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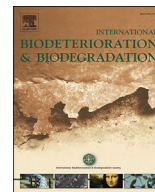
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Assessing the performance of an MBR operated at high biomass concentrations



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ABSTRACT

Reducing the footprint requirements of membrane bioreactors (MBR)s can both decrease the surface area needs for new wastewater treatment plants (WWTP)s, and increase the treatment capacities of existing WWTPs at a given surface area. In addition, it may promote the development of movable/portable containerized MBRs for a diverse range of wastewater treatment applications. Applications may include the provision of municipal/industrial wastewater treatment in remote areas without sewerage, and the provision of sanitation services under challenging site-specific conditions such as after the occurrence of a human-made or a natural disaster. The reduction of the footprint requirements of MBRs is constrained by the maximum amount of biomass that can be accommodated in the aerobic basin. The biomass concentration is mainly limited by the extremely low oxygen transfer efficiency (OTE) experienced by conventional aeration bubble diffuser systems at mixed liquor total suspended solids (MLSS) concentrations higher than 20 g L⁻¹. Another potential limitation for the operation of MBRs at such high MLSS concentrations is the reduction on the membrane permeability due to excessive fouling. A pilot MBR with a treatment capacity of one m³ d⁻¹ was installed at the research hall facilities at the Harnaschpolder wastewater treatment plant in Delft, The Netherlands. The MBR was operated at MLSS concentrations of up to 28 g L⁻¹ at sludge retention times (SRT)s ranging from 30 to 35 days. The MBR was provided with a Speece cone concentrated oxygen delivery system to overcome the oxygen transfer limitations of conventional bubble diffuser aeration systems at high MLSS concentrations. The MBR performance was evaluated by monitoring the influent and effluent water quality, the membrane permeability, the sludge filterability, the dissolved oxygen (DO) concentration, and the oxygen uptake rate (OUR). The Speece cone proved to be effective in delivering enough oxygen to maintain DO concentrations in the MBR of approximately 2 mg L⁻¹ at MLSS concentrations of up to 22 g L⁻¹. OUR values above 200 mg L⁻¹ h⁻¹ were observed at 14 g L⁻¹ MLSS and higher than 300 mg L⁻¹ h⁻¹ at 22 g L⁻¹ MLSS. The MBR exhibited chemical oxygen demand (COD) removal efficiencies of up to 99% even at a hydraulic retention time (HRT) as low as 3.7 h. A reduction in permeability from 33 to 11 lmh bar⁻¹ was observed when the MLSS concentrations increased from 18.7 to 27.8 g L⁻¹. Sludge filterability values expressed as the added resistance (ΔR_{20}) fell in the range of “poor filterability” for all the evaluated operational conditions; however, a lower filtration resistance in the range of “moderate filterability” at approximately 23 g L⁻¹ MLSS was noticed. The experimental results suggest that at the evaluated experimental conditions the existent limitations on poor oxygen transfer and low permeability when operating a MBR at high MLSS concentrations can be overcome; therefore, the footprint requirements of MBR systems may be further reduced.

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1. Introduction

Considering all the existent alternatives for the provision of wastewater treatment, MBRs present some additional advantages including the production of a high quality effluent suitable for

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water reuse, (Arceivala, 2008; Hai and Yamamoto, 2011; Henze et al., 2008; Judd, 2008, 2010; Melin et al., 2006; Stephenson, 2000), the reliability of the technology, the potential production of small amounts of already stabilized sludge, and the operational flexibility to adjust to changes in the organic loads, among others. The reduction of the footprint requirements of membrane bioreactors MBRs can allow both the reduction of the surface area needs when constructing new WWTPs, and the increase of the treatment capacities of existing WWTPs at a given surface area. In addition, the achievement of an additional footprint reduction on MBRs may promote the development of movable/portable containerized MBRs for a diverse range of applications including the provision of municipal/industrial wastewater treatment in remote areas without sewerage and the provision of sanitation services under challenging site-specific conditions such as after the occurrence of a human-made or a natural disaster. However, the reduction of the footprint requirements of MBRs is constrained by the maximum amount of biomass that can be accommodated in the aerobic basin.

The maximum biomass concentration that can be achieved in a MBR is mainly limited by the extremely low OTE experienced by conventional aeration systems such as fine and coarse bubble diffusers at MLSS concentrations higher than 20 g L^{-1} (Germain et al., 2007). Another limitation for the operation of MBRs at such high MLSS concentrations is the reduction on the membrane permeability observed due to excessive fouling. This drastic decrease in permeability is caused mainly by the accumulation of fouling substances and the increased mixed liquor viscosity (Trussell et al., 2007). The relation between the potential benefits of operating a high MLSS MBR and the negative impact on the system permeability has been addressed in the literature as the “Capex-Opex dichotomy” (Judd, 2008). Therefore, and in order to avoid these adverse conditions, conventional MBR systems are currently designed to operate at MLSS concentrations of approximately 10 g L^{-1} setting the footprint requirements of this technology.

Oxygen transfer in aerobic wastewater treatment processes has been extensively addressed in the past decades. Several studies demonstrated that both the suspended solids as well as the mixed liquor viscosity negatively affect the oxygen transfer process (Cornel et al., 2003; Germain et al., 2007; Germain and Stephenson, 2005; Moreau et al., 2009; Trussell et al., 2007; Wu et al., 2007). Krampe and Krauth (2003) reported a decrease on the OTE as the biomass concentration increased. The evaluation was conducted on a biological system provided with a conventional fine bubble diffuser up to biomass concentrations of approximately 28 g L^{-1} . Alpha factors as low as 0.1 were reported at a 20 g L^{-1} MLSS concentration demonstrating an extremely low OTE at the evaluated conditions. A study conducted by Henkel et al. (2009) investigated the OTE of fine and coarse bubble diffusers at MLSS concentrations ranging from 4.7 to 19.5 g L^{-1} under different air flow conditions and operating the biological systems at high SRTs. A decrease on the alpha factor was reported as the biomass concentrations (expressed as MLSS) increased. In addition, a more direct correlation was noticed between the decrease of the alpha factor and the increase of the mixed liquor volatile suspended solids (VSS). The authors concluded that the mixed liquor VSS concentration in the reactor is the main factor impacting on the oxygen transfer process. At mixed liquor VSS concentrations higher than 20 g L^{-1} negligible alpha factors were reported; therefore, very little DO at a very low OTE could be supplied at the evaluated experimental conditions. The rheological and physiological properties of MBRs were investigated by Wu et al. (2007); the authors demonstrated that the MLSS concentration has a direct impact on the mixed liquor apparent viscosity, which consequently affects the oxygen diffusion process. The effect of the high MLSS concentration on the apparent viscosity

was also demonstrated by Trussell et al. (2007). The negative impact of the apparent viscosity on the oxygen transfer process was reported in a more recent publication by Durán et al. (2016) for fine bubble diffuser aeration. In a comparative study carried out by Krampe and Krauth (2003), different bubble diffuser aeration systems were evaluated at MLSS concentrations of up to approximately 20 g L^{-1} . In accordance with previously reported studies, the authors concluded that the alpha factor decreases exponentially with increasing MLSS concentrations. In addition, an increase on the viscosity was observed as the MLSS concentration increased. The authors proposed that the increased viscosity of the mixed liquor could promote the formation of large bubbles via coalescence resulting in a reduced available interfacial gas-liquid area negatively impacting the oxygen transfer process. Even though several studies were carried out evaluating the OTE on biological systems at different MLSS conditions, there is still a need and a clear interest for advancing on alternative oxygen delivery systems for efficiently supplying DO; particularly, when designing biological systems to operate at higher than usual MLSS concentrations.

Alternative aeration systems are needed to cope with the high oxygen demands and low OTEs commonly observed on MBRs operated at high MLSS concentrations. The oxygen transfer rates and OTEs of innovative concentrated oxygen delivery systems such as the super saturated dissolved oxygenation system – (SDOX) were recently evaluated by Kim et al. (2015). The SDOX system recirculates activated sludge through a chamber that is pressurized with pure oxygen. The activated sludge is introduced into the chamber through a nozzle generating a mist enhancing the gas-liquid interaction; consequently, the oxygen mass transfer between the pure oxygen gas phase and the mixed liquor solution is maximized. The authors reported similar alpha factors compared to conventional bubble diffuser systems; however, the SDOX system exhibited nearly 100% OTEs when working at MLSS concentrations of up to 40 g L^{-1} . That is, nearly all of the oxygen supplied to the pressurized chamber ended up as DO in the biological reactor. In addition, such aeration systems are not subject to clogging or scaling as it is the case for membrane fine bubble diffusers. The clogging or scaling of the diffuser reduces the OTE even further causing an increased backpressure in the air distribution line (Garrido-Baserba et al., 2016). Another concentrated oxygen delivery technology, the Speece cone system, may present a feasible alternative for providing the required DO in biological systems working at high MLSS concentrations. The Speece cone system has been commonly used in the past for hypolimnetic aeration applications mainly for bioremediation of lakes and other water courses (Ashley et al., 2008). The Speece cone system recirculates the mixed liquor from the aerobic basin of the reactor through a pressurized inverted cone structure. Pure oxygen gas is directly supplied at the top of the cone and is dissolved into the mixed liquor, which is introduced into the top of the pressurized inverted cone without the use of any nozzle, as compared to the situation previously described for the SDOX system. For this reason, the Speece cone system minimizes the head losses of the system allowing to process large volumes of mixed liquor without large energy expenditures (McGinnis and Little, 1998). The improvement on the oxygen mass transfer observed at the Speece cone is based on both the high pure oxygen pressure conditions inside the cone, and on the specially designed cone geometry. That is, based on the geometry of the inverted cone and on the selected mixed liquor flow rate through it, a particular downward velocity can be set for the mixed liquor. The mixed liquor velocity at the top of the cone is higher than the pure oxygen bubbles buoyancy due to the small cross sectional area. Therefore, the oxygen bubbles are forced down inside the cone to be in contact with the mixed liquor. As the oxygen bubbles and mixed liquor travel down, the cross sectional area of the inverted

cone increases and the mixed liquor's downward velocity decreases preventing the oxygen bubbles from escaping the cone at the bottom of the structure. Consequently, the contact time between the pressurized pure oxygen and the mixed liquor inside the cone is maximized enhancing the oxygen mass transfer into the mixed liquor. The Speece cone system may present a feasible alternative for providing DO in biological systems working at high MLSS concentrations.

The operational performance of MBRs is commonly assessed in terms of water quality, permeability, transmembrane pressure (TMP), membrane fouling rates, and more recently in terms of sludge filterability. Previous research on membrane fouling has focused on evaluating several factors influencing this phenomenon such as: the accumulation of substances and particles on the membranes (Delrue et al., 2011), the effects of the SRT on fouling (Van den Broeck et al., 2012), differences between suspended and attached microorganisms growth (Jamal Khan et al., 2011), the application of membrane coating for fouling reduction (Deowan et al., 2016), and the influence of operational conditions and membrane cleaning routines (Delrue et al., 2011) among others. A considerable number of studies were conducted on membrane fouling (Drews, 2010); however, limited research was carried out evaluating the effects of high biomass concentrations above 20 g L⁻¹ MLSS on membrane fouling. Some of these studies included the evaluation of the biomass characteristics on membrane fouling (Chen et al., 2015), the fouling characteristics at different MLSS and COD loadings (Lee and Kim, 2013), and the fouling mitigation mechanisms using bio carriers (Chen et al., 2016). However, most of these studies were carried out by severely diluting or concentrating the sludge samples to reach the desired MLSS concentrations. This dilution or concentration processes could affect some properties of the sludge when comparing to the fresh and naturally occurring high MLSS sludge from a full scale system. That is, the manipulation of the sludge could modify its structure for instance by de-flocculation (Lousada-Ferreira et al., 2015), or could promote the release of polymeric materials (Drews, 2010). Hence, there is a need for better understanding the performance of the membrane filtration component on MBRs operating at high MLSS concentrations using fresh activated sludge produced *in situ*.

The objective of this study was to evaluate the technical feasibility of an MBR operated at high MLSS concentrations provided with a Speece cone concentrated oxygen delivery system. This study evaluated the overall performance of the MBR at different MLSS concentrations by monitoring the influent and effluent water quality, the membrane permeability, the sludge filterability, DO concentration, and the OUR. In addition, this study assessed up to which extent the footprint of MBRs can be reduced by increasing the MLSS concentration in the aeration basin.

2. Materials and methods

This research evaluated the performance of a pilot MBR operated at MLSS concentrations ranging from approximately 7 to 28 g L⁻¹. Specific MLSS concentrations set points were reached in that MLSS range by modifying the operational conditions and loads to the MBR system. The system performance was evaluated at each of the targeted MLSS concentration set points.

2.1. Pilot MBR setup description

A pilot MBR with a standard treatment capacity of approximately 1 m³ day⁻¹ was operated at the Delft Blue Innovations (DBI www.delftblueinnovations.nl) research hall at the Harnaschpolder wastewater treatment plant in Delft, The Netherlands. The pilot

MBR consisted of the following main components: an anoxic chamber (volume 0.25 m³), an aerobic chamber (volume 0.85 m³), a permeate collection tank (volume 0.2 m³), a low pressure blower (SECOH, EL-S-250; USA), and a bidirectional pump for permeate production and membrane backwash (Liverani EP NEOS; Italy). The MBR was provided with a submerged ultrafiltration membrane module made of single tubular polyvinylidene fluoride membrane elements with an average pore size of 0.01 μm and a total filtration area of 20 m² (Memos; Germany). A coarse bubble distribution manifold was installed at the bottom of the membrane module for membrane scouring. A ceramic fine bubble diffusers was introduced for supplying much of the DO needs to the MBR. However, anticipating the low OTE commonly observed by fine bubble diffusers when operating at high MLSS concentrations (Krampe and Krauth, 2003), a concentrated oxygen delivery system – Speece cone was provided as an additional source of DO. A schematic of the experimental MBR system is presented in Fig. 1.

The Speece cone system continuously recirculated the mixed liquor from the aeration basin of the MBR into a pressurized inverted cone by means of a progressive cavity pump (Netzsch, NEMO NM045BY02512B; Germany). At the cone, the mixed liquor got in contact with pressurized pure oxygen; therefore, the oxygen gas was dissolved into the mixed liquor for supersaturation. The oxygen flow to the cone was regulated by means of a gas mass flow controller (Alicat, MC-5SLPM-D; USA). The amount of DO transferred by the Speece cone system was governed by two main parameters: the pressure, and the recirculation flowrate through the cone.

During the entire execution of this research the MBR was fed screened (0.45 mm) non settled municipal wastewater. The membrane operating cycles were controlled by a PLC (Mitsubishi FX3G-24M, USA). One cycle corresponded to 10 min of permeate production and one minute backwash. A 10 min long backwash was performed automatically every 50 cycles.

2.2. Operational conditions

The pilot MBR was seeded with returned activated sludge from the Harnaschpolder wastewater treatment plant, and it was operated for approximately six months. Different operational conditions were established to achieve the targeted/desired MLSS concentration set points as indicated below. A unique numerical identification code (IDs 1 to 13) was assigned to each targeted MLSS concentration (MLSS set point) which corresponds to a particular combination of operational parameters such as SRT, influent flowrate, influent strength, and aerobic basin volume.

- (i) First phase (numerical identification code IDs 1 to 5 corresponding to MLSS_{target} concentrations of: 8, 9, 10, 15, and 18 g L⁻¹). The increase on the MLSS concentrations for this phase was achieved by setting the SRT at 30 days; no activated sludge was purged, while the influent flowrate and the reactor volume were kept constant at 3.5 m³ d⁻¹ and 0.85 m³, respectively. During this phase the influent COD concentration was not modified.
- (ii) Second phase (IDs 6 to 11 corresponding to MLSS_{target} concentrations of: 23, 24, and 36 g L⁻¹). Once the SRT was fixed at 30 days, the MLSS concentration was increased by modifying the applied COD load to the MBR. In addition, the MBR aerobic volume was reduced to 0.73 m³ to achieve the desired MLSS concentrations.
- (iii) Third phase (IDs 12 to 13 corresponding to MLSS_{target} concentrations of: 27, and 29 g L⁻¹). The MLSS targeted concentrations in this phase were achieved by applying higher COD loads by using sugar cane molasses. The reactor volume

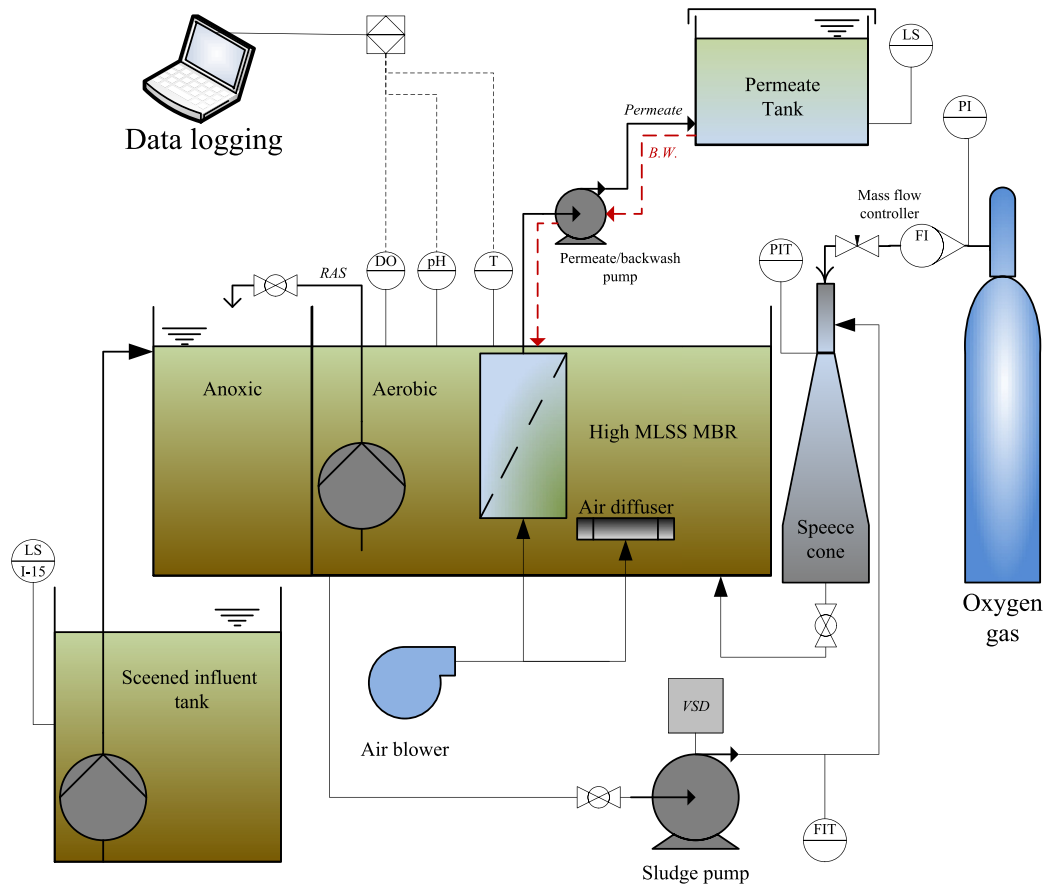


Fig. 1. Schematic process flow diagram. High MLSS MBR-Speece cone pilot setup (VSD: Variable speed drive, PIT: Pressure indicator transmitter, FI: Flow indicator, LS: Level switch, B.W: Backwash, DO: Dissolved oxygen, RAS: Return activated sludge, T: Temperature).

was returned back to its original value (0.85 m^3), and the flowrate was halved to approximately $2 \text{ m}^3 \text{ d}^{-1}$. In addition, the SRT was increased to 35 days.

The MLSS concentration in the MBR can be increased by changing any of the following operational parameters: the SRT, the influent load (flow and COD concentration), and/or the reactor volume. The achievement of the desired MLSS set points requires changing at least one of the operational parameters of the MBR. After reaching the desired SRT of approximately 30 days, it was decided to keep the SRT as constant as possible for the entire MLSS range to have a similar sludge with a similar biomass active fraction for the entire evaluated MLSS range allowing to perform a better comparison of the performance of the MBR-Speece cone systems.

A detailed description of the different phases and set point configurations are shown in Table 1. The working operational conditions for each operational set point or IDs are also reported in Fig. 2. The operational conditions related to the Speece cone system; that is, the pressure-flow combinations, as well as the theoretical oxygen delivered by the Speece cone at each experimental set point are presented in Table 2.

2.3. System evaluation

The MBR was evaluated at the different MLSS concentration set points as previously indicated and shown in Table 1 by monitoring the following parameters: (i) TMP and MBR permeability; (ii) Permeate water quality (in terms of COD removal); (iii) Sludge activity by measuring the OUR; (iv) Speece cone theoretical DO

delivery capabilities; and (v) Sludge filterability.

In addition, a theoretical comparison of the footprint requirements (in terms of the required volume) between a conventional activated sludge (CAS) system, a conventional MBR, and a high MLSS MBR was carried out.

The reported TMP values correspond to the mean value in a series of 50 cycles for each operational MLSS set point. From the reported TMP and applied flux, the operational permeability was calculated. The permeability was later normalized at $25 \text{ }^\circ\text{C}$ and reported as a normalized operational permeability (OP_n). Neither fouling mechanisms nor fouling rates were assessed during this study; the TMP and OP_n were reported as indicators of the overall performance of the system.

2.4. Analytical procedures

Water quality analyses were performed following the standard methods for the examination of water and wastewater (Awwa, 1998). COD and total suspended solids (TSS) were determined at each MLSS concentration set point. The reported values correspond to the average from duplicate determinations for TSS and VSS and triplicate determinations for COD. DO and pH were measured daily using electrode probes (Cellox325 and WTW SenTix21-3 respectively) mounted on portable data loggers (WTW3310, Germany).

2.4.1. Oxygen uptake rate

The total OUR was measured twice at each MLSS concentration set point following the EPA method 1683 (Specific Oxygen Uptake Rate in biosolids) with addition of substrate for maximum OUR

Table 1
MBR operational conditions for each MLSS concentration set point.

Aeration source	Date	08/05/2015	11/05/2015	13/05/2015	18/05/2015	20/05/2015	22/05/2015	26/05/2015	29/05/2015	01/06/2015	02/06/2015	03/06/2015	11/12/2015	17/12/2015
Point ID		1	2	3	4	5	6	7	8	9	10	11	12	13
		Air	O ₂ gas	O ₂ gas	O ₂ gas	O ₂ gas	O ₂ gas	O ₂ gas	O ₂ gas	O ₂ gas	O ₂ gas	O ₂ gas	O ₂ gas	O ₂ gas
Q (Flow)	m ³ d ⁻¹	3.5	3.5	3.5	3.5	3.5	5.3	6.0	4.8	4.3	4.1	4.1	2.0	2.0
SRT	d	20	23	25	32	30	30	30	30	30	30	30	35	35
HRT	h	5.9	5.9	5.9	5.9	5.9	3.9	3.4	3.7	4.1	4.3	4.3	10.4	10.4
MLSS (target)	g L ⁻¹	7.6	8.9	10.1	14.8	17.8	23.5	24.0	22.9	23.8	22.8	36.3	26.7	29.1

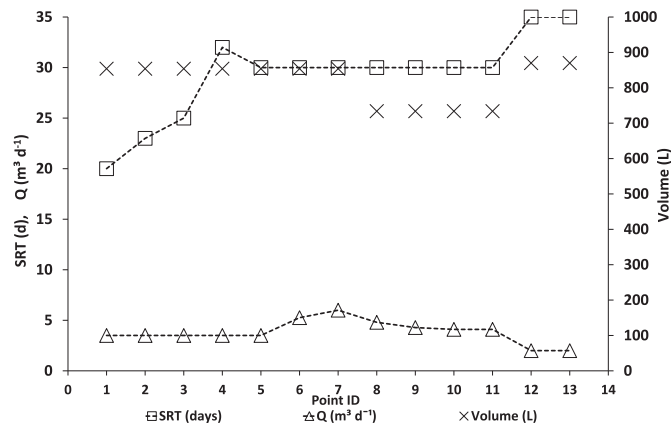


Fig. 2. MBR operational conditions including solid retention time (SRT), flow rate (Q), and aerobic chamber volume.

measurement. The mixed liquor sample (600 mL) was saturated with pure oxygen gas to a concentration of approximately 10 mg O₂ L⁻¹, then the oxygen flow was stopped and 50 mL of influent wastewater were added. The decrease in the DO concentration was recorded automatically every 5 s. The decrease on the DO concentration indicated the velocity at which the DO was consumed (the total OUR) both for substrate oxidation and for the endogenous respiration. For data analysis and comparison the OUR values were normalized at 20 °C and are reported as OUR₂₀ (mg L⁻¹ h⁻¹).

2.4.2. Filterability

The sludge filterability was evaluated twice at each MLSS concentration set point using the Delft Filtration Characterization method (DFC_m) developed at the Delft University of Technology (TUD), The Netherlands (Evenblij et al., 2005; Geilvoet, 2010). This method allows to calculate the sludge added resistance to the filtration process (ΔR). The method uses a single membrane element (X-flow F5385, The Netherlands) to filtrate a mixed liquor sample of approximately 30 L in a recirculation circuit, at a controlled flux (80 L m⁻² h⁻¹) and crossflow velocity (1 m s⁻¹) (Evenblij et al., 2005; Geilvoet, 2010; Gil et al., 2011; Lousada-Ferreira et al., 2010). The reported values correspond to the ΔR_{20}

which is the mean resistance increment after producing 20 L of permeate per membrane square meter. The sludge filterability depends on the temperature due to its influence on the fluid viscosity; however, the impact of viscosity on the filterability was considered negligible when compared to the influence of other factors such as the operational conditions and membrane maintenance and cleaning regimes (Krzeminski, 2013). The temperature at which the filterability tests were carried out ranged between 18.1 and 23.2 °C.

3. Results and discussions

3.1. MLSS concentrations and MBR permeability

The target and actual MLSS concentrations and the mixed liquor VSS concentrations in the aerobic basin of the MBR were monitored at each MLSS set point (IDs 1 to 13). Fig. 3 describes both the desired/target and measured/actual MLSS as well as the measured mixed liquor VSS values. Table 3 describes the measured MLSS concentrations and the influent wastewater characteristics for the reported set points.

For the first range of evaluated points (first phase - IDs 1 to 5 as described in the materials and method section), the influent flowrate was kept constant and the increase on the MLSS concentration was achieved mostly by increasing the SRT up to 30 days as can be observed in Fig. 2. During this initial phase the MBR was still running at biomass concentrations below 15 g L⁻¹ MLSS. The targeted and measured MLSS concentration exhibited very similar values as observed in Fig. 3 for IDs 1 to 4. The solids concentration difference between the target and measured MLSS for set point ID 5 was caused by operational problems which disturbed the continuous influent feeding and thus the final MLSS concentration.

For the second range of evaluated points (second phase - IDs 6 to 11) the influent flowrate was initially increased from 3.5 to 6 m³ d⁻¹ as observed in Fig. 2 corresponding to a higher organic load applied to the reactor. However, the flow rate was needed to be reduced back for the set point IDs 8 to 11 to compensate for the observed increase on the TMP values typically reported at higher MLSS concentrations (Lee and Kim, 2013). When higher flowrate conditions were not possible to maintain due to the reduced permeability observed in set points IDs 8 to 11, the reactor volume was reduced by 14% (0.12 m³) to achieve the desired MLSS

Table 2
Speece cone operational set points and theoretical oxygen delivered by the cone in clean water.

	Date	08/05/2015	11/05/2015	13/05/2015	18/05/2015	22/05/2015	29/05/2015	03/06/2015	11/12/2015	17/12/2015
	Point ID	1	2	3	4	6	8	11	12	13
Speece Cone										
Cone flow	m ³ h ⁻¹	0	3	3	3	4	4	5.6	3.7	4.6
Pressure	psig	0	12	12	12	13	13	11	30	44
O ₂ delivered by cone	kg O ₂ d ⁻¹	0	2.57	2.57	2.57	3.55	3.55	4.53	5.3	8.5

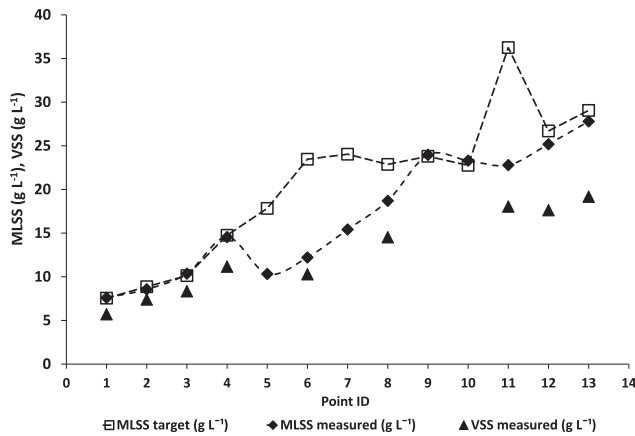


Fig. 3. MLSS (target and measured) and VSS measured concentration at the different experimental set points.

concentrations as also indicated in Fig. 2. This was done before adding the external substrate to increase the overall influent COD concentration. The solids concentration difference between the target and measured MLSS (IDs 6 to 8) was caused by operational problems which disturbed the continuous influent feeding and thus the final MLSS concentration. An unusually high concentration of influent TSS coming to the wastewater treatment plant was observed during the set point ID11. This high influent TSS value of 1006 mg L^{-1} led to a very high target MLSS of 36.3 g L^{-1} as observed in Fig. 3. Therefore, that explains the large differences between the targeted and measured MLSS corresponding to the set point ID 11. Despite the gaps observed between the targeted and measured MLSS at this second phase, it was confirmed that the MBR systems was biologically active and performing well by evaluating the COD removal of the system. As reported more precisely below in section 3.2, COD values in the effluent as low as 12 mg L^{-1} were observed for the evaluated range even at HRT conditions as low as 3.7 h as reported for set point ID 8.

For the third and last operational range corresponding to IDs 12 and 13, sugar cane molasses were added as an external source of COD to increase the influent concentration. Since the MBR influent feed was steady during this final stage, the measured and targeted MLSS values matched very closely for this last two points as observed in Fig. 3.

Fig. 4 reports the TMP, flow rate (Q), and OP_n at the evaluated range of measured MLSS concentrations. Fig. 4 shows that the operational permeability of the MBR system overall decreased as the MLSS increased. In addition, an increase on the TMP was observed as the MLSS concentration increased at the evaluated flow rates. Both the increase on TMP values as well as the decrease on the OP_n indicates an overall negative impact on the performance of the filtration system under this operational conditions. Previous studies indicated that the increase on TMP and the decrease on permeability can be related both to the increase of the MLSS concentrations and viscosity (Delrue et al., 2011), and to the presence of extracellular polymeric substances (EPS) that contribute to foul the

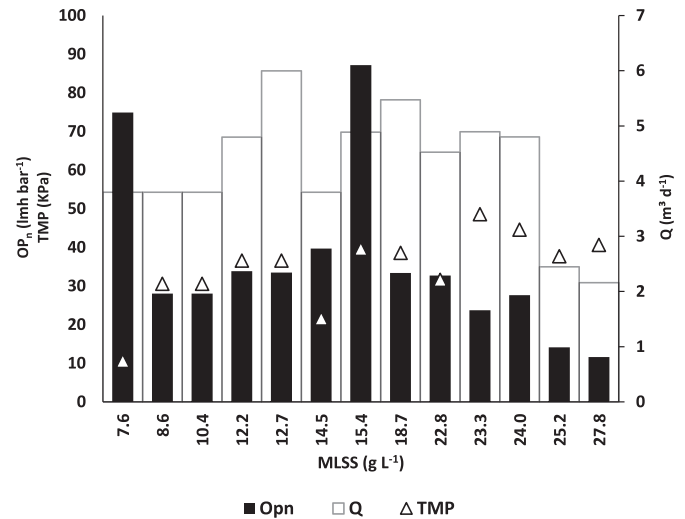


Fig. 4. Normalized operational permeability (OP_n), flow (Q), and transmembrane pressure (TMP) and at the evaluated MLSS concentrations in the MBR.

membranes (Krzeminski, 2013). The decrease on the filtration system performance can be ultimately translated as higher pressure (energy) demand to produce a progressively reduced permeate volume (Trussell et al., 2007).

3.2. COD removal

The system was fed wastewater from a full scale treatment plant; therefore, the influent COD concentration was not steady. The influent COD concentration to the pilot MBR system was ranging approximately from 600 to $1000 \text{ mg COD L}^{-1}$ for IDs 1 to 10. An external source of COD was added for the experimental set points IDs 11 to 13 to strengthen the influent wastewater in order to provide enough substrate to sustain higher biomass concentrations. The performance of the MBR system regarding COD removal is presented in Fig. 5. The COD effluent concentrations were mostly below 35 mg COD L^{-1} with a maximum value of 61 and a minimum of 12 mg COD L^{-1} (with the exception of the last two set points IDs 12 and 13). Similarly, the COD removal showed efficiencies above 90% during most of the operational period with the exception of the last two set points IDs 12 and 13 where it decreased to 77% and 79%, respectively. The cause for this reduced COD removal values was attributed to an insufficient dose of DO to the MBR; a theoretical OTE provided by the Speece cone manufacturer based on clean water tests results was used for calculating the oxygen delivery capacity of the Speece cone without considering the effects of the MLSS on the OTE (similar to the alpha factor effects on conventional bubble diffuser systems). As indicated by the removed COD values for set points IDs 12 and 13, enough DO was effectively delivered to remove nearly 80% of the applied substrate. However, not sufficient oxygen was supplied to satisfy all the oxygen needs of the system and leave a residual DO to be measured.

Table 3
Measured MLSS concentrations and influent characteristics.

MLSS _(measured)	Point ID	1	2	3	4	5	6	7	8	9	10	11	12
	g L ⁻¹	7.6	8.6	10.4	14.5	10.3	12.2	15.4	18.7	24.0	23.3	22.8	25.2
COD in	mg L ⁻¹	611	698	615	917	670	1045	450	1141	600	600	1513	2500
TSS in	mg L ⁻¹	300	300	410	404	300	468	300	300	300	300	1006	350
Temp	°C	18.8	21.9	21.6	20.4	21.6	20.8	21.9	19.3	20.6	20.9	20.8	18.1
pH		7.0	6.7	7.0	6.5	6.8	7.1	6.6	6.9	6.7	6.9	6.9	7.4

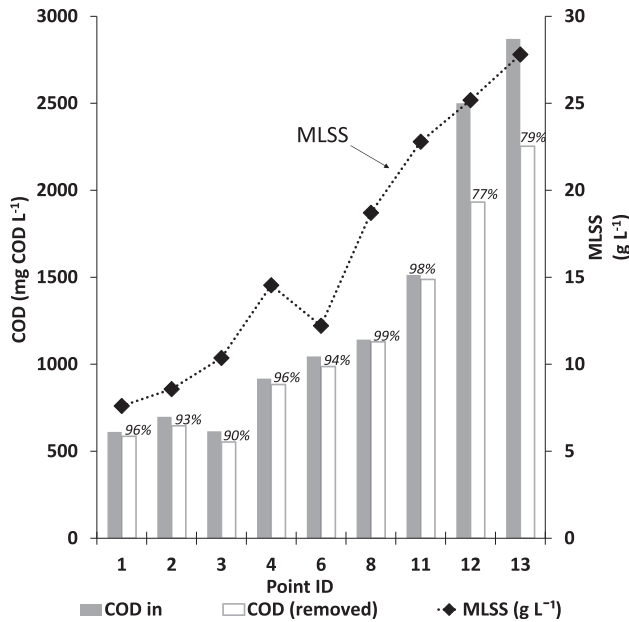


Fig. 5. Applied and removed COD at the measured MLSS concentrations range.

3.3. DO and OUR

The OUR increased following a similar trend as observed with the increase of the MLSS concentration except for the last two MLSS set points (ID 12 and 13) as indicated in Fig. 6. The trend observed for set points ID 1 to 11 was as expected with more active biomass consuming more DO resulting in a maximum reported OUR value of 332 mg L⁻¹ h⁻¹ corresponding to a measured MLSS concentration of 22.8 g L⁻¹. The reported trend for the OUR values was as expected assuming that enough DO was available in the aerobic basin of the MBR system. However, that was not the case for the set points ID 12 and 13 when the system was oxygen limited due to an insufficient dose of oxygen as explained in the previous section. The reported

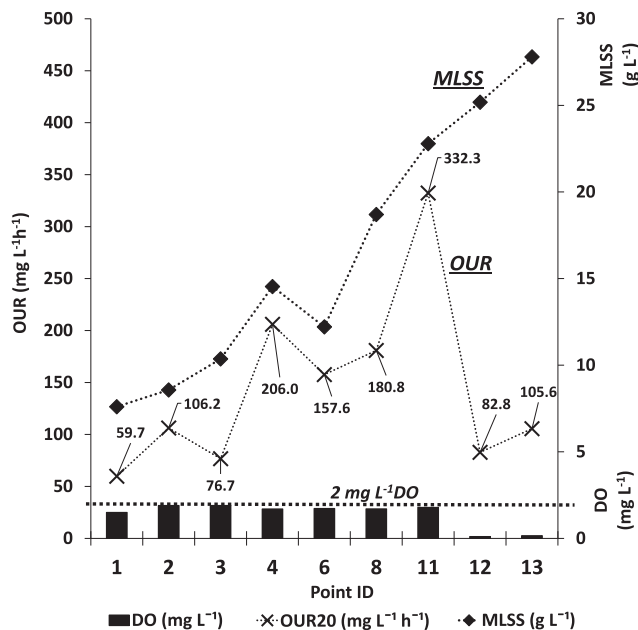


Fig. 6. Dissolved oxygen concentrations (DO), oxygen uptake rates normalized at 20 °C (OUR₂₀), and MLSS concentrations at the different MBR operational set points.

OUR for these last two set points, 82.8 and 105.6 mg L⁻¹ h⁻¹ for measured MLSS of 25.2 and 27.8 g L⁻¹, respectively, were comparable to the OUR values observed at the lower range of MLSS concentrations. Nevertheless, as observed in Fig. 5, a considerable COD removal still took place on the system considering that most of the applied substrate load (2870 mg COD L⁻¹) was removed (2253 mg COD L⁻¹).

Fig. 7 shows the theoretical OUR calculated using the oxygen flux (kg O₂ d⁻¹) required to carry out the oxidation of: (i) the removed COD - this would be the system boundary or the maximum potential oxygen consumption value; (ii) the ultimate BOD (UBOD) which represents the soluble and particulate substrate subject to biological oxidation; and (iii) the calculated BOD₅. These three calculated OUR series were compared to the actual (measured) OUR values for validation. From this comparison, the UBOD provided a better approximation to the measured OUR values with exception of the last two points where insufficient DO was provided as described on the previous section. The OUR values calculated using the UBOD represent all the substrate that could be subject to biological oxidation; thus, consuming oxygen. Therefore, under the particular experimental conditions evaluated in this research the OUR_{UBOD} could be used to estimate the expected/actual OUR.

3.4. Speece cone aeration system

Fig. 8 presents a comparison between the theoretical DO delivered by the Speece cone system in clean water, and the calculated oxygen requirements as oxygen flux (FO_c) considering both the total measured removed COD (FO_c 1) and the calculated theoretical UBOD (FO_c 2). Fig. 8 indicates that the theoretical DO supplied by the Speece cone system was apparently more than enough to satisfy the theoretical UBOD oxygen demand of the pilot MBR system (FO_c 2). However, according to the observed DO concentrations previously reported in Fig. 6 the MBR system was oxygen limited in the last two operational set point points (ID 12 and 13). This oxygen limitation also imposed a negative effect on the partial COD removal noticed for the same operational set points as previously indicated in Fig. 5. The theoretical DO delivered by the Speece cone system was provided by the manufacturer based on

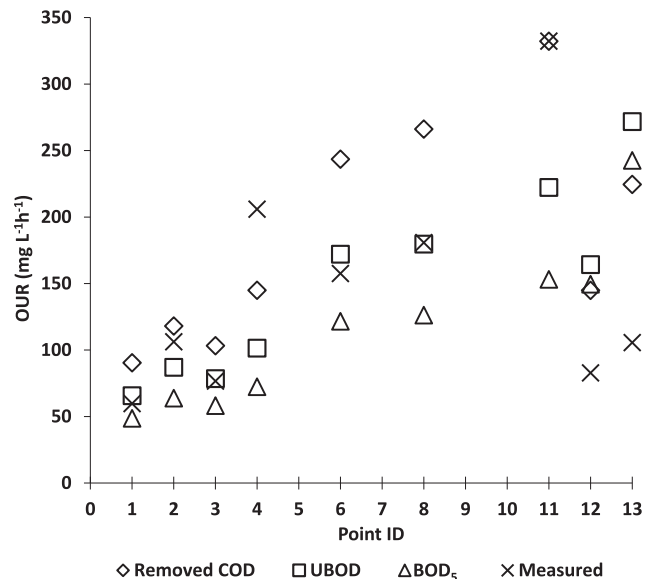


Fig. 7. OUR values: (i) Calculated based on removed COD ◊; (ii) Calculated based on UBOD □; (iii) Calculated based on BOD₅ Δ; and (iv) Measured OUR values ×.

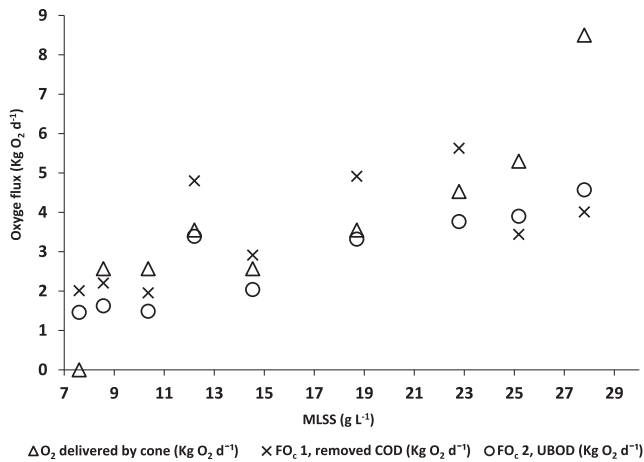


Fig. 8. Theoretical oxygen delivered by the Speece cone in clean water, and theoretical oxygen requirements by the system. O_2 delivered by the cone = theoretical dissolved oxygen delivered by the cone in clean water; FO_{c1} removed COD = calculated oxygen requirements of the system based on total COD removal; FO_{c2} UBOD = calculated oxygen requirements of the system based on UBOD removal.

oxygen transfer evaluation conducted in clean water without considering the impact of the MLSS concentrations on the oxygen transfer. Therefore, the theoretical DO delivery by the Speece cone system needs to be corrected considering the negative impact of the MLSS concentration on the oxygen transfer. However, the evaluation of the oxygen transfer efficiencies of the Speece cone system at different MLSS concentrations (that is, the impact of the different MLSS concentrations on the OTE of the Speece cone system) was not part of the scope of this research. Even though the oxygen transfer efficiency of the Speece cone system was negatively affected by the MLSS, still the amount of DO supplied by the Speece cone to the MBR system was enough to remove 77 and 79% of the influent COD at the most challenging evaluated experimental conditions as indicated in Fig. 5.

3.5. Filterability

As indicated in Fig. 9, most of the measured filterability values fell in the poor filterability range ($\Delta R_{20} > 1 \times 10^{12} \text{ m}^{-1}$) with the exception of the set point ID 11 (MLSS concentration of 22.8 g L^{-1}) which showed a remarkable low resistance value falling in the range of moderate filterability ($\Delta R_{20} = 0.1 \times 10^{12} \text{ m}^{-1}$). This effect

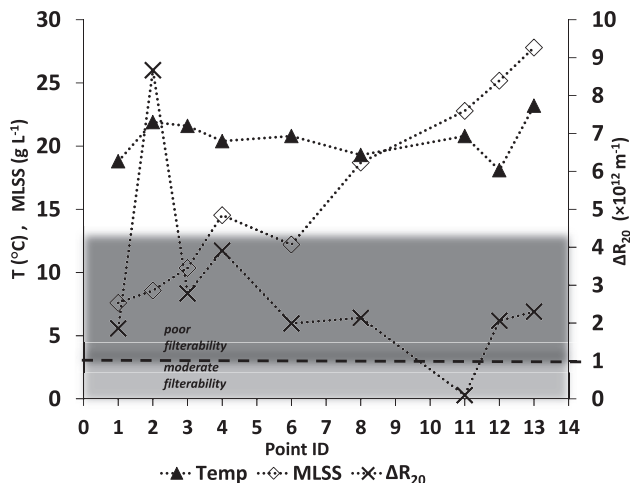


Fig. 9. Sludge filterability (ΔR_{20}) at the evaluated MLSS concentration.

may be in accordance with the decrease in the resistance values at higher MLSS reported by (Gil et al., 2011; Lousada-Ferreira et al., 2010). As observed in Fig. 9, the filtration resistance did not increase proportionally to the MLSS concentration; on the other hand, the filtration resistance showed similar values at different MLSS concentrations. That is, the added resistance at very high MLSS concentrations ($>20 \text{ g L}^{-1}$) was not much different than the values observed at the mid-range MLSS concentrations ($\Delta R_{20} < 20 \text{ g L}^{-1}$). On previous studies conducted at the Delft University of Technology (TUD), it was suggested that there may be a breakpoint, or as the author suggested, an MLSS critical concentration for which the resistance to filtration (ΔR_{20}) is reduced (Gil et al., 2011; Lousada-Ferreira et al., 2010). Similarly (Lousada-Ferreira et al., 2010) proposed that high concentrations of mixed liquor could act as a sludge blanket retaining most of the fouling particles causing a reduction in the resistance to filtration; in other words, this might indicate the possibility of better filterability set points at some specific operational conditions as it was observed for the set point ID 11 during this research. That is, operating a MBR at such high MLSS concentrations may probably require the same operational efforts in terms of filtration resistance as when operating a conventional low biomass concentration MBR, but having the associated advantages such as the footprint reduction and the lower capital expenses.

3.6. A comparison with conventional systems

One of the main advantages of operating an MBR at high MLSS concentrations is the reduction of the footprint requirements of the system. A comparison between a CAS system, a conventional MBR operated at low MLSS concentrations, and a high MLSS MBR is shown in Fig. 10. The same operational conditions were considered for all the proposed scenarios as follows: flow rate (Q) = $4 \text{ m}^3 \text{ d}^{-1}$; SRT = 20 d; temperature $20 \text{ }^\circ\text{C}$, and UBOD = 500 mg L^{-1} . The only parameter that was changed during this evaluation was the MLSS concentration which is the theoretical biomass corresponding to the applied organic load. Since this amount of biomass is the same in all cases, the changes on the MLSS concentrations were obtained by just changing the required volume of the systems necessary to accommodate that particular mass for that particular MLSS concentration. Fig. 10 shows the theoretical volume reduction that can

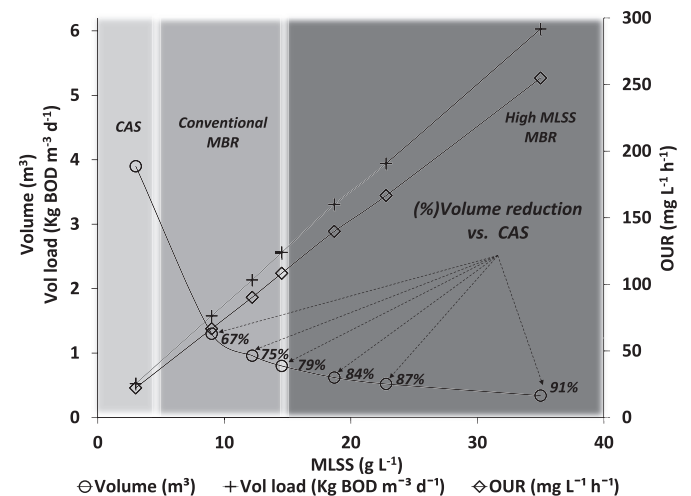


Fig. 10. Comparison of the required biological system volumes (Volume), theoretical OURs (OUR), and volumetric organic loads (Vol load) for: (i) a conventional activated sludge system (CAS) – operated from 0 to 5 g L^{-1} MLSS, (ii) a conventional MBR – operated from 15 to 15 g L^{-1} MLSS, and (iii) a high MLSS MBR-Speece cone – operated from 15 to 40 g L^{-1} MLSS. Assumed operational conditions: Flow rate (Q) = $4 \text{ m}^3 \text{ d}^{-1}$; SRT = 20 d; Temperature $20 \text{ }^\circ\text{C}$, and UBOD = 500 mg L^{-1} .

be achieved by operating a high MLSS MBR compared to both a CAS system operated at 3 g L^{-1} MLSS and to a conventional (low MLSS) MBR operated at 9 g L^{-1} MLSS. The volume reductions and consequently the footprint requirement reductions can be as large as 90% and 70% compared to CAS and conventional MBRs, respectively.

Advantages of operating MBRs at high MLSS concentrations include the reduction on the footprint requirements lowering the associated capital costs. At the experimental conditions evaluated in this research, it was demonstrated that an MBR can be operated at high MLSS concentrations; a good quality effluent was obtained in terms of COD concentrations, high OURs were observed, and the filterability of the sludge was not much affected at the evaluated high MLSS concentrations compared to conventional systems.

Another scenario that may be feasible for implementing the high MLSS MBR concept may include the upgrade of existing CAS systems or conventional MBR wastewater treatment facilities to cope with ever increasing treatment demands. This situation may be particularly attractive in developing countries where funding availability could be limited. In the case of treatment plant upgrading most of the required infrastructure would be already in place (i.e. pre-treatment, biological reactors, pumping systems, and control-instrumentation systems). The installed treatment capacity may be increased by providing additional membrane area to compensate for the increased flow rate, but keeping the same reactor volumes. The additional treatment capacity is provided by the higher biomass concentration and increased membrane area. This, combined with the introduction of an alternative aeration system such as the concentrated oxygenation system - Speece cone or similar could make the necessary capital investment significantly less compared to the cost of building a entire new additional treatment train to cope with an increased influent load or treatment demand.

Moreover, the reduction of the footprint requirements may promote the development of innovative systems such as movable/portable containerized MBRs for a diverse range of applications including the provision of municipal/industrial wastewater treatment in areas without sewerage and the provision of easily deployable sanitation services under challenging site-specific conditions such as after the occurrence of a human-made or a natural disaster.

4. Conclusions

The results obtained under the experimental conditions of this research suggest that the existent limitations for reducing the footprint requirements of MBR systems can be overcome. The oxygen transfer limitations can be solved by incorporating an alternative aeration system. The measured OUR values matched closely the calculated values corresponding to the UBOD required oxygen flux at the evaluated MLSS concentrations. Filterability values falling in the range of poor filterability (ΔR_{20} above $1 \times 10^{12} \text{ m}^{-1}$) were observed for most of the evaluated MLSS concentrations. However, the decrease on filterability was not much worse for the upper MLSS concentration range ($\text{MLSS} > 25 \text{ g L}^{-1}$) compared to the middle MLSS concentration range. Consequently, MBRs can be designed to operate at higher than usual MLSS concentrations. Further research should be carried out evaluating both the MBR performance on the very high MLSS range above 30 g L^{-1} , as well as the OTE of the Speece cone system at the evaluated range of MLSS concentrations. That is, further research is needed for pushing even further the limits for MBR applications operating at high MLSS concentrations.

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