Denne artikkelen bidrar til å styrke koblingen mellom membranens tilbøyelighet til å tettes igjen og aktivslammets filtrerbarhet. Videre framkommer viktig innsikt knyttet til funksjonen av MBR i fullskala, dvs. designmuligheter, drift, stabilitet, effektivitet og energibetraktninger, for å komme et skritt nærmere optimale driftsbetingelser og effektiv styring av MBR-teknologien.

Artikkelen er basert på doktorgradsavhandlingen til Pawel Krzeminski (2013): *Activated sludge filterability and full-scale membrane bioreactor operation*. Delft University of Technology, the Netherlands, ISBN: 978-94-6186-092-7.

Summary

Despite continuous developments in the field of MBR technology, membrane fouling together with the associated energy demand and related costs issues remain major challenges. The efficiency of the filtration process in an MBR is governed by the activated sludge filterability, which is still limitedly understood and is determined by the interactions between the biomass, the wastewater and the applied process conditions. This paper provides better understanding of membrane fouling propensity based on activated sludge filterability assessment. Furthermore, it provide important insights on full-scale MBR overall functioning, i.e., design options, operation, performance and energy efficiency, in order to provide a step forward towards optimum performance conditions and efficient operation of the MBR technology.

The paper is based on the Ph.D. dissertation: Krzeminski, P. (2013). *Activated sludge filterability and full-scale membrane bioreactor operation*. Delft University of Technology, the Netherlands, ISBN: 978-94-6186-092-7.

Introduction

The technology of membrane separation of activated sludge, commonly referred to as MBR, is the combination of activated sludge treatment

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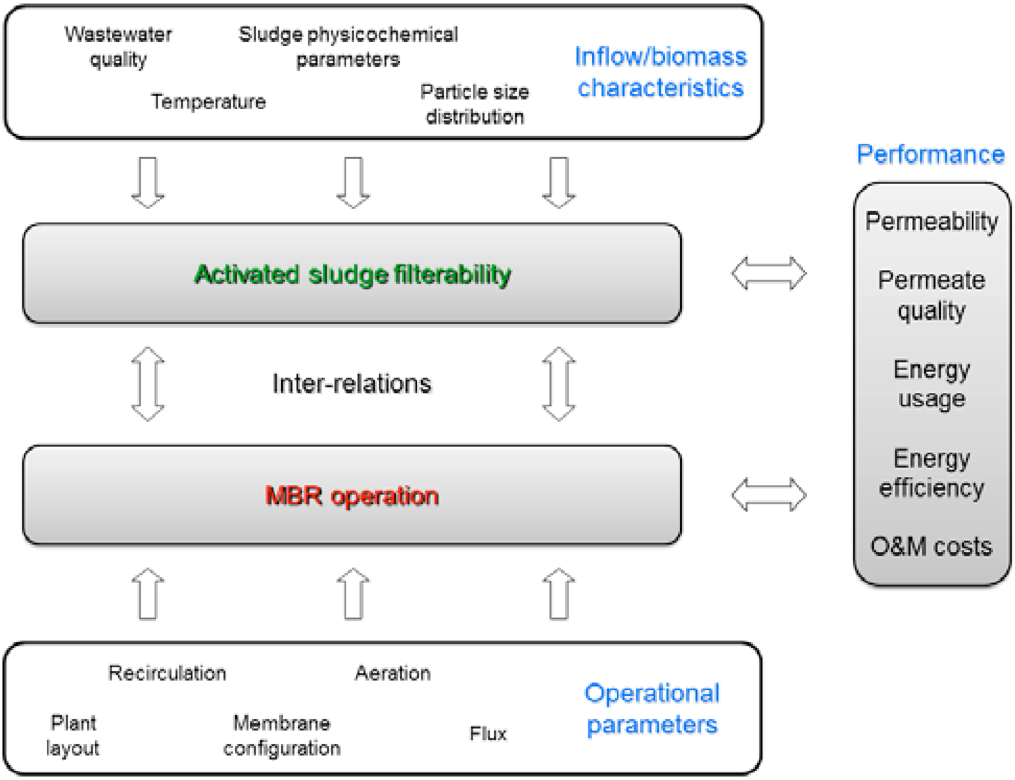

Figure 1. Visualization of the research hypothesis.

together with a separation of the biological sludge by micro- or ultra-filtration membranes to produce the particle-free effluent[2]. The MBR technology is now regarded as mature and has become an increasingly popular municipal wastewater treatment process alternative (Kraume and Drews 2010, Lesjean et al. 2011). The amount and capacity of full-scale MBR plants is continuously increasing worldwide[3]. Among other prospects, MBRs provide high effluent quality, free of suspended solids and very low levels of bacteriological contamination, at a relatively small plant footprint (Judd 2011).

However, although MBR technology attracted significant attention for more than a decade, old problems still remain unsolved (Le-Clech et al. 2006, Meng et al. 2009, Drews 2010). Despite continuous developments, membrane fouling mitigation and related high operational and maintenance (O&M) costs remain a major challenge and restrain wide MBR application. Due to the interactions between the membrane and constituents present in activated sludge and wastewater, the phenomenon of membrane fouling occurs during the filtration process. In result, the performance of membrane filtration decreases over time. Due to the interdependency of the aforementioned factors and the dynamic nature of the feed and biomass, membrane fouling is a very complex phenomenon. Implemented strategies for prevention and removal of membrane fouling lead to an increase in the O&M costs of the treatment system. In particular, the high energy requirements arisen from frequent membrane cleaning by air scouring remains a challenge in terms of energy consumption and overall cost efficiency of full-scale MBRs.

The purpose of this research was to increase understanding of the factors impacting activated sludge filterability during full-scale MBR opera-

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[2] www.mbr-network.eu (Last accessed 20.12.2012)

[3] www.thembrsite.com (Last accessed 16.09.2012)

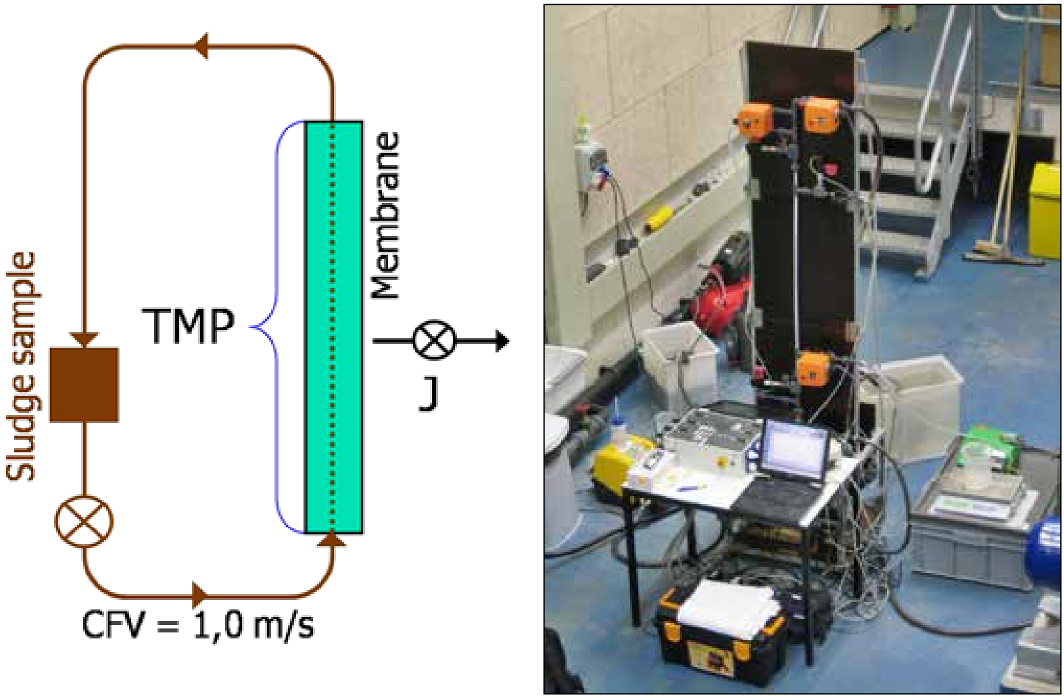


Figure 2. Schematic representation of the DFCm filtration characterization installation.

tion. Therefore, the research links activated sludge filterability assessment and full-scale MBR functioning, i.e., design options, operation, performance and energy efficiency. The overall research goal was to determine conditions for enhanced and efficient operation of the MBR technology. The research hypothesis is further visualized in figure 1.

Material and methods

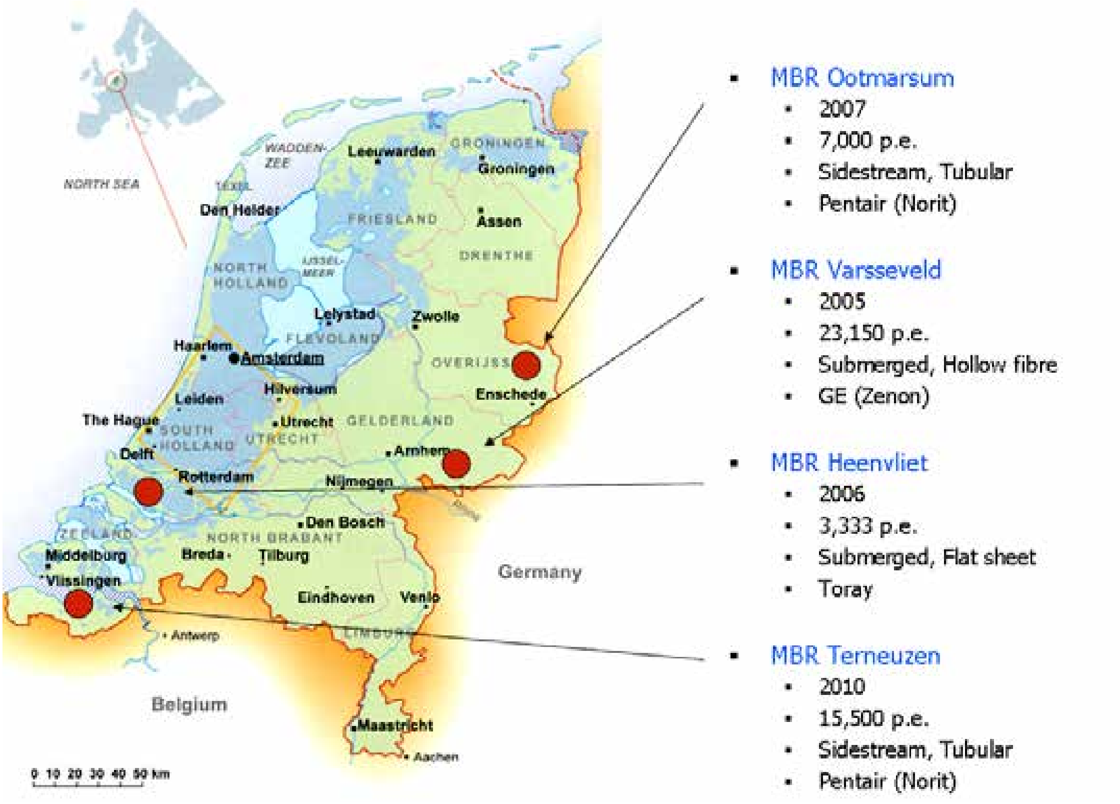
The research work included extended on-site measurements, lab experiments and operational data analysis. The Delft Filtration Characterization method (DFCm), developed by Evenblij et al. (2005) and presented in figure 2, was applied to experimentally determine the activated sludge filterability in full- and pilot-scale MBRs treating both municipal and industrial wastewater.

For easy comparison between different tests, the value ΔR_{20} is used, table 1, based on the classification proposed by Geilvoet (2010). This value is defined as the increase in resistance after a specific permeate production of 20 L/m^2.

ΔR_{20} [10^{12} m^{-1}]	Classification
0 – 0.1	Good
0.1 – 1.0	Moderate
1.0 – 3.0	Poor

Table 1. ΔR_{20} and corresponding filterability classification.

During the studies activated sludge samples were collected from 14 different MBRs and subjected to filtration tests and a set of physico-chemical analyses (e.g., COD, TOC, MLSS, MLVSS and SVI). Some of the samples were also analysed in respect to particle size distribution, biodegradability assessment, microscopic image analysis, BPC, EPS and SMP. Subsequently, the most influential parameters influencing activated sludge filterability were determined. In addition, the design, operational and performance data were collected from the selected full-scale municipal MBR plants and analysed with respect to plant functioning, i.e., operation, energy efficiency and operational costs, figure 3.



- MBR Ootmarsum
  - 2007
  - 7,000 p.e.
  - Sidestream, Tubular
  - Pentair (Norit)
- MBR Varsseveld
  - 2005
  - 23,150 p.e.
  - Submerged, Hollow fibre
  - GE (Zenon)
- MBR Heenvliet
  - 2006
  - 3,333 p.e.
  - Submerged, Flat sheet
  - Toray
- MBR Terneuzen
  - 2010
  - 15,500 p.e.
  - Sidestream, Tubular
  - Pentair (Norit)

Figure 3. Overview of the investigated full-scale municipal MBR plants in the Netherlands.

Activated sludge filterability

Typical seasonal fluctuations and deterioration of activated sludge filterability, coupled with worsened settling properties, during low temperature periods were observed, figure 4a. Our results show that the temperature and wastewater composition are important influencing parameters with respect to filterability, figure 4b.

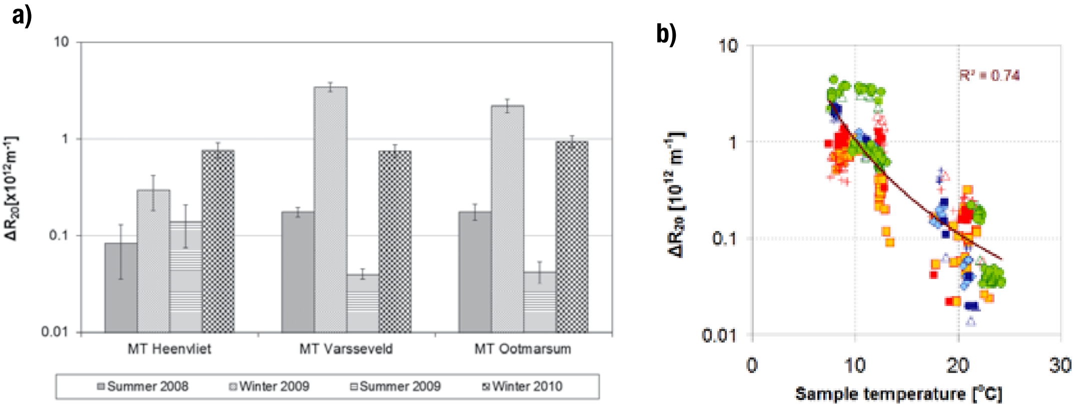


Figure 4. (a) Seasonal filterability fluctuations in membrane compartments (MT) of investigated MBRs and (b) filterability in relation with temperature.

Low temperatures and sudden changes in the influent concentration and composition are the most common causes leading to poor sludge filterability. Moreover, the combination of undesirable events, e.g., hydraulic and/or organic load shocks, harmful composition of the incoming wastewater, is extremely difficult to overcome without filterability deterioration and operational problems. Furthermore, filterability is reciprocally correlated with the incoming organic loading, as increase in the influent COD loading resulted in filterability deterioration, figure 5. However, activated sludge loading should not be considered a predominant parameter with respect to filterability in municipal MBRs.

Biological activity of the biomass was decreasing with temperature decrease to reach a minimum during winter period. Deterioration of filterability under low temperatures was linked to a slower biodegradation of the wastewater in the mixed liquor compared to high temperatures (Krzeminski et al. 2012b). The results revealed also that sludge parameters usually denoted in literature as membrane fouling indicators, e.g., BPC, SMP and TOC, are not clearly correlated with sludge filterability. Moreover, every parameter alone is a weak indicator of biomass fouling propensity. Combination of activated sludge parameters, i.e., the sludge morphology and relative hydrophobicity, better indicated sludge filterability than the parameters alone (Van den Broeck et al. 2011).

Nevertheless, MBR is a robust and reliable technology as permeate quality mostly complies with the regulations and is independent of the activated sludge quality and encountered operational problems.

MBR plant layout and membrane configurations

It was found that, both the MBR plant layout and membrane configurations do have some influence on overall plant functioning. In both municipal and industrial plants, hollow fibre (HF) membranes were protected by stricter pre-treatment and were cleaned more frequently physically (backwash) and chemically. Moreover, hollow fibre configurations were designed to work at higher fluxes, but were operated at lower MLSS concentrations compared to flat sheet (FS) configurations (Krzeminski et al. 2012a). In other words, membrane configuration selection influ-

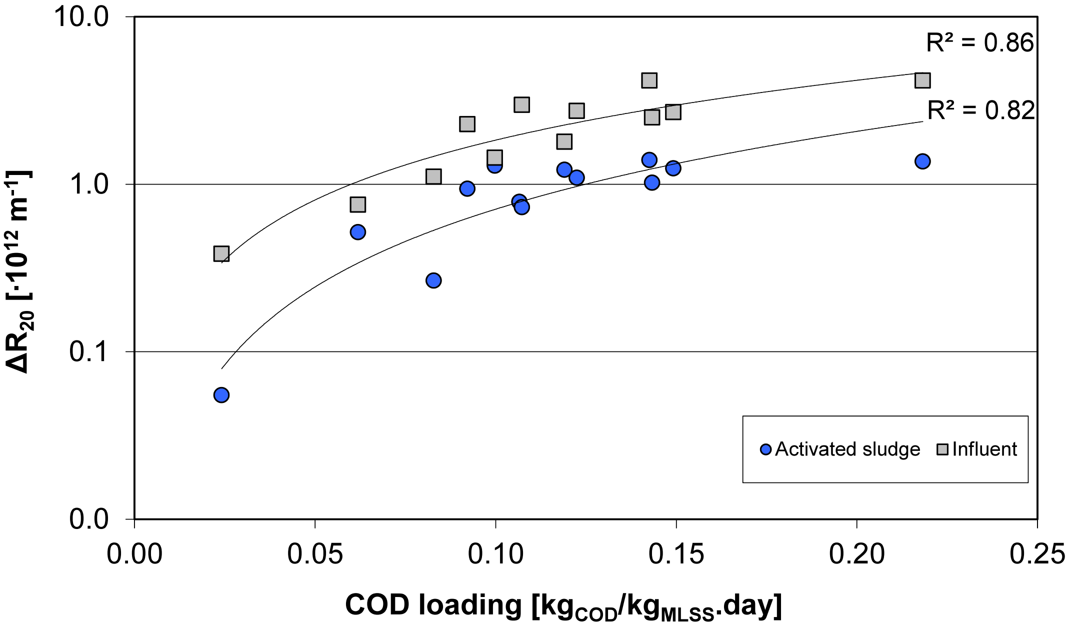


Figure 5. Filterability of activated sludge and influent vs. COD loading.

ences mainly the plant operational strategies and, indirectly through associated aeration strategy, energy demand and consumption of the installation. Moreover, the activated sludge filterability was found independent of membrane configuration but not of the MBR plant layout.

The MBR plant layout has more distinct influence on overall plant functioning due to indirect impact on operational flexibility and reliability, performance and O&M costs. In the stand-alone and parallel operated hybrid MBRs, figure 6, activated sludge is more often subjected to unsteady-state conditions that increase the likelihood of an operational upset. A stand-alone MBR is the most vulnerable to rapid changes compared to the hybrid configurations.

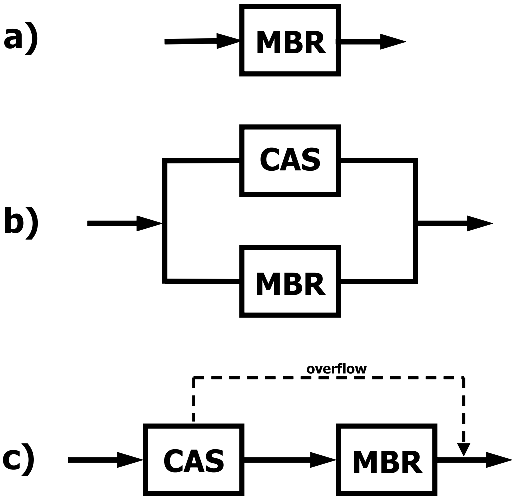


Figure 6. Schematic representation of basic configurations: (a) stand-alone, (b) parallel and (c) serial.

Hybrid configurations provide operational flexibility. Especially in the serial hybrid concept, the conventional activated sludge (CAS) system acts as a hydraulic and biological buffer zone which ensures more stable conditions for the activated sludge in the MBR (Krzeminski et al. 2012c). Therefore, the activated sludge filterability, operational flexibility and reliability as well as lower operational costs favour hybrid MBR over a stand-alone MBR. Furthermore, the aforementioned features have influence on operation and thus on energy consumption and efficiency.

The specific energy consumption of the stand-alone MBR was approximately 12% higher than the hybrid MBR during in series operation, yet 27% and 0.3 kWh/m^3 lower than the hybrid MBR during parallel operation. The MBR in the parallel concept is hindered by operation under sub-optimal flow conditions and is consequently less cost-efficient than serial hybrid MBR, approximately by a factor of 2 figure 7.

According to figure 7a, the specific energy consumption is lower when the MBR is operated in series to the CAS system mainly due to more favorable flow conditions, i.e., exceeding the dry weather flow (DWF) that the MBR was designed for. The MBR operated according to the parallel concept can also be energy efficient, with the specific energy consumption in the range of 0.8-1.0 kWh/m^3, but at least 50% overall MBR utilization is required.

The impact of membrane capacity usage on energy consumption follows from the efficiency increase with the treated flow. The flow dependency of differently designed MBR plants, i.e., one stand-alone and two hybrid MBRs, is shown on figure 7b. For example, operation of the underloaded (60% of DWF) stand-alone MBR result in specific energy consumption of 1.05 kWh/m^3, whereas operation at the capacity exceeding 100% result in low specific energy consumption of 0.63 kWh/m^3. Hence, the lowest specific energy efficiency is attained when operating the MBR above, or close to, the design flow at dry weather conditions.

Nevertheless, determination of the optimal plant configuration depends on the particular local situation such as the presence and condition of old infrastructure, availability of equalization tanks and space requirement. For example, when an old CAS system is available it is more economically feasible to extend the existing plant into hybrid MBR than to stand-alone MBR. Furthermore, the final choice will depend on local regulations and required effluent quality. If high quality effluent is continuously required a stand-alone MBR should be the one to choose. However, if the high quality effluent is not always required, then the hybrid MBR is an option to consider.

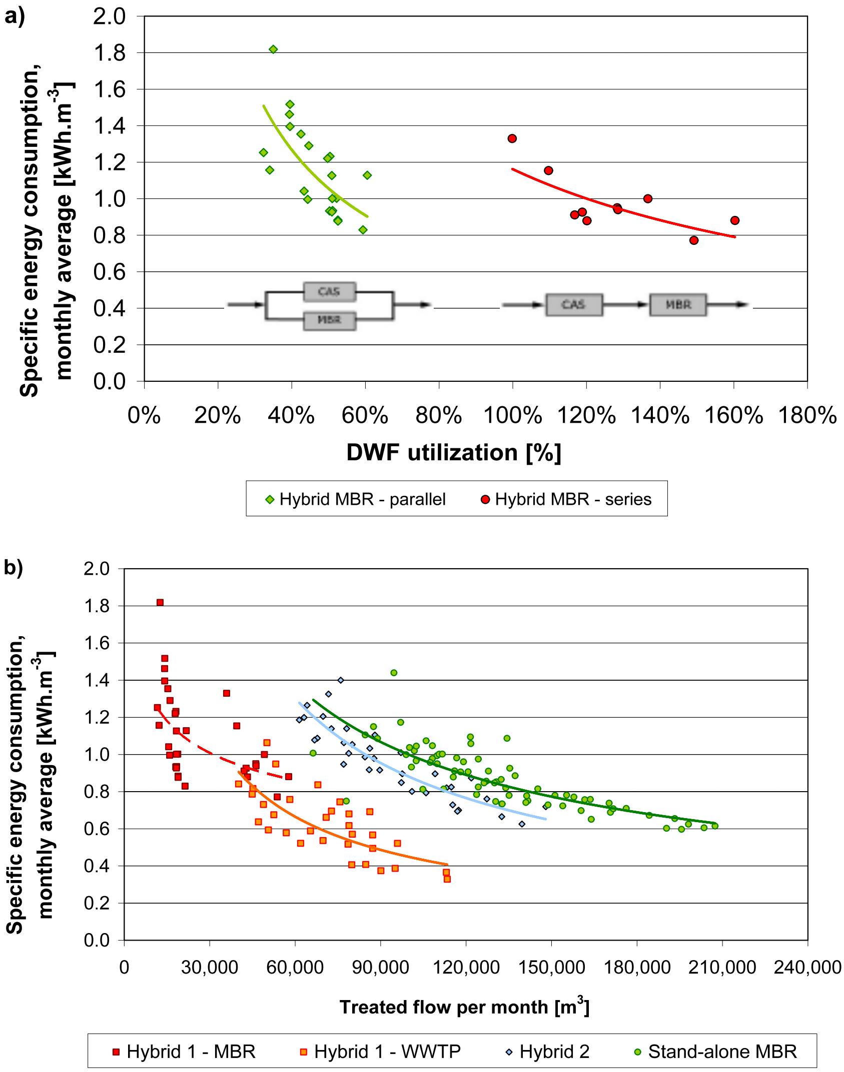


Figure 7. Energy consumption in relation to the flow for different design concepts: (a) Hybrid#1 in parallel (2008-2009) and serial (2009-2010); and (b) Hybrid#1 MBR (2008-2010) and Hybrid#1 WWTP (2008-2010), Hybrid#2 (2008-2010) and stand-alone (2005-2010).

Energy consumption and energy efficiency

Energy demand is one of the major components of O&M costs of MBRs and has become an essential focus point in the full-scale MBR operation. The investigated MBRs are operated below the design loading rates and consequently are operated under sub-optimal flow conditions which in turn results in reduced energy efficiency of the plant. Despite often sub-optimal operation, MBRs consumed on average 0.8-1.1 kWh/m^3, values similar to other comparable installations. Operation at optimal flow conditions, i.e., close to design flow at dry weather conditions (DWF), results in 5-20% energy consumption reduction compared to the average energy consumption, figure 8.

Other factors like the system design and layout, the membrane hydraulic utilization and the strategy applied for the membrane air-scou-

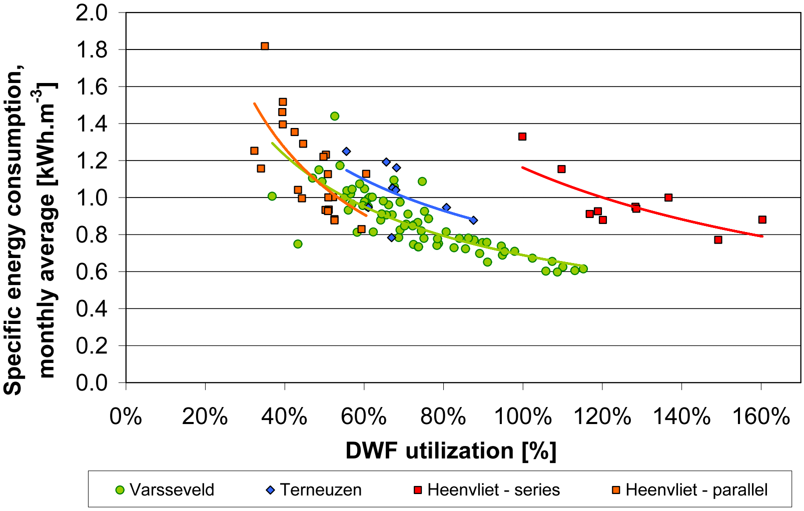


Figure 8. Specific energy consumption as a function of hydraulic utilization during dry weather flow at three plants: Heenvliet (2008-2010), Varsseveld (2005-2010) and Terneuzen (2010-2011).

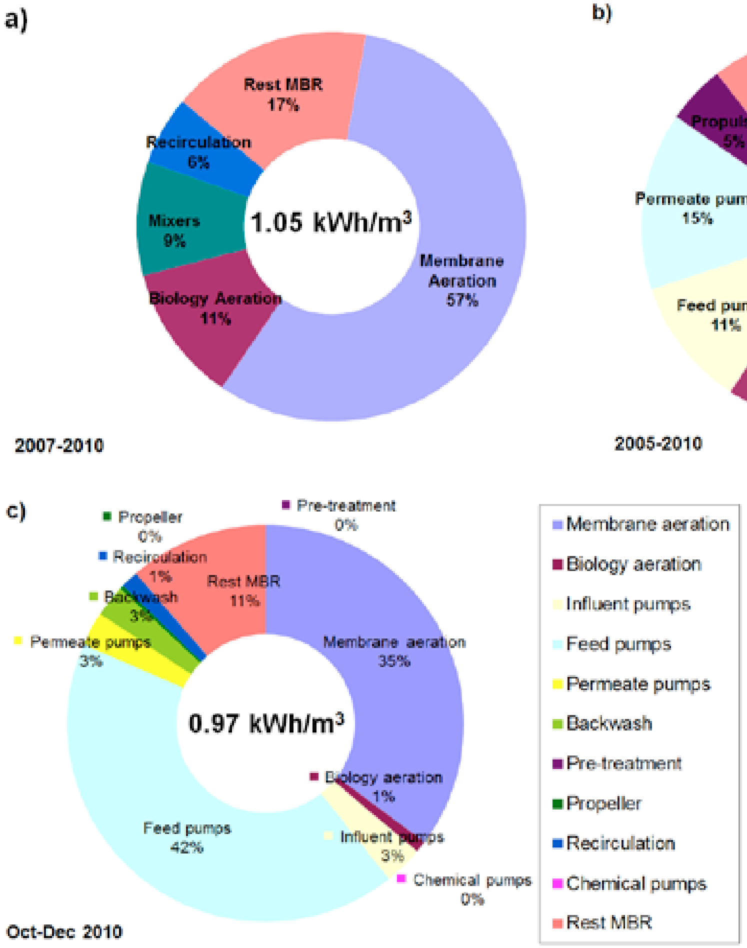


Figure 9. Energy consumption distribution of MBR equipment for: (a) Heenvliet (FS), (b) Varsseveld (HF), (c) Terneuzen (MT) MBRs.

ring are influencing the energy consumption and energy efficiency of an MBR system (Krzeminski et al. 2012d). Aeration is still the major energy consumer, often exceeding 50% share of total energy consumption, therefore the coarse bubble aeration applied for continuous membrane cleaning remains the main target for energy saving actions, especially for installations with flat sheet membranes, figure 9.

Conclusions

Filterability is the connecting parameter between membrane bioreactor 'biology' and membrane operation. It can be concluded that good filterability of the activated sludge is indispensable for efficient and optimal operation of an MBR. In case of a poor activated sludge filterability the membrane performance will be hampered due to sub-optimal filtration conditions. An MBR may also be operated with a poor filterable sludge, however, with a cost penalty associated with the membrane fouling counteractions, i.e., conservative process settings, frequent membrane cleanings and increased energy consumption. Wastewater composition and temperature were identified as main parameters influencing activated sludge filterability. The activated sludge filterability goes hand in hand with the amount of submicron particles and flocculation properties of the activated sludge, which in turn are influenced by the inflow conditions. Prediction of the activated sludge filterability is not possible based on a single parameter and a combination of parameters is more appropriate.

MBR plant layout and membrane configuration influence overall MBR functioning and should be chosen carefully. The energy efficiency of an MBR is driven by the hydraulic utilization of the membranes and can be improved by implementation of flow equalization, new aeration strategies and adjusting operational settings to the incoming flow.

The main research findings are illustrated in figure 10.

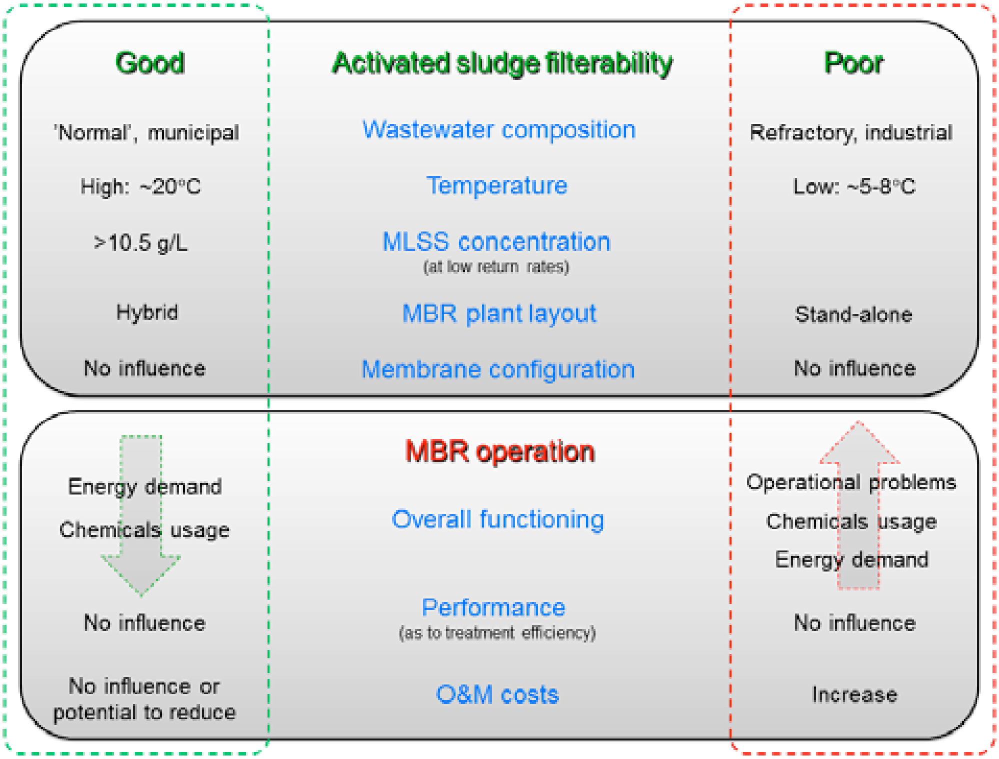


Figure 10. Graphical research outcome.

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