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# Flat sheet or hollow fibre — comparison of full-scale membrane bio-reactor configurations

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## ABSTRACT

Membrane bioreactors (MBRs) are widely used for wastewater treatment and reuse applications. Selection of a membrane configuration is a crucial step in the design process and has a high impact on further plant operations. Despite increasing experience with full-scale applications, practical knowledge concerning the impact of different membrane configurations on process performance and operational costs is still lacking. This paper provides full scale MBR performance data comparing the use of flat sheet and hollow fibre membranes and analyses the consequences on operation, performance and treatment efficiency. Hollow fibre configurations, comparing to the flat sheet, are designed for higher fluxes, operated at lower concentrations, cleaned more often and protected by stricter pre-treatment. Filterability of activated sludge from municipal MBRs is better than from industrial MBRs and does not depend on membrane configuration. The energy consumption depends more on the influent type than on the membrane configuration.

*Keywords:* Activated sludge filterability; Cleaning protocols; Flat sheet; Hollow fibre; Membrane bioreactors; Membrane configurations comparison

## 1. Introduction

Water shortage is a global issue, as clean and consumable fresh water is becoming a scarce resource. Hence, efficient purification methods are required for reclaiming wastewaters for subsequent usage. Membrane technology is widely used for various treatment and reuse applications. Over the last few years membranes have become recognised as one of the preferred treatment technologies for both municipal and industrial water treatment sectors [1]. An example of such technology is the membrane bioreactor (MBR) process. The MBR technology has lately attracted considerable attention as an improved wastewater treatment process offering significant advantages in terms of effluent quality and footprint [2]. Three membrane configurations are predominant in the market: flat sheet, hollow fibre and tubular. Advantages and disadvantages of each membrane configuration were discussed in the past [3–6]. However, despite a world-wide experience with full-scale

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applications, practical operational knowledge concerning the effect of different system configurations and membrane types on performance and operational costs are still lacking [7,8]. Moreover, selection of system configuration is a crucial step in the design of the MBR-plants and further plant operations. Thus, this information is of major importance to MBR-technology [9]. A better understanding on the impact of membrane configurations on MBR performances will allow further optimisations of MBR operations and, consequently, MBR cost reduction.

The aim of this research was to assess the impact of using either hollow fibre or flat sheet membranes on operational performances and plant efficiencies. An extensive multi-aspect comparison of four full-scale MBRs was implemented and a major monitoring campaign was carried out to investigate the impact of activated sludge filterability on MBR plant operations and performances. Experiments were performed with activated sludge samples from plants treating municipal and industrial wastewater, thereby including the parameter of wastewater strength into the comparison. This work provides information on the pre-treatment requirements, cleaning strategies and cleaning protocols applied in day-to-day operation of the full-scale plants. Consequently, it gives important insights about frequency of necessary chemical cleanings for each configuration and for a trouble-free operation of the system. Furthermore, the results of this research allow the comparison of two systems in terms of energy consumption.

The specific objectives of this study were:

- To asses activated sludge filterability in full scale MBRs equipped with either hollow fibres or flat sheet membranes;
- To analyse and compare flat sheet and hollow fibre configurations in both industrial and municipal scenarios;
- To asses impacts of different membrane configurations on MBR performances.

## 2. Materials and methods

### 2.1. COD determination

Chemical oxygen demand (COD) in the permeate, was determined photometrically with standard test kits (Test Cells Merck KGaA—Photometric method). COD cell test in the ranges of 25–1,500 mg $l^{-1}$ (Ref. 1.14541.0001) and 10–150 mg $l^{-1}$ (Ref. 1.14541.0001) were used. To carry out the reaction and to determine the concentration, a thermoreactor TR 620 and a photometer NOVA 60, both Spectroquant series, were used respectively. In the MBRs where COD measurements are included in regular on-site monitoring of the treatment plant, filed monitoring values were used.

### 2.2. MBR plants characteristics

Four full-scale MBRs treating both municipal and industrial wastewater were investigated. The MBRs were equipped with different types of membranes: two with Toray flat sheet membranes and two with Zenon hollow fibre membranes. Detailed description of the investigated plants is presented in Table 1.

### 2.3. The Delft filtration characterisation method (DFCm)

For the purpose of this research the DFCm, described in detail by Evenblij [10,11] and Geilvoet [12], was used. The DFCm is a standardised small-scale membrane filtration unit operated on the basis of a standardised measuring protocol. The DFCm facilitates the measuring and characterisation of different samples of activated sludge under the same conditions [13]. Subsequently differences in filterability of activated sludge are linked to differences in activated sludge characteristics.

The portability of the installation permits to measure the filterability directly at the MBR location, minimising artefacts during the measurement. During each experiment an activated sludge sample is circulated through a

Table 1
Characteristics of MBRs

| Parameter | Unit | Location A | Location B | Location C | Location D |
|---|---|---|---|---|---|
| Wastewater | – | municipal | industrial(chemical) | municipal | industrial(rendering) |
| Hydraulic capacity (RWF) | $m^3 h^{-1}$ | 100 | 35 | 775 | 120 |
| Permeate production | $m^3h^{-1}$ | 100 | 10 | 775 | 70–20 |
| Process configuration | – | Submerged | Submerged | Submerged | Submerged |
| Membrane type | – | Flat sheet | Flat sheet | Hollow fibre | Hollow fibre |
| Membrane supplier | – | Toray | Toray | Zenon-GE | Zenon-GE |
| Total membrane area | $m^2$ | 4115 | 1680 | 20,160 | 3520 |
| Membrane pore size | μm | 0.08 | 0.08 | 0.04 | 0.04 |

single tubular membrane (X-flow, inside-out, $D = 8$ mm, nominal pore size 0.03 μm) with the constant cross flow velocity of 1 m s$^{-1}$. Activated sludge circulation and permeate extraction are achieved by two peristaltic pumps. Extraction of permeate during the standardised experiment is achieved at a constant flux of 80 l m$^{-2}$ h$^{-1}$. The transmembrane pressure (TMP) is monitored during filtration with three pressure sensors installed at the feed, concentrate and permeate side of the membrane. Subsequently filtration resistance is calculated according to Darcy's law.

For easy comparison between the tests the so-called $\Delta R_{20}$ value is used. This value refers to the resistance increase after a specific permeate production of 20 l m$^{-2}$. Filterability is qualified as poor when $\Delta R_{20}$ is higher than $1 \times 10^{12}$ m$^{-1}$, moderate when $0.1 \times 10^{12}$ m$^{-1} < \Delta R_{20} < 1 \times 10^{12}$ m$^{-1}$ and good when $\Delta R_{20}$ values are lower than $0.1 \times 10^{12}$ m$^{-1}$ [12].

### 2.4. Experiments description

An extensive measurement campaign was performed for a period of nearly two years. During those measurements, activated sludge samples were collected from the four investigated MBRs and subjected to filtration characterisation test. Samples were collected directly from the membrane tanks or as close as possible to the membranes. Furthermore, parallel to the filterability tests, plant operations and performances were monitored, analysed and compared with the other investigated plants. For this purpose, design, operational and membrane performance data were collected from each MBR for the respective periods.

## 3. Results and discussion

### 3.1. Activated sludge filterability

Experimental results, obtained during filtration characterisation tests of activated sludge, differ between locations. The difference in activated sludge filterability can be clearly observed between plants treating municipal (locations A and C) and industrial (locations B and D) wastewater. Typical DFCm outputs are presented in Fig. 1 where results of four filtration experiments, representing each MBR, are plotted. Filtration curves representing industrial MBRs are steeper than filtration curves representing municipal MBRs, which is related with a worse filterability of activated sludge.

As a general trend, activated sludge samples collected from municipal MBRs present better filterability (lower $\Delta R_{20}$ values) and are less prone to cause membrane fouling problems than the samples collected from industrial MBRs. Filterability results for each MBR, together with the MLSS concentration are shown in Fig. 2.

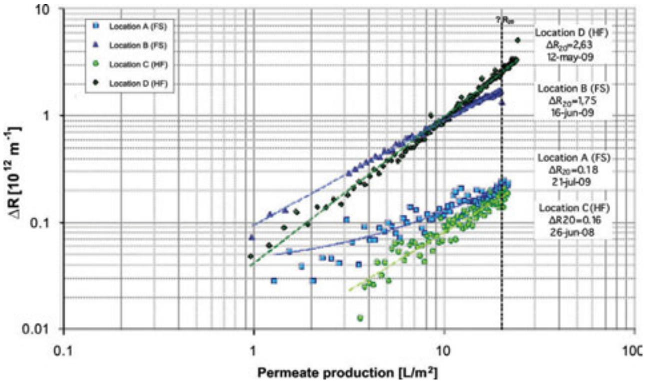

Fig. 1. Filtration characterisation curves of activated sludge from four full-scale MBRs.

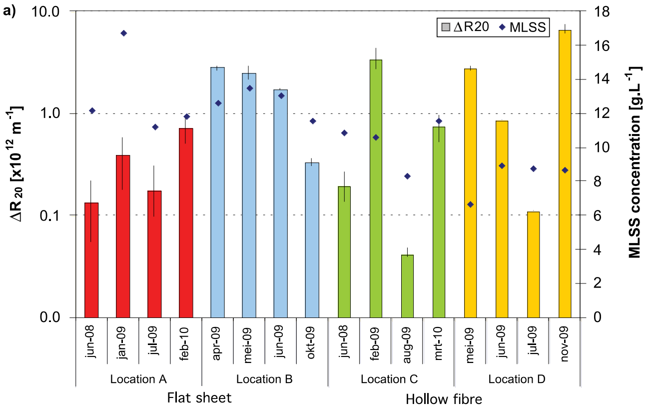

Fig. 2. Activated sludge filterability (bars) and MLSS concentration (points).

In case of locations treating municipal influent, filterability is at least moderate ($\Delta R_{20} < 1.0$) unless extreme events take place, such as abrupt temperature changes, excessive snow melt or variations in the influent wastewater composition. In addition, significant differences in the temperature of the different activated sludge samples were observed between municipal and industrial MBRs. Seasonal fluctuations have a stronger temperature impact on municipal inflows compared to industrial inflows (Fig. 3). With regard to the industrial locations, the activated sludge filterability is rather poor ($\Delta R_{20} > 1.0$) and less influenced by seasonal temperature fluctuations due to the constant and relatively high temperature of the industrial wastewaters, which were never below 16°C in winter.

Although there is no clear correlation between filterability and MLSS concentration, higher MLSS concentrations in the membrane tank samples were observed for the flat sheet than for the hollow fibre configurations, that is between 11.5–16.7 g l$^{-1}$ and 6.7–11.5 g l$^{-1}$, respectively. Differences in activated sludge filterability are

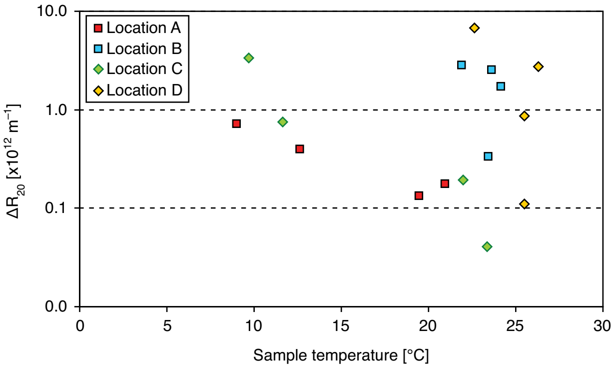

Fig. 3. Activated sludge filterability and sample temperature.

likely caused by the biological process, the composition of the inflow and possible differences in the recirculation-aeration rates and not by the type of installed membranes. Nevertheless, visible differences in activated sludge filterability, in both municipal and industrial locations, were observed between the two investigated configurations (flat sheet – 0.67 × 10$^{12}$ m$^{-1}$ and hollow fibre – 1.37 × 10$^{12}$ m$^{-1}$). Moreover, in both cases, strong variations in the filterability were observed.

### 3.2. MBR operation

Detailed operational characteristics of each full-scale MBR are presented in Table 2. Hollow fibre configurations are designed to operate at higher fluxes compared to flat sheet configurations. Moreover, differences in the applied fluxes could also be influenced by lower flows treated by the flat sheet systems at the specific cases. Furthermore, in case of hollow fibre systems, MLSS concentrations were lower (6–10 g l$^{-1}$) than for flat sheet (10–17 g l$^{-1}$) systems.

Reported permeability values were similar for municipal locations: 300 l h$^{-1}$ m$^{-1}$ for location A and 263 l h$^{-1}$ m$^{-1}$ for location C. Very likely, the applied lower flux in location A was mainly responsible for the observed differences between the flat sheet and hollow fibre systems. The observed high permeability value for the industrial location B can be ascribed to a decrease in the permeate extraction from 35 to 10 m$^3$ h$^{-1}$ since part of the company was closed. Consequently, operation under low transmembrane pressure leads to a high permeability and high sludge retention time (SRT). It is important to note that membrane permeability alone does not provide a clear picture of a current situation. Additional information about MBR performance is needed to draft the full picture.

The performed energy analysis revealed that the specific aeration demand per membrane surface area (SAD$_m$) was in the same range for municipal facilities and lower in case of industrial plants with flat sheet membranes. Additionally, hollow fibre systems shows a somewhat lower specific aeration demand per permeate produced (SAD$_p$) for both industrial and municipal applications.

Table 2 also shows that municipal MBRs equipped with hollow fibre membranes consumed less energy than the ones with flat sheet membranes during the investigated period (0.88 kWh · m$^{-3}$ vs. 0.95 kWh · m$^{-3}$). As expected, higher energy consumptions is observed for the industrial locations. For location B, the MBR was consuming 1.54 kWh · m$^{-3}$ at full loading and 4.45 kWh · m$^{-3}$ when part of the company was closed down. Table 2 lists two values for location D, owing to the fact that this location has retrofitted their actual wastewater treatment plants (WWTP) including an MBR in the treatment line. The low value of 0.11 kWh · m$^{-3}$ refers only to the membrane tank. The high 6.63 kWh · m$^{-3}$ value takes into account both the conventional WWTP and the membrane tank. For comparison, the latter value should

Table 2
Operational characteristics of investigated MBRs

| Parameter | Unit | Location A | Location B | Location C | Location D |
|---|---|---|---|---|---|
| Membrane type | – | Flat sheet | Flat sheet | Hollow fibre | Hollow fibre |
| Design Flux | L · m$^{-2}$ · h$^{-1}$ | 24 | 21 | 38 | 34 |
| Average Flux (net; DWF) | L · m$^{-2}$ · h$^{-1}$ | 12–24 | 6 | 15–25 | 39 |
| Permeability | L · m$^{-2}$ · h$^{-1}$ · bar$^{-1}$ | 300 | 1200 | 263 | 76 |
| MLSS | gL$^{-1}$ | 12–15 | 10–17 | 8–10 | 6–9 |
| Temperature | ºC | 14.7 | 30.8 | 16.6 | 29.9 |
| SRT | days | 40 | 160 | 24–26 | 29 |
| SADm | Nm$^3$air · h$^{-1}$m$^{-2}$ | 0.29 | 0.36 | 0.20–0.55 | 0.52 |
| SADp | Nm$^3$ · m$^{-3}$ permeate | 12.85 | 17.1 | 12.32 | 15.4 |
| Energy consumption | kWh · m$^{-3}$ | 0.95 | 154–4.45 | 0.83–0.88 | 0.11(MBR) 6.63(WWTP) |

be considered since the MBR needs the conventional WWTP to achieve the discharge limits.

### 3.3. MBRs performance

During the research period of 2008–2009, COD removal efficiency accomplished discharge limits in all the locations. Municipal MBRs removed COD to effluent concentrations of 25 mg $l^{-1}$ with removal efficiency between 93% and 95%. Industrial MBRs removed COD to a lesser degree, but with significantly higher inflow concentrations, that is 1566 mg $l^{-1}$ for location B and 3973 mg $l^{-1}$ for location D. Both systems present high level of robustness as COD was removed with efficiencies of 97%–99% down to concentrations in the range of 40–46 mg $l^{-1}$. Slightly better efficiencies were observed for hollow fibre systems probably due to smaller pore sizes, that is 0.08 versus 0.04 µm.

Biological oxygen demand (BOD) was removed below the requirements (10 mg $l^{-1}$) to concentrations just above 2.6 mg $l^{-1}$.

Total Kjeldahl Nitrogen (TKN) removal efficiencies achieved 96%–99% and lowered effluent concentrations down to 1.1 mg $l^{-1}$ for flat sheet and 2.0 mg $l^{-1}$ for hollow fibre configurations. Location D achieved removal efficiencies around 99% with discharge limits around 6.8 mg $l^{-1}$.

The removal of phosphorous was achieved by means of biological uptake (location A) or by means of a combination of biological P-removal and chemical precipitation (locations C and D). Industrial location B does not measure phosphorus removal as its chemical activity is not related to this compound. Differences in applied strategy for phosphorous removal are clearly observed when total phosphorous concentrations in the effluent are analysed. In the case of flat sheet systems, when only biological treatment took place, removal efficiencies around 70% were obtained. In the case of hollow fibre systems, when also chemical treatment was used, efficiencies in the range of 90%–96% were achieved. However, high dosage of ferric salt for phosphorous removal purposes may have adverse effects on the membranes and increases the salt content in the permeate. Table 3 summarizes the available influent and effluent characteristics data and removal efficiencies achieved in each plant.

In general, industrial MBRs demonstrated better overall removal efficiencies due to higher concentrations in the influent but residual effluent pollutant concentrations were slightly higher.

Table 3
Influent & effluent characteristics and removal efficiency

| Parameter | Unit | Location A | Location B | Location C | Location D |
|---|---|---|---|---|---|
| Influent characterization | | | | | |
| COD | $mgL^{-1}$ | 370 | 1566 | 723 | 3973 |
| BOD | $mgL^{-1}$ | 164 | – | 302 | – |
| $NH_4^+$-N | $mgL^{-1}$ | – | 47 | – | 713 |
| $NO_3^-$-N | $mgL^{-1}$ | – | 6 | – | – |
| TKN | $mgL^{-1}$ | 46 | – | 60 | 827 |
| $P_{total}$ | $mgL^{-1}$ | 7 | – | 13 | 17.3 |
| Effluent quality | | | | | |
| COD | $mgL^{-1}$ | 25 | 46 | 25 | 40.2 |
| BOD | $mgL^{-1}$ | 1.5 | – | 0.8 | 2.6 |
| $NH_4^+$-N | $mgL^{-1}$ | 0.1 | 3.9 | – | 3.7 |
| $NO_3^-$-N | $mgL^{-1}$ | 2.5 | 5.5 | 2.7 | 11.9 |
| TKN | $mgL^{-1}$ | 1.1 | – | 2 | 6.8 |
| $N_{total}$ | $mgL^{-1}$ | 3.6 | – | 4.8 | 18.9 |
| $P_{total}$ | $mgL^{-1}$ | 2.1 | – | 0.5 | 1.7 |
| $PO_4^+$ - P | | 1.9 | 1.0 | 0.5 | – |
| Removal efficiency | | | | | |
| COD | % | 93.2 | 97.1 | 96.5 | 99.0 |
| TKN | % | 97.6 | – | 96.7 | 99.2 |
| $P_{total}$ | % | 70.0 | – | 96.2 | 90.2 |

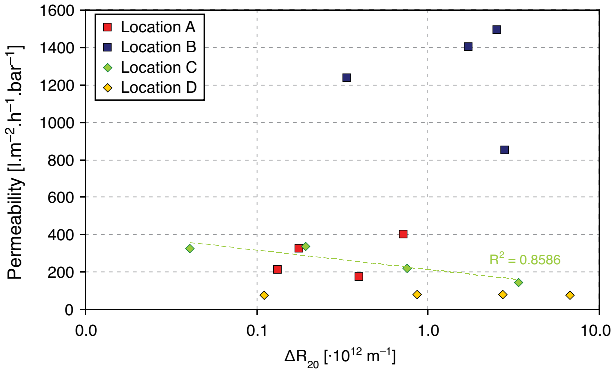

Fig. 4. Activated sludge filterability and permeability.

Results of activated sludge filterability analysis and relation with permeability are presented in Fig. 4. It is observed that the permeability values decrease when the filterability increases (location B). If so, activated sludge filterability is not a limiting factor in the filtration process and the operation can be subjected for improvement. On the other hand, stable permeability even with a poor filterability (location D) indicates that a poor filterability is overcome by excessive operational circumstances (cost- and energy inefficient).

Effect of seasonal temperature fluctuations on membrane performance was observed when summer and winter permeability in municipal MBRs in location A and C are compared. During winter periods, the permeability decreased about 20%–50% mainly due to activated sludge filterability deterioration.

### *3.4. Pre-treatment and cleaning strategies*

Pre-treatment is required to remove coarse materials, hairs and other fibrous material in order to protect installed membranes. Hence, importance of proper wastewater pre-treatment in the MBR is essential for the overall process [14]. In the municipal MBRs a two step mechanical pre-treatment is installed, that is 6 mm screen and 3 mm or 1 mm sieve, whereas in the industrial MBRs one but more rigorous step is installed, that is a fine screen of 0.5–0.75 mm. In both municipal and industrial plants, hollow fibre membranes are protected by stricter mechanical pre-treatment.

Distinct differences are observed in applied cleaning methods between the two types of membrane configurations. Flat sheet membranes are cleaned mechanically through relaxation periods of 1 min performed every 9 min of filtration. Additionally, when further filtration cannot be sustained because of an increase in the transmembrane pressure (TMP) intensive chemical cleaning is performed on yearly basis (once or twice per year). During chemical cleaning most prevalent cleaning agents are used: citric acid and sodium hypochlorite in location A or sodium hypochlorite alone as is the case in location B.

Hollow fibre membranes are cleaned mechanically through the backwash stage (25 s) performed every 6 min of filtration. The mechanical cleaning is supported by the maintenance chemical cleaning performed every week (can be extended to two weeks). Comparing to the flat sheet cleaning protocol, chemicals are applied in reverse order: first sodium hypochlorite and second citric acid. Hollow fibre membranes are cleaned more frequently both mechanically (backwash) and chemically. The latter one, result in higher chemicals cost comparing to FS case. However, when cost are normalized for the membrane area, the specific cleaning cost (expressed in € m$^{-2}$ membrane area yr$^{-1}$) is double for FS comparing to HF installation. Thus, higher cleaning cost for HF system can be associated with the more frequent cleanings applied (and as such with the amount of chemicals consumed) but might be also the effect of the plant scale and bigger membrane area to clean. Nevertheless, each treatment facility can have specific chemical cleaning protocols, specially in industrial locations, that is chemical concentrations and cleaning frequencies, as recommended by the membrane suppliers [15].

## 4. Conclusions

Striking differences are observed between flat sheet and hollow fibre membranes applied in full-scale MBRs. In both municipal and industrial plants, hollow fibre membranes are protected by stricter pre-treatment and are cleaned more frequently mechanically (backwash) and chemically. Moreover, hollow fibre configurations are designed to work at higher fluxes, but are operated at lower MLSS concentrations compared to flat sheet configurations.

Samples collected from municipal MBRs present better filterability then samples from industrial MBRs. Results indicate that this is likely due to differences in the prevailing biological processes or the influent composition and not to the type of installed membranes. Also seasonal fluctuations have a stronger temperature impact on municipal inflows compared to industrial inflows. All investigated MBRs meet the required BOD and COD discharge limits. The energy consumption depends more on the influent type than on the membrane configuration, as opposite trends were observed for industrial and municipal locations.

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