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Upgrading of submerged membrane bioreactor operation with regard to soluble microbial products and mathematical modeling for optimisation of critical flux

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ABSTRACT

Recent studies have shown that the colloidal and soluble fraction of the sludge (sludge water) correlates well with Membranes Bioreactor (MBR) fouling. Soluble microbial products (SMP) are the main constituent of MBR sludge water. However, it is not clear how to predict the foulant concentrations, how foulants are deposited onto the membrane, and how to predict the impact of deposited foulants on membrane permeability. The goal of this paper was therefore to characterize the foulants in MBRs and to develop a mathematical model to predict both membrane fouling and effluent quality. The focus of this study is the interaction between the MBR biology, membrane fouling and the optimum critical flux for the treatment of a municipal wastewater was determined. A lab-scale MBR reactor was constructed for biological nutrient removal, equipped with a tubular membrane in side-stream configuration. Laboratory-scale tests were performed at two sludge retention time conditions: 15 and 40 d, respectively, while maintaining a hydraulic retention time of 7 h. The sludge obtained from this membrane was used in specifically designed batch experiments to produce biomass associated products (BAP) and utilization associated products (UAP) separately, which allowed their characterisation using a new tool, liquid chromatography—organic carbon detection (LC-OCD). Both BAP and UAP exhibited a very wide molecular weight (MW) distribution. The biopolymer fraction of SMP exhibited a very high 230 MW and a good correlation with MBR fouling. The UAP produced during the biomass growth phase exhibited a lower MW than the BAP, suggesting UAP has a lower fouling potential than BAP. Finally. Based on experimental values from submerged membrane bioreactor and on values predicted by a simulation model generated using the back propagation neural network (BPNN) theory and the MBR-ASM2d model was used to predict the impact of operational parameters on SMP concentration. The results showed that the critical flux measured by the stepwise flux method was almost related to UAP/SMP ratio the optimum critical flux for the treatment of a municipal wastewater were determined. Therefore, it is suggested that the UAP/SMP ratio be used as a new filterability index for SMBR processes in wastewater treatment.

Keywords: Wastewater Treatment; Submerged membrane bioreactor; Soluble microbial products (SMP); Critical flux; Activated sludge model; Back propagation neural network (BPNN)

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1. Introduction

The breakthrough of the SMBR technology emerged in 1989 with the idea of Yamamoto and co-workers to submerge the membranes in the bioreactor [1]. Submerged membrane bioreactors (SMBR) have been developed for municipal wastewater treatment in the last decade in order to produce high quality water, to reduce reactor sizes and to minimize sludge production [2]. The complex interactions between operating conditions, biomass physiological state and sludge characteristics, in relation to removal efficiencies and fouling potential, still need to be investigated [3,4]. The filterability of activated sludge is an important factor for the economical operation of membrane bioreactors. The composition of the liquid phase was found to affect most the filterability of activated sludge, a major influence being the concentration of suspended extracellular polymeric substances (EPS); the higher the suspended EPS concentration, the lower the filtration index. Suspended EPS concentration increases with high mechanical stress in the SMBR and high food per microorganism ratios (F/M), if the treated wastewater contains considerable amounts of proteins or polysaccharides. Recent research activities point towards the importance of soluble and colloidal material on membrane fouling in wastewater applications. Results of case studies show the clear relevance of liquid phase constituents, either colloidal or soluble, with regards to membrane fouling [5].

Soluble microbial products have been reported to act as major foulants in the operation of MBRs used for wastewater treatment depending on sludge retention time (SRT) [6]. The results of investigations about impact of protein/carbohydrate ratio in the feed wastewater on the membrane fouling in SMBRs showed increased concentrations of SMP as carbohydrate and protein at the highest P/C ratio (i.e. 8/1) as well as increased relative hydrophobicity which resulted in pore blocking and increased the fouling rates [7]. The polysaccharides and lipid fractions (polymeric compounds) are major components of bacterial lipopolysaccharides and are impacting membrane fouling. The results of related research suggest that fatty acids from bacterial lipopolysaccharides, as well as from synthetic sources, are of much higher relevance to membrane fouling than previously assumed.

Membrane flux, a key parameter in MBR design and application, is closely related to MBR filtration characteristics and membrane fouling. To describe the membrane fouling phenomenon, the concept of critical flux was introduced by Field et al. [8]. It was initially defined as a flux below which no fouling would occur [9]. In order to better control membrane fouling and maintain sustainable operation, the concept of critical flux was proposed by Wu et al. in submerged membrane bioreactor (SMBR) [10]. The effects of mixed liquor suspended solids (MLSS) concentration on critical flux and/or filterability have been subjected to numerous studies in the past 20 y, because membrane fouling is often considered to be caused by the deposition of particles on the membrane surfaces [11]. The effects of sludge characteristics on critical flux were examined by Fan and Zhou [12], and it was suggested that colloidal TOC be used as a new filterability index for MBR processes in wastewater treatment. Due to the intrinsic complexity and uncertainty of MBR processes, basic models that can provide a holistic understanding of the technology at a fundamental level are of great necessity. Compared to experimental research and development, followed by commercialization of the technology, modeling studies are at a relatively rudimentary state [3]. A mathematical model has been developed for submerged membrane bioreactors, combining the activated sludge model No. 1 (ASM1) with a membrane fouling model. Using this model, one can predict effluent quality and membrane fouling behavior during the SMBR process [13]. Mathematical modeling was used to quantify the relationships among bacteria, extracellular polymeric substances (EPS), inert residual biomass, two soluble microbial products (SMP), original substrate, and an electron acceptor [14]. A new model, called ASM2dSMP, was developed to predict both effluent quality and SMP concentration. Attention was paid in model development to minimize parameter correlation and to obtain reasonable parameter estimates [15].

In this study, a Laboratory-scale SMBR was simulated to investigate the relationship between sludge characteristics and membrane flux that was focused on sludge characteristics, with regard to membrane fouling at low and high sludge retention time. The sludge was characterized by colloidal particle concentration, EPS, MLSS, temperature, SMP, UAP and BAP. Furthermore, a simulation model of operational parameters was established based on the theory of back propagation neural network (BPNN). The simulation model was used to identify the most important factors and to determine the optimal critical flux of the SMBR.

2. Material and methods

A laboratory-scale SMBR system was constructed to evaluate the developed model and to determine the constants necessary for model runs. The SMBR system was fed with synthetic wastewater; seeding of the wastewater in the SMBR system was fulfilled by using the sludge from a wastewater treatment plant.

A municipal-like synthetic wastewater was adapted from Boeije et al. [16]. Both soluble and colloidal components (e.g., acetate, milk powder, peptone and starch, etc.) were used as COD source, which is expected to be more representative than using completely soluble COD source, e.g., acetate or glucose.

The system consists of three commercial hollow-fiber MF membrane modules (Mitsubishi Rayon, Japan) with an effective filtration area of 0.6 m^2/module. The membrane is made of polyethylene with hydrophilic coating, and its nominal pore size is 0.03 μm (200 kDa). Each membrane was fully immersed and symmetrically placed in the system. An air diffuser was installed underneath each membrane module to provide dissolved oxygen in the reactor, as well as to control membrane fouling by hydraulic shear force and agitation. The bioreactor was divided into an anaerobic and an aerobic/anoxic and a membrane compartment. Alternating aeration (20 min DO = 1.5–2.5 mg/l, 25 min DO = 0) was applied in the aerobic/anoxic compartment for nitrification and denitrification. Fig. 1 shows a schematic of the constructed SMBR system [17]. The experimental conditions and operating strategies are listed in Table 1. A data acquisition/control system, called Lab View, was employed for remote monitoring as well as remote control. The modelling and simulation software WEST (MOST for-WATER NV, Belgium) was used to perform model simulations and parameter estimations. Furthermore, a simulation model of operational parameters was established based on the theory of back propagation neural networks (BPNN).

The simulation model was used to identify the most important factors and to determine the optimal critical flux of the SMBR. Influent characteristics were measured twice per week. The effluent COD, NO_3–N, and PO_4–P were monitored daily. The effluent NH_4–N, NO_2–N, TN, TP, COD and sludge total COD were monitored twice a week. For batch experiments, fresh sludge was taken from the aerobic/anoxic compartment of the SMBR, washed with dilution water and used to run three batch experiments. All experiments were conducted under conditions of constant temperature (20°C) and controlled pH (7.6 ± 0.3). The BAP batch experiment was conducted under starvation conditions without substrate addition. Hence, the produced SMP should be dominated by BAP. Alternating aeration was applied to maintain the same aerobic: anoxic time ratio as in the lab-scale SMBR: 50 min aerobic (on/off aeration, DO = 1.5–2.5 mg/l) and 71 min anoxic. The UAP batch experiment was spiked with acetate (end concentration of 1,000 mg/l) under completely aerobic conditions

Table 1
Process conditions of the laboratory-scale SMBR

Parameter	Run 1		Run 2	
	Run 1a	Run 1b	Run 2a	Run 2b
Period (day)	1–42	43–88	89–135	1306–210
Temperature (°C)	10.9–15.8	13–18.5	17.3–21.1	20.2–23.1
SRT (day)	15	15	40	40
MLSS (g/l)	10.9–12.1	10.9–12.1	11.4–22	11.4–22
MLVSS/MLSS ratio	0.76–0.72	0.67–0.70	0.67–0.68	0.68–0.60

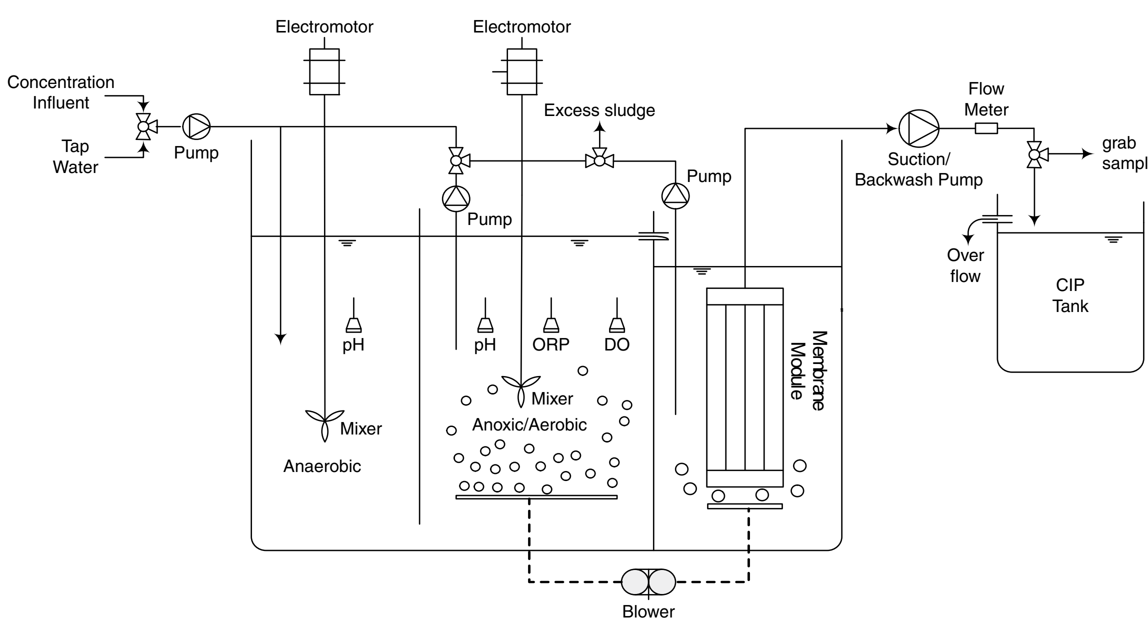

Fig. 1. Schematic diagram of the Laboratory-scale SMBR system.

(on/off aeration, DO = 1.5–2.5 mg/l). Meanwhile, a reference batch experiment was conducted without acetate addition to obtain the background SMP concentration. In the UAP batch, the external substrate acetate was also measured as SCOD. The UAP_{COD}, UAP_{PT} and UAP_{PS} are the net UAP concentrations as COD, proteins and polysaccharides, respectively. The constant 0.64 is a correction factor accounting for the underestimation of polysaccharides and proteins using the colorimetric methods [18]. In this study, this factor was estimated from six-month average measurements of the SMBR sludge water (filtrate of SMBR sludge using 0.45 mm filter).

$$UAP_{COD} = (1.5UAP_{PT} + 1.07UAP_{PS})/0.64 \quad (1)$$

The model description of the UAP production and degradation was also based on experimental observations. After the acetate addition, the net UAP production was estimated using Eq. (1). This method eliminated/reduced the interference of BAP and allowed a more accurate net UAP estimation and its characterization. A more detailed UAP characterization using LC-OCD was performed for samples collected at 2, 6.8 and 25.6 h (Fig. 2).

The critical flux was determined according to the flux step method [3], consisting in setting increasing values of permeate flux and registering the relative TMP variations. For each flux step, two TMP values were considered: the initial TMP is corresponding to the initial sudden increase of the filtration resistance, and the final TMP, i.e., the TMP at the end of the step. From these two TMP values, two parameters connected to fouling can be evaluated: the average TMP and the rate of TMP increase (dTMP/dt). The critical flux was assumed to be the flux at which dTMP/dt ≥0.5.

The total filtration resistance $R_{tot} = R_m + R_c + R_f$ was calculated using the resistance in series model, where R_m is the intrinsic membrane resistance (obtained from pure

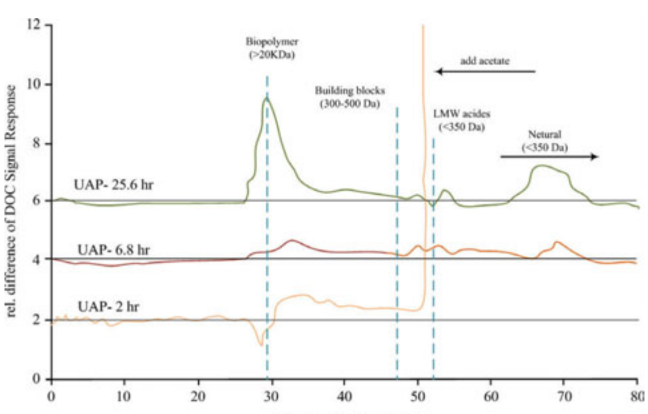

Fig. 2. Differences of DOC signal between UAP and reference batches measured by LC-OCD.

water permeability measurements), R_c is the cake resistance and R_f is the fouling resistance due to irreversible adsorption and pore plugging. R_m and R_{tot} were calculated according to Darcy law R = TMP $\mu^{-1}J^{-1}$, where μ is the fluid viscosity.

In order to a non-dimensional number Z was introduced in the study and its effect on the critical flux was found. Therefore, can be rewritten as:

$$J_c = f\ (Z, \text{MLSS}, \text{SMP}, \text{UAP}, \text{BAP}, T) \quad (2)$$

$$Z = (\text{UAP}/\text{SMP}) \quad (3)$$

3. Results and discussion

3.1. *ASM2d model calibration for the laboratory-scale SMBR*

The laboratory-scale SMBR was first calibrated using the standard IWA ASM2d model [19]. The key points of calibration are shortly described below. The two bioreactors and the volume in the feed membrane were treated as completely mixed reactors, which were justified based on the results of a tracer test. The membrane was assumed to retain all particulates (inert particulate COD (X_I), slowly biodegradable COD (X_S) and biomass), but allowed passing of all solutes (S_{NH}, S_{NO}, S_{PO}, S_F, S_A and S_I). The periodical membrane backwashing and relaxation was normalized as continuous flow. This simplified model was compared with a complete model describing the membrane backwashing and relaxation. The difference between the simulation results of these two approaches was found insignificant. The decay rate of the autotrophic biomass was obtained from batch experiments. The majority of the remaining parameters were taken as the defaults from the ASM2d. A few parameters (Table 2) were tuned during dynamic calibration to achieve a better fit of both in-cycle dynamic data (obtained from a measurement campaign) and six-month average steady state measurements. The sequential methodology proposed was used to calibrate the nitrification, denitrification, and biological phosphorus removal related parameters of the model [20,21].

Comparing the model predicted sludge and effluent concentration with measurements, the ASM2d model well predicted the mean sludge concentration and effluent quality. It failed in predicting the SCOD of sludge water due to the overlook of SMP in the ASM2d (Table 3). The simulated SCOD in the sludge water (6.5 mg/l) only contained S_F, S_A and S_I. The actually measured SCOD (88.5) also contained colloidal organics retained by the membrane. It should be noted that although it overlooks SMP, the ASM2d still allowed good prediction of COD

Table 2
Summary of calibrated ASM2d parameters (20°C)

Parameter name	Symbol	Unit	Default	Calibrated
Decay rate of nitrifiers	b_{aut}	l/d	0.16	0.6
Maximum growth rate of nitrifiers	μ_{aut}	l/d	1.1	0.65
Oxygen half-saturation coefficient of nitrifiers	$K_{O,aut}$	mg O_2/l	0.4	0.2
Ammonium half-saturation coefficient of nitrifiers	$K_{NH4,aut}$	mg N/l	0.8	0.2
Reduction factor of anoxic growth of heterotrophs	$\eta_{NO3,het}$		1	1.1
Fermentation rate of acetate production	q_{fe}	l/d	3.5	1
PHA storage rate	q_{PHA}	l/d	4	5.5
Phosphate uptake rate	q_{PP}	l/d	1.6	1
Reduction factor of anaerobic hydrolysis	$\eta_{NO3,PAO}$		0.65	0.45

and biological nutrient removal processes. If the objective of modeling is limited to this perspective, ASM2d is valid for SMBR. Hence, the model extension proposed below is only of interest if SMP and SMBR fouling are pursued.

3.2. SMBR-ASM2d model development and parameter estimation

The ASM2d model was extended to SMBR-ASM2d by introducing two new components: S_{BAP} and S_{UAP}. The general model assumptions are: (1) SMP are defined as colloids and solutes smaller than 0.45 μm and thus SMP can only be partially retained by SMBR membranes; (2) both BAP and UAP are produced; and (3) BAP and UAP are biodegradable with the same biomass yield coefficient (Y_H) but at a lower degradation rate than readily biodegradable substrate.

3.3. BAP production and degradation

The production of BAP can be described as proportional to the biomass decay with a stoichiometric parameter [22]. A stoichiometric parameter f_{BAP} into the biomass lysis process is introduced in ASM2d. Thus, Biomass lysis produces BAP in addition to inert particulate COD (X_I) and slowly biodegradable COD (X_S) as depicted in the Petersen matrix (Table 4).

The BAP hydrolysis rate can be described either as a Monod type surface reaction, as in ASM2d (Eq. 5), or as a simple first-order reaction with respect to BAP and biomass concentration (Eq. (6)).

Direct growth with Monod type kinetics:

$$\Upsilon_{SBAP} = -\mu_{BAP}.(S_{BAP} / K_{BAP} + S_{BAP}).X_H \quad (4)$$

Hydrolysis with Monod type surface reaction:

$$r_{SBAP} = -k_{h,BAP}\left[(S_{BAP}/X_H)/(K_{BAP} + S_{BAP}/X_H)\right].X_H \quad (5)$$

Hydrolysis with first order kinetics:

$$r_{SBAP} = -k_{h,BAP}.S_{BAP}.X_H \quad (6)$$

All three forms of the BAP degradation process (Eqs. (4)–(6)), together with the BAP production process, were incorporated into the ASM2d model for parameter estimation using a Simplex optimization algorithm.

The BAP production and degradation processes using Monod type kinetics (Eqs. (4) and (5)) require estimating three parameters (f_{BAP}, μ_{BAP}, K_{BAP} in Eq. (4) or f_{BAP}, $k_{h,BAP}$, K_{BAP} in Eq. (5)) [9], the processes using first-order BAP hydrolysis kinetics (Eq. (6)) requires estimating only two parameters (f_{BAP} and $k_{h,BAP}$). All optimization runs using different initial parameter estimates converged to the same optimal parameter set (Fig. 3). It was decided to describe the BAP degradation using the first-order kinetics. Parameter confidence intervals were calculated from the parameter estimation error covariance matrix. Hessian matrix was numerically estimated resulting in a narrow 95% parameter confidence interval, i.e., $f_{BAP} = 0.0213 \pm 0.0023$ and $k_{h,BAP} = (7.51 \pm 0.44) \times 10^{-7}$ 1/d [23].

It appears that UAP were produced immediately after the acetate addition and degraded simultaneously. There was a net accumulation between 1 and 5 h, but most of the UAP was degraded subsequently between 5 and 9 h (Fig. 4). After around one day, high MW UAP (>20 kDa) accumulated (Fig. 2). Fig. 4, clearly demonstrates that UAP_{sto} were biodegradable and probably more readily biodegradable than BAP. Thus, a separate first-order kinetic parameter ($k_{h,UAP}$) was assigned to UAP hydrolysis (Eq. (7)). UAP parameters were estimated using a similar method as that of BAP resulting in $f_{UAP} = 0.0953 \pm 0.0397$ and $k_{h,UAP} = 0.0103 \pm 0.0043$ 1/d.

Table 3
Comparison of the SMBR-ASM2d model simulation with steady state experimental results

Sample	Parameter	Six-month average	Standard deviation	Simulation (ASM2d)	Simulation (SMBR-ASM2d)
Waste sludge	Total COD (g COD/l)	11.9	0.65	11.83	11.85
Sludge water					
(from sludge waste)	SCOD (mg COD/l)	88.5	22.7	6.5	93.5
	BAP (mg COD/l)	n.a	n.a	n.a	78.5
	UAP (mg COD/l)	n.a	n.a	n.a	11.5
Sludge water[a]					
(from membrane feed)	SCOD (mg COD/l)	108.4	33.4	5	108.5
	BAP (mg COD/l)	n.a	n.a	n.a	91.7
	UAP (mg COD/l)	n.a	n.a	n.a	11.7
Effluent	COD (mg COD/l)	11	3.1	5	14.2
	BAP (mg COD/l)	n.a	n.a	n.a	7.1
	UAP (mg COD/l)	n.a	n.a	n.a	0.85
	TN (mg N/l)	10.2	2.6	8.8	9.45
	NH_4–N (mg N/l)	0.16	0.42	0.18	0.5
	NO_3–N (mg N/l)	7.05	1.73	8.6	8.6
	NO_2–N (mg N/l)	0.2	0.21	n.a	n.a
	PO_4^{3}–P (mg P/l)	5.63	2.19	5.5	5.8

[a]Sludge water = sludge filtrate using 0.45 membrane filter.

Table 4
Stoichiometry of the BAP model (only new items to ASM2d are presented)

Processes	S_I	S_F	S_{BAP}	X_I	X_H	H_{PAO}	X_{AUT}	X_S
Aerobic hydrolysis of BAP	f_{SI}	$1-f_{SI}$	–1	–	–	–	–	–
Anoxic hydrolysis of BAP	f_{SI}	$1-f_{SI}$	–1	–	–	–	–	–
Anaerobic hydrolysis of BAP	f_{SI}	$1-f_{SI}$	–1	–	–	–	–	–
Lysis of X_H	–	–	f_{BAP}	f_{XI}	–1	–	–	$1-f_{XI}-f_{BAP}$
Lysis of H_{PAO}	–	–	f_{BAP}	f_{XI}	–	–1	–	$1-f_{XI}-f_{BAP}$
Lysis of X_{AUT}	–	–	f_{BAP}	f_{XI}	–	–	–1	$1-f_{XI}-f_{BAP}$

First order UAP hydrolysis: $r_{SUAP} = -k_{h,\ UAP} S_{UAP} X_H$ (7)

The UAP model should be applied with caution: (1) the measured polysaccharides, proteins and equivalent UAP had quite high standard deviations (1.04, 0.64 and 5.44 mg/l, respectively) due to their low concentrations; (2) only UAP_{sto} was included in the model and UAP_{pro} was not modelled; (3) a simple substrate, acetate, was used, whereas UAP production is known to be substrate specific [22]; (4). a sewage-like synthetic wastewater was used as the SMBR feed, whereas a real wastewater can produce different sludge and SMP characteristics; and

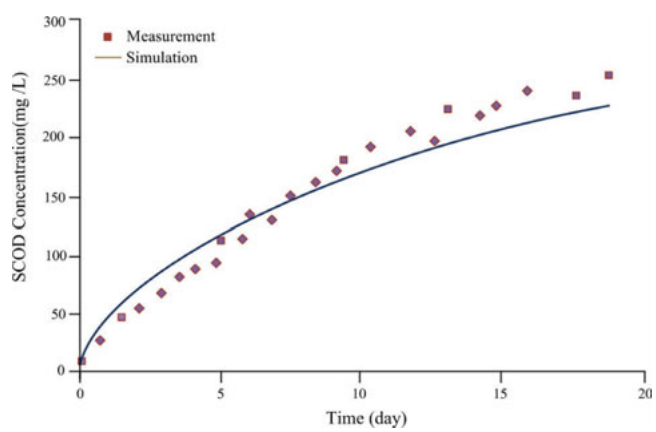

Fig. 3. Simulated and measured SCOD concentration in a BAP batch experiment (SCOD is an estimate of the BAP concentration under starvation conditions).

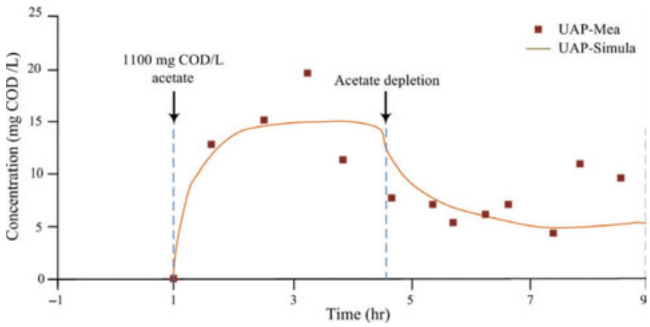

Fig. 4. Simulated and measured net UAP concentration in the UAP batch experiment (1,100 mg COD/l of acetate was added at 0 h).

(5) UAP production is related to the S_0/X_0 (substrate/MLSS) ratio at the start of the batch experiment. A low S_0/X_0 ratio (0.097) in a one-day batch test was used here, which is close to the common F/M ratio for nitrifying activated sludge processes. A higher S_0/X_0 ratio may produce a higher percentage of UAP due to more intensive cell proliferation [24].

3.5. SMBR-ASM2d model validation for the lab-scale SMBR

The SMBR-ASM2d model was validated using independent experimental results of a lab-scale SMBR monitored under steady-state conditions. The SMBR-ASM2d model parameters estimated in the SMP batch experiments (f_{BAP}, $k_{h,BAP}$, f_{UAP} and $k_{h,UAP}$) were directly used. Most ASM2d-related parameters were adapted directly from a calibrated ASM2d SMBR model. First, the yield of X_H and X_{PAO} growth had to be adjusted according to the COD mass balance. In SMBR-ASM2d, a portion of the influent substrate COD is directed to UAP production, allowing additional X_H and X_{PAO} production from UAP. This can be easily compensated by decreasing their yields (Y_H and Y_{PAO}) from 0.625 to 0.57 using Eq. (8). The validity of this approach can be demonstrated by the fact that in this way the same simulated sludge concentrations are obtained in the ASM2d and SMBR-ASM2d (Table 3).

$$Y_{SMBR-ASM2d} = Y_{ASM2d} / (1 + f_{UAP}) \quad (8)$$

In the previous ASM2d model calibration, the default ASM2d parameters had to be adjusted to improve the anaerobic VFA (Volatile Fatty Acids) uptake and aerobic phosphorus uptake. However, the production of UAP in the SMBR-ASM2d model delayed the fermentation process (VFA production) and enabled restoration of some PAO-related parameters ($\eta_{NO,PAO}$ and q_{fe}) to their default ASM2d value.

3.6. Predicting the impact of SMP concentration and filtration flux on SMBR fouling

The impact of SMP on SMBR fouling can be illustrated using the developed model. Filtration behaviors at two SMP concentrations (50% and 150% of reference conditions, 129 mg COD/l) are simulated in Fig. 5.

A TMP of 20 kPa is assumed as an upper limit for chemical cleaning TMP. Under the reference conditions (C_b = 129 mg/l, J = 33.5 l/(m^2 h)), it takes 35 d for the TMP to reach 20 kPa. Halving the SMP to 64.5 mg/l allows the SMBR to operate for 65 d without chemical cleaning. However, a 50% increase in the SMP concentration (194.25 mg COD/l) decreased the chemical cleaning interval to only 25 d Similarly, filtration behaviours at two filtration fluxes (50% and 150% of reference conditions, 33.5 l/(m^2 h)) are simulated in Fig. 6. Under the reference conditions (J_G = 33.5 l/(m^2 h), C_b = 129 mg/l), it takes 35 d for the TMP to reach 20 kPa. Halving the

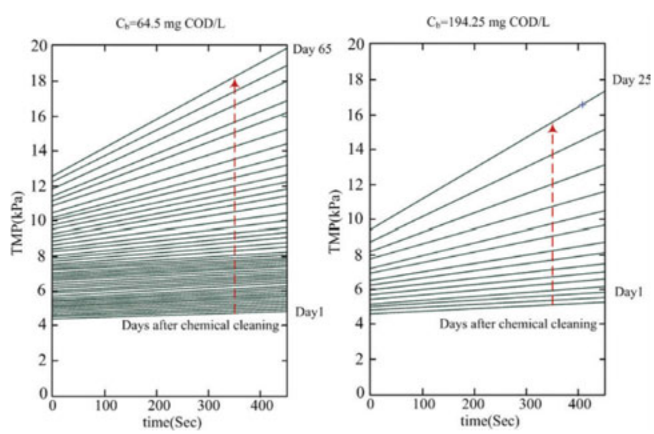

Fig. 5. Simulating the impact of SMP concentration on TMP increase and chemical cleaning under constant flux conditions (J_G = 33.5 l/(m^2 h)).

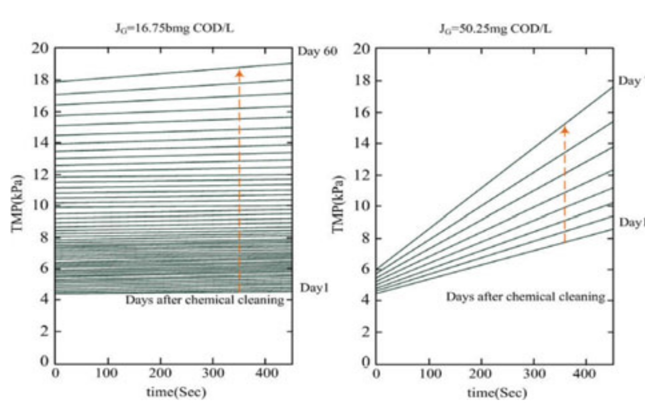

Fig. 6. Simulating the impact of filtration flux on TMP increase and chemical cleaning under constant SMP concentration conditions.

flux to 16.75 l/(m^2 h) allows the SMBR to operate 60 d without chemical cleaning. A 50% increase in flux (50.25 l/(m^2 h)) decreased the chemical cleaning interval to a mere seven d. Comparing the significance of SMP concentration and filtration flux on the chemical cleaning frequency showed interesting results. Given the same SMP mass flux delivered to the membrane ($C_b J_G$, 64.75 × 33.5 vs. 129 × 16.75 mg COD/h), decreasing filtration flux allows the SMBR operating 60 d without chemical cleaning, while decreasing bulk SMP concentration only extended the chemical cleaning frequency to 65 d. Clearly, filtration flux has a higher impact than SMP concentration. This can be attributed to the fact that a lower flux reduces the particle permeation velocity and consequently reduces the likelihood of SMP deposition. Thus, reducing flux reduces the percentage of foulants (SMP) that can actually reach the membrane in addition to decreasing filtration volume. However, reducing SMP concentration has no direct impact on hydrodynamic conditions.

3.7. Simulation model of Sludge Characteristics

The sludge characteristics of the SMBR for synthetic municipal wastewater are also determined using a three dimensional simulation model of *Z*, MLSS and J_c based on BPNN (MATLAB the language of Technical Computing) [25]. This provided a feasible way for on-line control of the process. The topological architecture of BPNN illustrated in Fig. 7 shows a three-level network comprising five nodes in the input layer, four nodes in the hidden layer and three nodes in the output layer. Each node was a BP neuron. Epoch was 5036. For debugging and perfecting the program, experimental and BPNN values were compared. As shown in Fig. 8, the theoretical values compared almost perfectly with the experimental values. The results of interactive program debugging showed that a better approximation can be achieved through the introduction of nodes in the network hidden layer which represent unobserved state variables. The mean square error (MSE) was 0.001265.

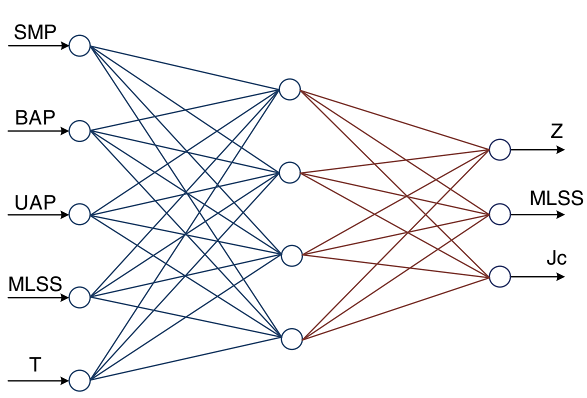

Fig. 7. Topological architecture of the BPNN model.

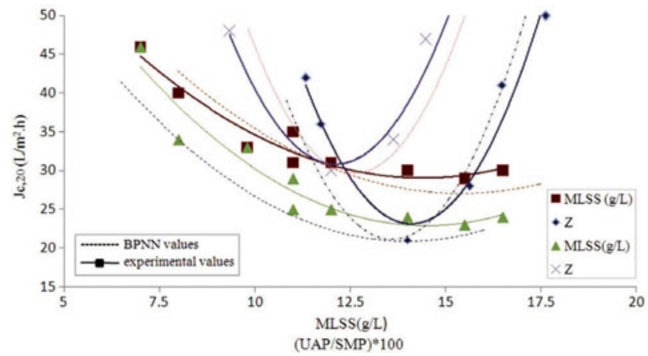

Fig. 8. Comparison of experimental and BPNN values.

The model was based on the reactor running at a HRT of 7 h, a SRT of 40 d and a temperature of 20°C. Under these set conditions, the optimums prediction of the critical flux of the SMBR were *Z* and MLSS, when that SRT were 15, 40 d, critical flux were 29 and 21 l/m^2 h respectively.

The prediction critical flux conditions determined from the simulation model shown in Fig. 8 are consistent with the experimental values and thus further strengthen our conclusions. This indicated that the simulation model based on BPNN is practical. Thus, choice of sludge characteristics and prediction of critical flux in the SMBR can be determined using such BPNN models. Furthermore, the simulation model can be used to control the operational parameters for obtaining the best effluent quality of the SMBR treatments.

4. Conclusions

The ASM2d model was extended to SMBR-ASM2d, introducing only four additional parameters. Care was taken in minimizing model complexity and parameter correlations, and as a consequence model parameter estimation resulted in reasonable confidence intervals. Finally, the SMBR-ASM2d model was successfully validated using independent experimental results of a lab-scale SMBR under steady-state conditions. Filtration flux has a higher impact on membrane fouling than SMP concentration, which is attributed to the fact that reducing flux reduces the percentage of foulants (SMP) that can actually reach the membrane in addition to decreasing filtration volume. The results showed that the critical flux measured by the stepwise flux method was almost related to UAP/BAP ratio. Therefore, it is suggested that UAP/BAP ratio be used as a new filterability index for SMBR processes in wastewater treatment.

The objective of this study was to establish a simulation model, and also to determine the optimal prediction critical flux and criteria for the operation of the SMBR. This study indicated that the simulation model based on BPNN is practical. Thus, choice of sludge characteristics and prediction of critical flux in the SMBR can be determined using such BPNN models. Furthermore, the simulation model can be used to control the operational parameters for obtaining the best effluent quality of the SMBR treatments. SRT is the key operational parameter controlling the predicted SMP concentration and eventually influencing SMBR fouling. A lower SRT increased the UAP concentration, but decreased the BAP concentration and vice versa. Modeling results are showing the sustainability of replacing sub-critical flux with critical flux in long term operation based on SRT variation.

Symbols

CTOC — Colloidal total organic carbon
EPS — Extracellular polymeric substances
TMP — Transmembrane pressure
J_c — Critical flux (l/m^2 h)
$J_{c',20}$ — Critical flux at 20°C (l/m^2 h)
LC-OCD — Liquid chromatography-organic carbon detection
ASM — ASM activated sludge model
BAP — Biomass associated products
UAP — Utilization associated products
f_{BAP} — fraction of BAP produced during cell lysis
f_{UAP} — fraction of UAP produced during substrate uptake
K_{BAP} — half-saturation coefficient of BAP
S_{NH} — Ammonium nitrogen
S_{NO} — Nitrate plus nitrite nitrogen
μ_{BAP} — biomass growth rate on BAP
S_{PO} — Phosphate phosphorous
S_F — Readily (fermentable) biodegradable substrate
S_I — Inert, non-biodegradable organics
X_H — heterotrophic biomass concentration
X_S — slowly biodegradable COD
X_I — inert particulate COD
X_0 — MLSS concentration
$k_{h,BAP}$ — hydrolysis rate of BAP
$k_{h,UAP}$ — hydrolysis rate of UAP
r_{SBAP} — production/consumption rate of BAP
r_{SUAP} — production/consumption rate of UAP
UAP_{PT} — protein content of UAP
UAP_{sto} — UAP produced during substrate storage phase
UAP_{PS} — polysaccharide content of UAP
UAP_{pro} — UAP produced during cell proliferation phase
UAP_{COD} — UAP as COD unit

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