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Appraisal of super-fast membrane bioreactors by MASM – A new activated sludge model for membrane filtration

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Abstract: The structure of existing activated models is inherently deficient in reflecting the major role of the membrane filtration. This study developed and proposed a novel model, MASM, for the membrane activated process. The effective filtration size imposed by the membrane module, entrapping larger size particles was adopted as the basis of the proposed model. The model defined a modified COD fractionation, accounting for the captured COD fractions as additional model components and utilizing related mass balance relationships. It was implemented for testing the fate of soluble hydrolysable COD and system performance of super-fast membrane activated sludge based on real data for the characterization and process kinetics of domestic sewage and denim processing effluents. Model evaluation was carried for parallel systems with gravity settling and membrane filtration operated at a sludge age range of 0.5-2.0 d. Results reflected significantly better performance of super-fast membrane activated sludge system for both wastewaters, underlining that it was crucially important to account for the captured COD fractions to provide an accurate evaluation of system behavior and effluent quality. This should also be identified as the major shortcoming of the ASM models for evaluating and predicting system performance of activated sludge configurations with membrane separation.

Keywords MASM, new model for membrane activated sludge system; super-fast membrane activated sludge; particle size distribution; modified COD fractionation; captured COD fractions.

1. Introduction

Membrane filtration of biomass should be recognized as a cutting-edge landmark that would perhaps reshape the future of the activated sludge process. It took over the function of gravity settling which accompanied the process since its discovery [1]. Gravity settling has always been the weak spot of the process mainly because, it could not cope with excessive biomass escape under conditions of filamentous bulking; it imposed limitations restricting biomass concentration in the reactor and most important, it distorted system design, where the main concern was to sustain good settling conditions for biomass based on empirical experience, often leading to higher footprints [2]. The membrane bioreactor, (MBR), with a membrane module replacing the gravity settling tank, liberated

the system from all constraints simply by uncoupling the hydraulic retention time (HRT) and the sludge age (SRT) in a much smaller footprint.

While it was originally conceived for the activated sludge process, the "*bioreactor*" part of the MBR system was greatly diversified in recent years, as a result of the creativity and inspiration of massive experimental studies: Nowadays, moving bed MBRs; membrane adsorption reactors; membrane coagulation reactors; vertical submerged MBRs; submerged rotating MBRs; Anammox MBRs; anaerobic MBRs, etc., have been proposed as MBR systems with different biological reactor alternatives [3-8]. It seems now that the term MBR has become quite ambiguous, since it does not specify the bioreactor configuration accompanying the membrane module. Therefore, activated sludge configuration with a membrane module should be differentiated from other alternatives as *membrane activated sludge*, (MAS). Furthermore, development of these process modifications was largely based on empirical experience; while such techniques, coupled with common sense and ingenuity were successful for the specific cases where they were utilized, they still require a rational mechanistic description to provide a reliable basis of evaluation.

The MAS system enabled total entrapment and control of biomass in the reactor. This ability was initially utilized for system operation at much higher sludge age levels with equally high biomass concentrations in the range of 10.000 – 50.000 mg/L [9]. This type of MAS systems with extended aeration was mostly tested for effective nitrogen removal [10,11]. Later, it was soon recognized that MAS also offered a stable system operation at much lower SRT values as excessively high rate systems. The concept of high rate activated sludge was first emerged in the forties, based on accidental observations of high BOD removal rates even when the aeration time was reduced to 2.0 hours[12]; however, its implementation did not prove satisfactory during that period, mostly due to sludge settling problems. The advent of MAS revived this concept: Initial studies with MAS systems sustained at a STR range of 0.25 to 5.0 days, reported COD removal efficiencies above 95% with stable system operation[13,14]. Later, numerous studies conducted with different substrates such as, readily biodegradable mixture, acetate, starch, peptone mixture and settled sewage, indicated that complete removal of biodegradable substrate could be achieved at SRT levels below 2.0 days[15-17]. They essentially proved that operation at high SRT values was simply a useless luxury for MAS systems.

Evolution of activated sludge modeling (ASMs) served as a tremendous asset for exploring and interpreting the waste array of biochemical mechanisms taking place in the mixed culture; adoption of COD as the major parameter for all substrate and biomass components; identification of COD fractions with different biodegradation characteristics and experimental support of respirometry enabled to harness and control the composition of the microbial community for performing the required metabolic functions through implementation of relevant models[18-20]. However, existing models simply overlooked the size distribution of substrate and involved only a single size threshold of 450 nm for differentiating "*particulate*" and "*soluble*" fractions. This modeling approach, while quite successful for conventional activated sludge configurations with gravity settling, becomes obsolete for MAS systems simply because the applicable size threshold drops down to the

effective filtration size of the selected membrane. This is a drastic change that would affect applicable COD fractionation, mass balance and model structure. It also underlines the need for reshaping ASMs because they would greatly distort and undervalue the behavior and performance of MAS systems.

In this context, the main objective of the study was to define a new model, MASM, for membrane activated sludge configurations based on a modified COD fractionation and particle size distribution. The objective of the study also involved to provide an accurate image for the microbial processes taking place in *super-fast membrane activated sludge systems*, (SFMAS), for organic carbon removal through implementation of the new model for domestic sewage and textile wastewater.

2. Materials and Methods

2.1. Conceptual approach

The effect of the membrane module on activated sludge modelling can best be recognized with a full insight of relevant experimental tools. These tools are currently used to understand the complex nature of organics (COD) in wastewaters as well as to assess model components and process kinetics used in the model structure; they mainly involve respirometric analysis, COD fractionation and particle size distribution, all leading to accurate mass balance of significant model components.

2.1.1. COD fractionation

The key feature of COD fractionation is the possibility that each fraction may be interpreted with a specific process kinetics when introduced into ASM models. The assessment of specific kinetics by respirometric techniques should perhaps be regarded as one of the major achievements to understand substrate behavior in biological systems [21].

Nowadays, the observation of the oxygen uptake rate profile (OUR) serves as the specific fingerprint of the wastewater for identifying its COD fractions and the coefficients of the process kinetics involved [22]. Direct experimental methods based on COD balance also enabled to quantify inert COD fractions and residual metabolic products [23,24]. This way, ASMs are now structured to include four "soluble" COD components below the size threshold of 450 nm, which could be differentiated with different biodegradation characteristics: They are identified as readily biodegradable COD, S_S; soluble hydrolysable COD, S_H; initial inert COD, S_I and residual soluble microbial products, S_P; the first three COD fractions essentially define the COD content of the influent wastewater stream and the fourth, S_P is generated as part of the biochemical reactions in the reactor. S_H was incorporated later into ASMs, in view of the significant difference in the rate of hydrolysis when compared with that of its particulate counterpart, the slowly biodegradable COD, X_S [25,26].

2.1.2 Particle size distribution

There is an obvious relationship between biodegradation properties and particle size of organic matter. Existing activated sludge models provided a much better understanding of biodegradation by means of COD fractionation, largely overlooked the significance of particle size distribution, PSD. Recently, the concept of PSD was revived and used for exploring major parameters such as COD, total organic carbon (TOC), color, protein and carbohydrates by means of a new procedure involving a sequential filtration/ultrafiltration from 1600 nm all the way down to 2 nm. This procedure offered a specific size fingerprint of the selected parameter and widely applied to domestic sewage and different industrial wastewaters [27-31]. Lately, a few pioneering studies implemented PSD analysis together with oxygen uptake rate measurements, in order to couple particle size with COD fractionation [32-34]. In this context, the experimental work was particularly significant, as it revealed a new aspect related to the fate of S_H in biological treatment: The PSD analysis of the influent stream indicated a small fraction of 5 mg/L between 220-450 nm size bracket. After biological treatment, S_H was observed to increase to 20 mg/L in the same size range. This finding could only be explained by sequential hydrolysis of a fraction of slowly biodegradable particulate COD, X_S into S_H.

2.2. Model structure

This study was essentially designed to address the following question: "Is a new model needed for assessing the fate of organic carbon (COD) in membrane activated sludge systems? Why?" It is unfortunate to note that related work mostly avoided this question, because they remained limited with empirical observations. This section will confirm and justify this need by uncovering radical changes imposed on major modeling concepts by replacing gravity settling with membrane filtration in the activated sludge process:

As a brief preamble, membrane activated sludge process, (MAS), is a device that provides retention and recycling of biomass, just like the gravity settling unit in the conventional activated sludge process (CAS). The gravity settling is conceived as a unit that retains all particles with a size higher than 450 nm, whereas the retention threshold of the membrane module is much lower and it goes even lower than the nominal pore size of the membrane filter due to cake layer formation. This change in the applicable size threshold reflects on modeling as a radical change in the selection of new model components – i.e. COD fractionation in the case of organic carbon removal. In CAS modeling, particulate and "soluble" compounds are differentiated by the arbitrary size threshold of 450 nm, which also defines biomass; however, MAS modeling should account for and adopt as additional model components entrapped fractions of a number of COD fractions, namely, $S_{H\_}$ S_I and $S_{P,}$ because these entrapped fractions will all be subject to a different mass balance controlled by sludge age.

2.2.1. Effective filtration size

At this point it is important to revisit the implication of 450 nm, the sole size threshold incorporated in existing ASMs. First, it is the filtration size to define suspended solids/biomass in wastewaters and biological reactors. This way it is used to differentiate particulate fractions that can be sustained in the reactor from soluble fractions of the treated wastewater escaping the system through the effluent stream. Therefore, soluble COD covers a wide range of particle size below 450 nm and existing ASMs define the total effluent soluble COD, S_{TE}, in terms of the remaining portion of the soluble hydrolysable COD, S_{HE}, after biodegradation; the initial soluble inert COD, S_I, and residual soluble microbial products, S_P; the readily biodegradable COD, S_S, would be most likely completely depleted and not detected in the effluent.

Membrane filtration completely changes this basic framework: First of all, the size threshold of 450 nm will be totally obsolete, as the pore size of membranes used MAS systems are usually in the ultrafiltration range and much smaller than 450 nm, offering a far greater capture potential for soluble COD fractions. Furthermore, in a MAS reactor, an effective filtration size would be created through the operation of the system at a level lower than the actual pore size of the membrane unit, due to additional cake filtration effect induced by biofilm formation on the surface of the membrane [33,35].

The effect of biofilm formation on the effective filtration size was observed in many cases: In a study, which investigated kinetics of acetate utilization by superfast membrane reactor, (SFMBR), the effective filtration size was reduced to approximately 8-13 nm range from the nominal filter size of 20 nm; the system completely removed acetate and generated S_P exhibiting a bi-modal distribution of >13 nm and <2 nm. 12-17 mg/L of S_P was lost in the effluent and the remaining 1-2 mg/L was entrapped by the membrane and accumulated in the reactor [15,16]. The entrapped fraction of S_P exhibited a slight increase from 1-2 mg/L to 3-6 mg/L with higher hydraulic retention time in a slightly earlier SFMBR study, conducted on the same system fed with a readily biodegradable COD mixture [36]. Sözen et al [17] investigated the energy conservation potential of SFMBR equipped with a 40 nm ultrafiltration membrane using settled sewage. They also observed the same range of 8-13 nm for the effective filtration size. Permeate COD levels were measured as 42, 35 and 33 mg/L, all including 18 mg/L of initial inert COD, S_I, for sludge ages of 0.5, 1.0 and 2.0 d, respectively; entrapped COD remained in the range of 3.3-4.8 mg/L. In another study on the biodegradation kinetics of black and grey fractions in segregated domestic sewage, effective filtration size was observed to be in the range of 8-14 nm for black water and 5-8 nm for grey water, regardless of the fact that the MBR used for the study included a membrane with a nominal filter size of 400 nm [33].

In this context, the membrane module coupled to an activated sludge configuration induces a radical change for the size threshold of 450 nm implemented for differentiating

COD fractions, bringing it down to the effective filtration size, which was determined as 8-13 nm in related experimental studies.

2.2.2. Modified COD fractionation and mass balance

COD fractionation is well reported in the literature: It basically identifies COD fractions with different biodegradation characteristics in wastewaters. Related experimental assessment relies on model calibration of the oxygen uptake rate profiles, (OUR), obtained for the selected wastewater [37]. Direct methods also supplement respirometry for the determination of inert COD fractions and residual microbial products [23,24]. This way ASMs are now structured to include four "soluble" COD components below the size threshold of 450 nm, namely, readily biodegradable COD, S_S; soluble hydrolysable COD, S_H; initial inert COD, S_I, and soluble residual microbial products, S_P; the first three COD fractions essentially define the COD content of the influent wastewater stream and the fourth, S_P is generated as part of the biochemical reactions in the reactor. S_H was incorporated later into ASMs, in view of the significant difference in the rate of hydrolysis when compared with its particulate counterpart, the slowly biodegradable COD, X_S [25,26]. In addition to X_S, ASMs also include, active biomass, X_H, initial inert particulate COD, X_I and particulate residual metabolic products, X_P as particulate components.

Membrane separation in MAS systems will induce a major change in the soluble range (> 450 nm) of COD fractionation, where the soluble hydrolysable COD, S_H is usually the major COD fraction. The decrease of the traditional size threshold of 450 nm down to the effective filtration size, will impose a compulsory subdivision of S_H into two new COD fractions: S_{HC}, which will be entrapped by the membrane and captured in the reactor, and S_H, the portion in smaller size than the effective filtration size. The remaining part of S_H after the hydrolysis reaction in the reactor, S_{HE} will by-pass the membrane module with the effluent. Similarly, the soluble inert COD, S_I will be split into S_{IC} and S_I fractions. The readily biodegradable COD, S_S will not be affected by the effective filtration size because it is located at the far end of the size spectrum.

Obviously, S_{HC} and S_H will be subject to the same reaction kinetics for hydrolysis. However, MAS systems will impose totally different mass balance for these two fractions, which will have significant impact on process performance. The fate of S_{HC} accumulated in the reactor will be defined by the following mass balance equation:

$$QS_{HC1} - P_{SHC} + V\, r_{SHC} = 0 \quad (1)$$

Where, P_{SHC} is S_{HC} discharged with excess sludge, and r_{SHC} is the rate expression for hydrolysis.

This equation clearly explains why the behaviour of S_{HC} that remains in the reactor will be just like slowly biodegradable particulate matter, X_S. Therefore, S_{HC} basically becomes a part of sludge and P_{SHC} can be expressed as:

$$P_{SHC} = \frac{V\, S_{HC}}{\theta_X} \quad (2)$$

Equations (2) and (3) provide clear indication that S_{HC} would be controlled in the reactor by the sludge age. A similar differentiation would be applicable and necessary for soluble residual COD fractions, S_I and S_P, in terms of prediction of system performance.

Similarly, the following mass balance equation defines the fate of S_H that would escape the system with the effluent stream:

$$QS_{H1} - QS_{HE} + V\, r_{SH} = 0 \quad (3)$$

This equation applies to all activated sludge configurations and clearly shows that the magnitude of S_{HE} is controlled by the hydraulic retention time, HRT, selected for system operation.

2.2.3. Model description

The basic concepts summarized above were used to define the structure of the new model, MASM, applicable to membrane activated sludge configurations: The model structure essentially involved the template of ASM1 for organic carbon removal, modified for endogenous decay [36,38]. Obviously, it reflected a modified COD fractionation, which also accounted for S_{HC} and S_{IC} as model components. As can be visualized in Table 1, which gives the usual matrix format, MASM included the modified COD fractions, namely, $S_{IC;}$ $S_{I;}$ $S_{SS;}$ S_{HC}; S_H; $X_{I;}$ X_S - in the wastewater as model components. Soluble and particulate residual microbial products, S_P and $X_{P,}$ were also defined in terms of endogenous respiration with the simplifying assumption of a decay associated generation process [39]. Obviously, the model template also included active heterotrophic biomass concentration, X_H, and finally, dissolved oxygen concentration, S_O, the basic parameter for the evaluation of the OUR profiles

Moreover, in the light of reported PSD analyses [40], the model also adopted a similar differentiation for the overall particulate slowly biodegradable COD fraction, X_{ST}, differentiating the settleable fraction, X_{SS} from the remaining part, X_S, both undergoing hydrolysis: While the hydrolysis of X_S would directly generate S_S, as assumed in the ASMs, the hydrolysis of X_{SS} was defined to follow a two-step reaction with an initial hydrolysis and conversion into $S_{HC.}$

At this point, it is crucially important to remember that from the pioneering work on modelling by Garret and Sawyer [41], to the ASM series, i.e. ASM1, ASM2, ASM2d; ASM3, etc., all AS models have been biological/biochemical models in nature. They have been also called "biokinetic" models defining mathematical interactions between substrate and the microbial culture/biomass. Thus, their structure, as in Table 1, only included model components, processes, process rates, process coefficients and the stoichiometry between processes. They started from two-process (microbial growth/endogenous respiration) and two-component (substrate/biomass) models and expanded into current multi-component/multi-process models.

Consequently, AS models do not include hydraulic characteristics such as average hydraulic residence time, reactor hydraulics, residence time distributions. These characteristics are only incorporated to the selected model for specific cases, i.e. case studies, where hydraulic configuration of the reactor systems and that of the membrane module are well defined. Therefore, the concept of validation is obsolete for activated sludge models, because they can only be used for calibration with experimental data generated from the wastewater to be treated, i.e. oxygen uptake rate (OUR) profiles, etc., to yield applicable COD fractionation and/or kinetic and stoichiometric coefficients that would be used in model evaluation [42].

It should be noted that model simulations for assessing system performance rely on mass balances established on the basis of process kinetics and reactor hydraulics. Process kinetics is provided by the adopted model calibrated for the selected wastewater. However, reactor hydraulics cannot be properly defined by the hydraulic retention time (SRT = V/Q), which only gives an average value of the *residence time distribution of fluid particles* involved in the real-size reactor. Generally, a completely mixed (CSTR) is used to simulate reactor hydraulics in mass balance. CSTR is an ideal reactor simulating extreme mixing conditions, just like a plug-flow reactor with no longitudinal mixing. Real biological reactors can only be placed between these two extremes. Thus, an accurate account of the *residence time distribution* in the biological reactor can only be obtained by using 3-4 CSTRs in series [43].

In this study, the activated sludge configuration for modeling was created by the SUMO program [44]. The configuration involved three CSTRs that were linked to each other and at the end of the process a point separator acting as a membrane module. From point separator, the return activated sludge was linked to the first CSTR compartment and the waste activated sludge was separated for dewatering. The flowrate of the system defined as 10000 m^3/d where the magnitude of recycled activated sludge flow rate (RAS) remained variable for different runs. Figure 1 displays the process configuration used in modeling.

The simulation using the proposed model was carried out by means of SUMO software. Since SUMO is a processor, where related mathematical calculations are reflected with 100% accuracy. Before the simulation, the model was calibrated with the oxygen uptake rate (OUR) profiles generated with the selected wastewater. In previous studies, the standard deviation of the OUR measurements was assessed as 3%, a level, which is the same as that of COD analysis [45].

Table 1. Matrix representation of the new model for membrane activated sludge

Model components → / Process ↓	S_I	S_{IC}	X_I	S_S	S_H	X_S	S_O	X_P	S_P	X_{SS}	S_{HC}	X_H	**Process rate**
Growth of X_H				$-\frac{1}{Y_H}$			$-\frac{1-Y_H}{Y_H}$					1	$\hat{\mu_H}\frac{S_S}{K_S+S_S}X_H$
Hydrolysis of S_H				1	-1								$k_{hS}\frac{S_H/X_H}{K_{hS}+S_H/X_H}X_H$
Hydrolysis of S_{HC}				1							-1		$k_{hS}\frac{S_{HC}/X_H}{K_{hS}+S_{HC}/X_H}X_H$
Hydrolysis of X_S				1		-1							$k_{hX}\frac{X_S/X_H}{K_{hX}+X_S/X_H}X_H$
Hydrolysis of X_{SS}										-1	1		$k_{hX}\frac{X_{SS}/X_H}{K_{hX}+X_{SS}/X_H}X_H$
Decay							-(1-f_S-f_X)	f_X	f_S			-1	$b_H X_H$
Parameter	COD	COD	COD	COD	COD	COD	O_2	COD	COD	COD	COD	Cell COD	

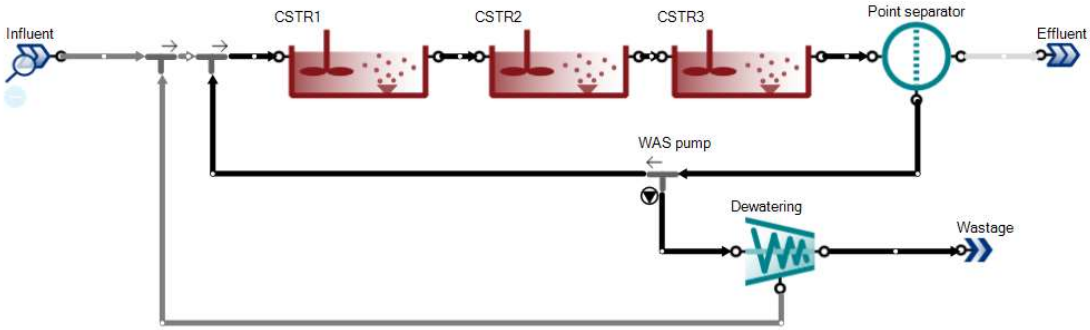


Figure 1. The SUMO configuration used in modeling

2.3. Model components and process kinetics

Modified COD fractionation associated with domestic sewage and textile wastewater was defined based on reported data in studies, which conducted parallel experimental work on the assessment of COD fractions by respirometry coupled with PSD analysis [28,40]. Modified COD fractions were also incorporated into the model structure as model components. This approach was a prerequisite for providing an accurate and reliable information concerning the fractions for soluble COD components that would be entrapped and captured in the reactor by means of membrane filtration. The modified COD fractionations characterizing selected wastewaters are given listed in Table 2.

A detailed literature survey was carried out for the kinetic coefficients defining process kinetics for the selected wastewaters. Values adopted for model evaluation generally approximated the average levels, indicated by the experimental data suggested in the literature for each type of wastewater, as listed in Table 3. It should be noted that the textile industry embraces various categories based on fabrics and processes involved, each generating a specific type of wastewater, quite different from one another. In this context, kinetic coefficients defining denim processing were adopted, since the characterization and particle size distribution given in Table 2, also related to the same textile category. The heterotrophic yield coefficient, Y_H, was adopted as 0.64 mg cell COD/mg COD for domestic sewage and 0.69 mg cell COD/mg COD for textile wastewater. Soluble and particulate residues of endogenous respiration, f_S and f_X were selected as 0.05 and 0.10, respectively [46,47].

In this context, the values reported in Table 2 and 3 essentially reflect the calibration of the proposed model, MASM, using the real data collected from the literature, since they were derived from the experimental characterization of the selected wastewaters.

Table 2. Modified COD fractionation for domestic sewage and textile wastewater

Wastewaters → / Parameters ↓	Domestic [40]	Textile [28]
Total COD (mg/L), C_{T1}	415	1340
Total soluble COD (mg/L), S_{T1}	120	965
Total particulate COD (mg/L), X_{T1}	295	375
Readily biodegradable COD (mg/L), S_{S1}	40	280
Total soluble hydrolysable COD (mg/L), S_{HT1}	62	460
Influent soluble hydrolysable COD (mg/L), S_{H1}	15	100
Captured soluble hydrolysable COD (mg/L), S_{HC1}	47	360
Total soluble inert COD (mg/L), S_{IT1}	18	225
Influent soluble inert COD (mg/L), S_{I1}	10	135
Captured soluble inert COD (mg/L), S_{IC1}	8	90
Total particulate hydrolysable COD (mg/L), X_{ST1}	253	360
Influent particulate hydrolysable COD (mg/L), X_{S1}	113	162
Settleable biodegradable COD (mg/L), X_{SS1}	140	198
Total particulate inert COD (mg/L), X_{IT1}	42	15
Influent particulate inert COD (mg/L), X_{I1}	19	7
Settleable inert COD (mg/L), X_{IS1}	23	8

Table 3. Selected values of kinetic coefficients for different wastewaters.

Wastewater type				Dual Hydrolysis				
	$\hat{\mu}_H$	K_S	b_H	k_{hS}	K_{hS}	k_{hX}	K_{hX}	References
Domestic								
	3.5	3	0.2	3.5	0.12	1.7	0.2	[48]
	4.2	3	-	1.6	0.07	0.8	0.04	[49]
	3.5	6	0.2	3.8	0.2	1.9	0.18	[50]
	4	4	0.18	2.8	0.03	1.1	0.1	[51]
	-	-	0.24	3.1	0.2	1.2	0.5	[52]
Selected for model	**4.2**	**3**	**0.2**	**2.96**	**0.12**	**1.34**	**0.20**	
Textile								
	-	-	-	2.5	0.4	0.1	0.5	[52]
	4.1	5	0.18	3	0.05	1	0.5	[53]
	5.3	5	0.14	3	0.05	1	0.2	[53]
	3.6	15	0.14	0.8	0.05	0.5	0.15	[53]
	6	1	0.1	3.5	0.04	0.72	0.04	[54]
Selected for model	**3.6**	**15**	**0.14**	**2.45**	**0.09**	**0.68**	**0.28**	

3. Modeling Results and Discussion

3.1. Basis for evaluation

Two wastewaters were selected for model evaluation, *domestic sewage* and *textile (denim processing) effluents*. Aside from the fact that the selected textile wastewater is much stronger, with a total COD content of 1340 mg/L more than three-fold higher than that of domestic sewage, it involves a totally different character in terms of COD fractionation, which is predominantly soluble, whereas in domestic sewage, particulate COD accounts for more than 60% of the total COD [25,40,55]. Accordingly, soluble total biodegradable COD is 100 mg/L, representing 24% of the total COD in domestic sewage, whereas it is 740 mg/L, corresponding to 55% of the COD content in the textile effluents. This significant difference in the COD fractionation of the two wastewaters was the main reason for their selection, to better emphasize and reflect the merit of both MASM and the performance of SFMAS.

In this context, the proposed model, MASM tested the performance of the MAS operation while a parallel CAS system was evaluated by means of ASM1, modified for endogenous decay. Model assessment of both systems was essentially focused on the impact of two key parameters, i.e. the sludge age, θ_X (SRT) and the hydraulic retention time, θ_H (HRT); it was carried out for a set of different operating conditions (i) In the first step, modeling involved different footprints, i.e. different HRT values for the two systems, usually adopted for design, but the same SRT values; this parameter was varied in different runs within the super-fast system operation. (ii) In the second step, models were implemented using the same HRT value, i.e., the same reactor volume and MLSS level (around 5000 mg/L) for the two systems.

3.2. Fate of soluble hydrolysable COD

Wastewater characteristics reflect a clear indication that the soluble hydrolysable COD fraction, S_H is the key COD component, affecting and controlling organic carbon removal. In fact, it corresponds to around 50% of the total soluble COD, S_T for domestic sewage and the textile wastewater. As far as the merit of the super-fast operation of MAS systems, they emphasize the major impact of the S_{HC} fraction, which accounted for 76% of the total S_{H1} in domestic sewage and 78% in textile wastewater. They also signal the major shortcoming of the existing activated sludge models (ASMs) as they are not structured to differentiate and depict S_{HC} fractions.

3.2.1. AS configurations with different HRT levels

In this step, the design principles and especially, mixed liquor suspended solids (MLSS) recommendations and restrictions were observed both for the SFAS and SFMAS systems. The SRT range adopted for evaluation was changed for each different run between 0.3-2.0 d. First, models (ASM1 and MASM) were implemented with MLSS levels of 4000-4400 mg/L and 10250 – 10500 mg/L for SFAS and SFMAS, respectively, yielding an HRT span

of 0.7-3.2 h for SFAS and 0.2-1.4 h for SFMAS, thus two sets of different reactor volumes and footprints.

Modeling results for achievable S_H removals are summarized in Table 4, which underline a few significant aspects on the behavior of parallel units: For domestic sewage, (i) at HRT values smaller than 1.0 h (SRT < 0.5 d), S_H simply by-passed the reactor with negligible removal; yet the effluent S_{HE} of the SFMAS unit could be reduced down to 14 mg/L, simply by entrapping and capturing the remaining S_{HC} portion in the reactor. (ii) at SRT values between 1.0-2.0 h, SFMAS preformed much better, with significantly lower S_{HE} values below 10 mg/L; this was also related to the captured S_{HC1} fraction, accounted for in the proposed model, MASM. For example, at SRT of 1.0 d, S_{HE} values of 15 mg/L and 8.0 mg/L may be compared for SFAS and SFMAS, respectively. (iii) S_H removal rates remained consistently lower for SFMAS, even though it was evaluated for the influent S_H fraction that escaped entrapment by the membrane. (vi) the modeling results indicated that the SRT level of 2.0 d could be regarded as a breaking point, which secures almost complete S_H removal, regardless of the type of the AS system.

The textile wastewater is much stronger with a total S_{H1} concentration of 460 mg/L, approximately four times higher than its counterpart in domestic sewage. Therefore, the discrepancy of S_H removals between the two systems was much more enhanced and visible, clearly underlining the decisive role of the captured S_{HC1} fraction on the better performance of the SFMAS system. Similarly, hydrolysis of S_H was practically negligible at SRT of 0.3 d, and only partial at SRT of 0.5 d. At SRT values between 1.0-2.0 d, the effluent S_{HE} ranges of 23-33 mg/L associated with the SFMAS units were significantly lower than 42-95 mg/L range obtained with SFAS systems. However, S_H removal rates remained again consistently lower for SFMAS units.

3.2.2. AS configurations adjusted to same HRT levels

In the second step, HRT levels of parallel systems were fixed at the same values by adjusting the MLSS to around 4.500-5.500 mg/L in both SFAS and SFMAS units. This adjustment induced in a slight HRT decrease for SFAS units and a corresponding HRT increase for SFMAS units in the range of 0.4-2.9 h for domestic sewage, and 1.2-5.0 h for textile wastewater, while SRT levels were maintained in the same bracket of 0.3-2.0 d, which characterizes SFMAS operation.

Model evaluations summarized in Table 5 basically confirmed the earlier results, that no matter how the HRT was selected, the performance of the SFMAS systems were far better, with effluent S_{HE} levels below 10 mg/L at SRT values higher than 0.5 d coupled with higher S_H removal rates.

Modeling of textile effluents highlighted the superior features of the SFMAS system: It showed that SFMAS proved to be successfully applicable to strong wastewaters, bringing

the 460 mg/l of S_{H1} contained in the textile effluent down to 18 mg/L at SRT of 1.0 d, and to 12 mg/L at SRT of 2.0 d compared to 95 mg/L and 50 mg/L in the corresponding AS units with gravity settling. This performance difference was mainly due to the effective filtration size created by the membrane module, which entrapped and captured the S_{HC} fraction.

Table 4. S_H removal in SFAS and SFMAS systems operated for different footprints (different HRTs)

Wastewaters	SRT (d)	AS with gravity settling				AS with membrane			
		HRT (h)	S_{HE} (mg/L)	S_H removal (%)	MLSS	HRT (h)	S_{HE} (mg/L)	S_H removal (%)	MLSS
Domestic									
	0.3	0.7	60	3	4.400	0.2	14	6	10.200
	0.5	1.1	30	52	4.250	0.4	10	33	10.250
	1	2.2	15	76	4.190	0.7	8	53	10.100
	1.5	2.5	13	79	4.050	0.9	7	54	10.100
	2	3.2	9	85	4.000	1.4	5.5	67	10.050
Textile									
	0.3	0.9	457	0.6	4.450	0.7	99	1	10.250
	0.5	2.2	212	54	4.300	0.85	54	46	10.240
	1	3.6	95	79	4.300	1.8	33	67	10.100
	1.5	5	56	88	4.150	2.2	29	71	10.000
	2	5.8	42	91	4.100	2.7	23	77	10.030

Table 5. S_H removal in SFAS and SFMAS systems operated at the same HRT values

Wastewaters	SRT (d)	HRT (h)	AS with gravity settling			AS with membrane		
			S_{HE} (mg/L)	S_H removal (%)	MLSS	S_{HE} (mg/L)	S_H removal (%)	MLSS
Domestic								
	0.3	0,4	60	3	4.800	14	7	5.500
	0.5	0.72	40	35	4.660	9	42	5.440
	1	1.44	25	61	4.520	6	60	5.210
	1.5	2.2	18	74	4.150	4.6	73	5.100
	2	2.9	13	81	4.160	3.4	77	5.150
Textile								
	0.3	1.2	459	0.2	5.210	99	1	5.550
	0.5	2.4	197	57	5.165	27	73	5.470
	1	3.6	95	79	5.020	18	82	5.400
	1.5	4.3	68	85	5.000	15	85	5.210
	2	5	50	89	4.980	12	88	5.100

3.2.3. Impact of HRT on S_H removal

Model evaluation was further extended to better visualize the impact of HRT on achievable S_H removal using again the same parallel reactors. For this purpose, HRT was stepwise increased from 1.0 h to 4.0 h for all system operations at different SRT levels. Results plotted in Figures 2 and 3 provided a clear indication that effluent quality in terms of S_{HE} significantly improved with higher HRT levels: For domestic wastewater, while the performance of SFMAS was superb, always producing S_{HE} levels below 10 mg/L, the one for SFAS significantly gradually recovered as the HRT increased: For example, for SFAS operated at an SRT of 1.0 d, S_{HE} decreased from 28 mg/L at HRT of 1.0 h, to 7.0 mg/L when the HRT was raised to 4.3 h (Figure 2b). Similar observations were confirmed at a much more visible scale for the textile wastewater: All S_{HE} values defined for each of the SRT level associated with superfast AS operation exhibited a substantial decrease when the HRT was gradually increased from 1.0 h to 4.0 h: At an SRT of 1.0 d, for example, the S_{HE} determined as 240 mg/L, showed a stepwise decrease to 165 mg/L; 107 mg/L and 81 mg/L, when the corresponding HRT levels were raised to 2 h, 3.2 h and 4.3 h, respectively.

Furthermore, it should also be noted that the S_{HE} levels, and S_H removal rates associated with SFMAS operation were substantially better than their counterpart in SFAS systems. These observations are far more interesting in confirming the merit of the new MASM model proposed in the study, mainly because the recognition of the S_H fraction captured in the biological reactor as a model component, clearly revealed the shortcomings of the conventional ASM approach in correctly evaluating and predicting the performance of high rate AS systems coupled with membrane filtration.

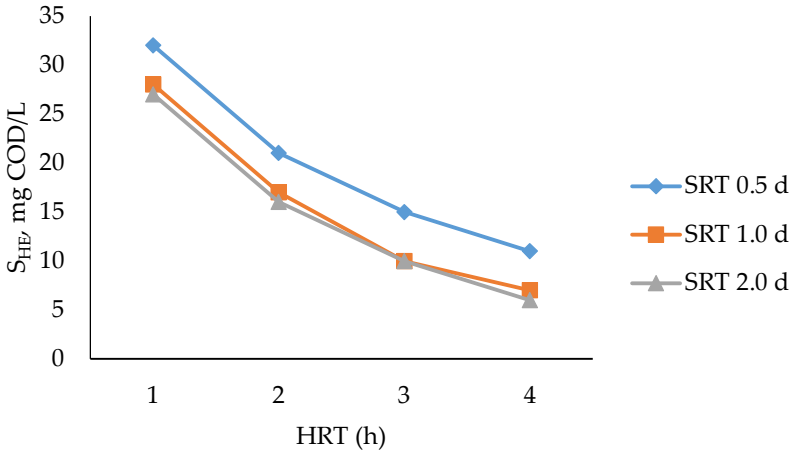
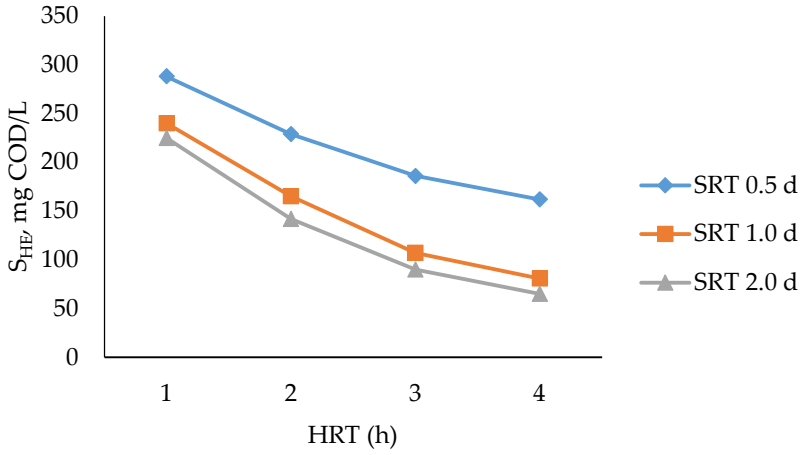
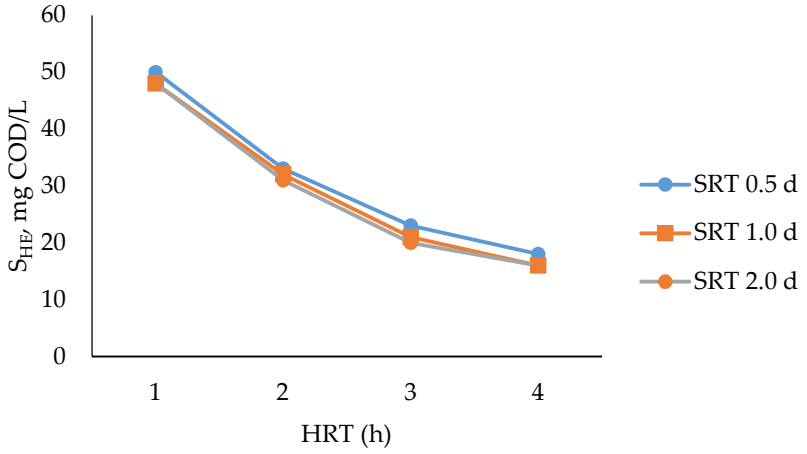


Figure 2. Impact of HRT on S_H removal from domestic sewage using SFAS



(a)



(b)

Figure 3. Impact of HRT on S_H removal from textile wastewater using (a) SFAS; (b) SFMA

3.3. Effluent quality

The second part of model evaluation was devoted to the assessment of effluent quality in terms of all COD fractions involved and performance comparison of super-fast activated sludge operation with and without membrane filtration. The modelling results were plotted for SFAS and SFMAS systems in Figure 4 for domestic sewage and Figure 5 for textile wastewater when the corresponding systems were adjusted to the same HRT levels.

The data displayed in these Figures are quite significant in the sense that they indicate the relative contribution of different COD fractions on the effluent quality under the operation conditions that define super-fast activated sludge configurations; together with S_H, they also reflect the major role of the influent soluble inert COD, S_{I1}, on the influent total soluble COD. Industrial wastewaters are usually characterized by high S_{I1} levels that threaten alone the effluent limitations. In fact, the S_{I1} value given in Table 2 was 225 mg/L

for the selected textile wastewater, compared to only 18 mg/L for domestic sewage. Therefore, it becomes crucially important to account for the captured fraction of S_{II} in SFMAS systems to provide an accurate evaluation of system behavior and effluent quality. This underlines the major shortcoming of the ASM models for evaluating and predicting system performance of activated sludge configurations with membrane separation.

The previous section showed that S_H removal could be optimized by assigning HRT values higher than the design levels associated with smaller footprints i.e. reactor volumes, due to related mass balance indicating the impact of HRT on S_H removal. Therefore, the effluent quality evaluations will be restricted to cases with the same HRT selections for parallel systems. The distribution of effluent COD fractions displayed in Figure 4 revealed significant observations that need to be further emphasized: First of all, they showed that SRT values below 0.5 d could not sustain conditions, which would allow the utilization of the readily biodegradable COD, S_S, for microbial growth; this is quite significant in the sense that the activated sludge configurations could no longer be qualified as biological systems under selected conditions of operation. Complete depletion of S_S could be secured in parallel units at SRT levels higher than 0.5 d. In the SRT range between 0.5-2.0 d, the effluent total COD of the SFMAS units remained below 20 mg/L, half the level that could be achieved with SFAS, due to capture of higher size fraction of S_H and S_I.

The positive attributes of the SFMAS configuration could better be visualized for the textile wastewater characterized with much higher S_{H1} and S_{II} values of 460 mg/L and 225 mg/L, respectively, as compared with domestic sewage. To start with, process modeling showed that it was possible to hold the effluent COD down to the vicinity of 150 mg/L, despite significant leakage of soluble inert COD to the effluent COD. This clearly confirmed the suitability of the membrane activated sludge process operated at extremely high rates to strong industrial wastewaters along with domestic sewage. The data displayed in Figure 5 showed that the discrepancy between the effluent quality of SFAS and SFMAS significantly increased, as the relative magnitude of S_{HE} with respect to the effluent inert COD became more pronounced. The COD difference computed as 126 mg/L at SRT of 2.0 d escalated up to 167 mg/L when the SRT level was reduced to 1.0 d.

Furthermore, activated systems with gravity settling also suffer from biomass escape from the settler, incorporating an additional particular COD load into the effluent. In a review on the performance of such systems, it was reported that the effluent particulate COD fluctuated between 100-200 mg/L when the SRT selected for operation was below 1.0 d [56].

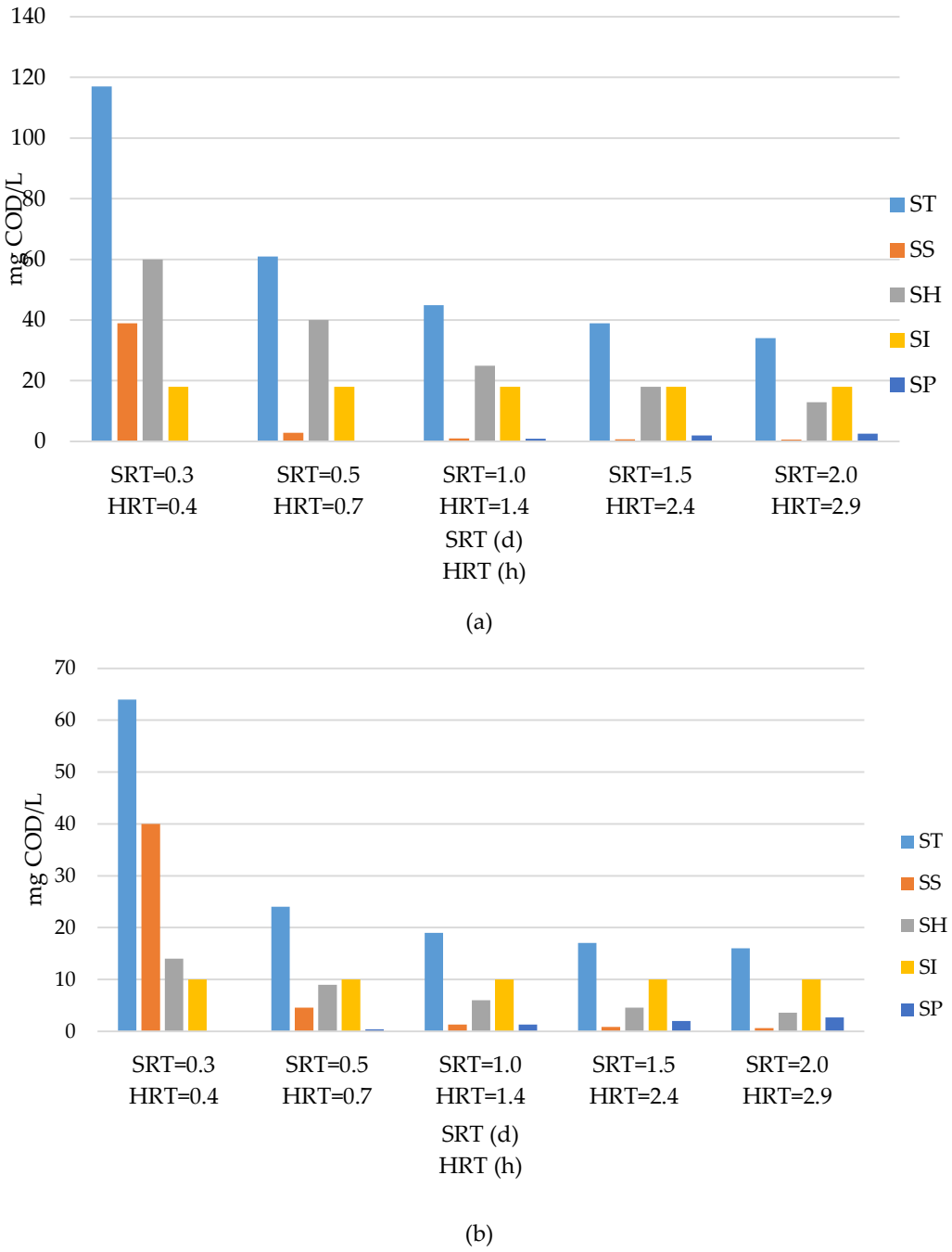
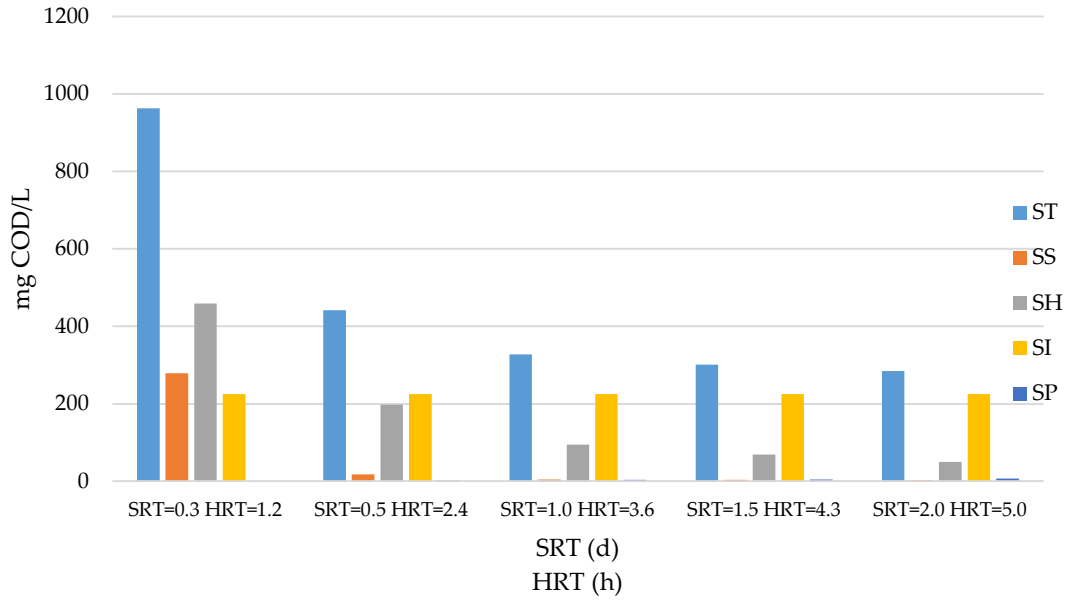
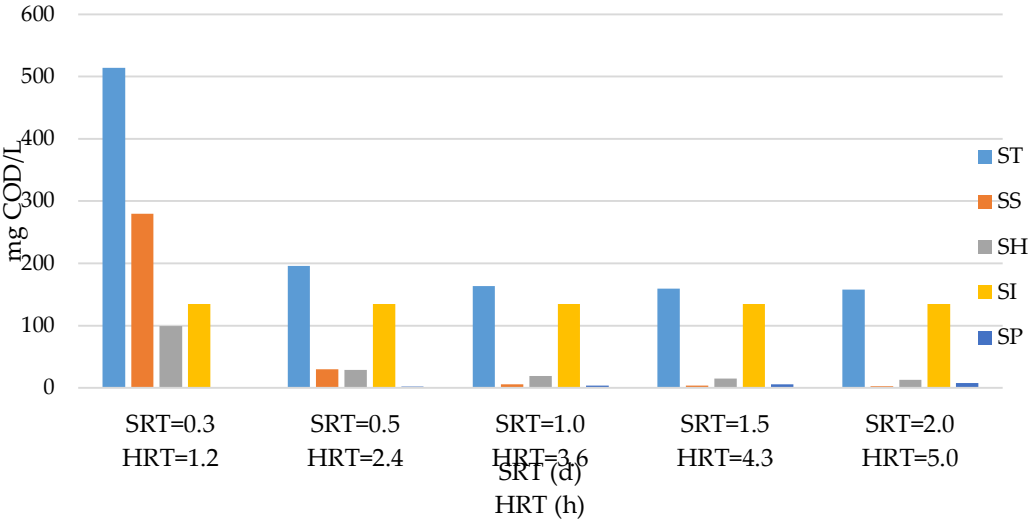


Figure 4. Effluent COD fractionation of domestic sewage for (a) SFAS and (b) SFMAS operated at the same HRT levels



(a)



(b)

Figure 5. Effluent COD fractionation of textile wastewater for (a) SFAS and (b) SFMAS operated at the same HRT levels

3.4. Evaluation of results

Modeling results summarized in the preceding section should be interpreted in two different ways: The first one, adopted in the results section, offers the comparative evaluation of two different activated sludge schemes, one with gravity separation and the other with membrane filtration of the treated effluent. This was a simplistic but useful approach emphasizing the merit of the membrane activated sludge operated at extremely low SRT levels. The second, and a more appropriate one, is to conceive a single *membrane activated sludge* configuration, where the fate of COD fractions and system performance are

evaluated by means of two different models, ASM1 and the proposed model MASM. This approach will essentially provide the answer of the question: "*Why a new model is needed for activated sludge systems with membrane separation?*"

Existing activated sludge models (ASMs) rely on a single size threshold, 450 nm, which basically differentiate COD fractions that would be kept in the reactor, i.e. particulate components, from all soluble COD fractions, remaining after biodegradation, which will leave the system through the effluent stream. This interpretation of *soluble COD* involves a wide particle size range for the distribution of COD fractions such as, soluble hydrolysable COD, S_H and soluble inert COD, S_I. This concept, which essentially defines the structure of ASMs becomes no longer valid and applicable for membrane filtration, which drastically reduces the 450 nm- size threshold down to the *effective membrane filtration size* level. This way, a fraction of S_H and S_I will be entrapped and controlled by the sludge age of the system. Consequently, the membrane activated sludge systems can only be properly evaluated by a new model structured on a modified COD fractionation with related mass balance implications. This is the basic novelty of the proposed model, MASM, which also underlines the shortcomings of the existing ASMs, when applied to MAS systems.

Modeling results also provided conclusive information on the suitability and limitations of SFMAS system in terms of achievable COD removal performance and applicable SRT levels: While the operation at extremely high rates was originally conceived and tested for domestic sewage, they showed that it was also quite effective for the treatment of strong industrial wastewaters, such as the tested textile effluent. It appears that an SRT level of 2.0 d could be accepted as the break-point threshold, i.e. a lower limit, for effective removal of biodegradable COD: This SRT level provide almost complete S_H removal (< 5mg/L) for domestic sewage and lowered the influent S_{H1} value of 460 mg/L down to 13 mg/L for the textile effluent, aside from the entrapment and capture of a significant fraction of the influent soluble inert COD, S_{I1}.

In recent years, it became quite fashionable to test and promote activated sludge systems with gravity settling operated at extremely high rate conditions (HiCAS) at SRT values lower than 0.5 d, presumably for energy recovery: Experimental results were reported for HiCAS operation at an SRT range of 0.1-0.5 d with municipal wastewater [57]; at SRT of 0.41 d with synthetic substrate mixture [58]; at SRTs of 0.24 d and 0.5 d again with synthetic substrate mixture [59]; at SRTs 0.2 d and 0.3 d with chemically enhanced primary treatment effluent [60]. However, the modeling results of this study delivered decisive proof that with the kinetic information so far derived for domestic sewage and textile effluents, microbial growth could not be sustained, mainly because no substrate utilization could take place during the very short retention time - controlled by the selected

SRT - of biomass in the aerated reactor. Therefore, the results clearly suggested that reactors operated at an SRT threshold below 0.5 d could not be considered as biological systems; they would merely serve as holding tanks.

Furthermore, the mass balance expressions related to the model structure clearly identified the decisive role of the selected HRT on the achievable level of S_H removal. While a small footprint is usually recognized as a significant asset for SFMAS systems, a compromise should be considered between better performance and smaller reactor volume.

4. Conclusions

Existing activated models (ASMs) are inherently incapable of reflecting the major role of the membrane filtration on the fate and biochemical reactions in the *membrane activated sludge process*. The structure of the novel MASM was based on the *effective filtration size* imposed by the membrane module, entrapping larger size particles. Hence, the novel model defined a modified COD fractionation, accounting for the captured COD fractions as additional model components and utilizing related mass balance relationships. This way, it was equipped to yield an accurate mechanistic description of microbial reactions taking place in MAS systems.

The calibration of the existing ASM models require experimented data generally derived from respirometry. For the novel model, MASM describing the impact of membrane filtration of the behavior of activated sludge systems, calibration can only be completed with the support of PSD analysis. Thus, *particle size distribution analysis* was introduced by MASM as a new and indispensable experimental tool; it was recommended as an integral complement of respirometry, for establishing size - biodegradation relationships of different COD fractions.

The merit of the super-fast membrane activated sludge in achieving better effluent quality for the treatment of domestic sewage and textile wastewater could be accurately interpreted by MASM in terms of captured fractions of soluble hydrolysable COD, and soluble inert COD.

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