New proposed conceptual mathematical models for biomass viability and membrane fouling of membrane bioreactor

Zuthi, M. F. R[a]., Ngo, H. H.[a,*] , Guo, W. S.[a], Li, J. X.[b], Xia, S. Q.[c], Zhang, Z. Q.[c]

[a]Centre for Technology in Water and Wastewater, School of Civil and Environmental Engineering, University of Technology Sydney, Sydney, NSW 2007, Australia
[b] State Key Laboratory of Hollow Fiber Membrane Materials and Processes, School of Materials Science and Engineering, Tianjin Polytechnic University, Tianjin 300387, P. R. China
[c]College of Environmental Science and Engineering, Tongji University, Shanghai 200092, P. R. China

[*]**Corresponding author, Email:** *h.ngo@uts.edu.au*, **Tel: +61 2 95142745, Fax: +61 2 95142633**

Abstract

The production and accumulation of soluble microbial products (SMP), extracellular polymeric substances (EPS) and colloidal inert compounds within a membrane bioreactor (MBR) may greatly affect the biomass viability and subsequently the permeability of the membrane. This paper aims at presenting new mathematical models of biomass viability and membrane fouling that has been conceptually developed through establishing links between these biomass parameters and operating parameters of the MBR. The proposed models can be used to predict the biomass viability and membrane fouling at any state of operation of MBR. Meanwhile, easily measurable parameters of the proposed model can also serve to estimate SMP/EPS concentration in the supernatant of MBR without the tedious and expensive measurement.

Keywords: Membrane bioreactor, soluble microbial products, colloidal compounds, biomass viability, membrane fouling.

1. Introduction

The cost-effective operation of a membrane bioreactor (MBR) for better effluent while enabling to control membrane fouling greatly depends on the viability of microbial activities within the bioreactor. The biochemical functions of the microbial communities within the MBR evolves by a continuous generation of new sludge soon after the organic feed enters the bioreactor and contacts the biomass (Hasar and Kinachi 2004; Navaratna et al. 2012). There have been a lot of studies evaluating the efficacy of the treatment and fouling control of different MBR systems credited to the particular configuration of the treatment system. Mathematical modelling of different types of MBR has typically been aimed at linking the biochemical functions within the bioreactor based on the know-how of the activated sludge processes. Some models have also linked the physical phenomena of the membrane fouling with the biological sub-model/s. Nevertheless, only a few studies (Hasar et al. 2002; Hasar and Kinachi 2004) were intended to reveal the biomass viability, which is particularly important for the operational control of an MBR for better treatability and fouling control.

Generally, the viability of microbial activities in the mixed liquor suspended solids (MLSS) can be conveniently monitored by the oxygen transfer efficiency within the treatment system. However, controlling the biomass (MLSS) properties that affect the oxygen transfer for the microbial activities is rather complex as biomass is a heterogeneous mixture of particles, microorganisms, colloids, organic polymers and cations, of widely varying shapes, sizes and densities (Germain and Stephenson, 2005). There is also a lack of general consensus about the methods of characterization of the components of MLSS and thus, no single component/s has yet been identified exclusively influencing the oxygen transfer for microbial activities.

The decrease of specific oxygen uptake rate (SOUR) generally corresponds well with the loss of microbial activity associated with the lower substrate utilization rate (Kim et al. 2001). Consequently, this results in higher chemical oxygen demand (COD) concentration in the reactor with increased fraction of colloids present in the bioreactor along with soluble microbial products (SMP) or extracellular polymeric substances (EPS). Therefore, the biomass viability of the activated sludge processes is conventionally monitored by the SOUR of the sludge supernatant of the bioreactor while evaluating its correlation to some other biomass parameters traced at the effluent flow. Hasar et al. (2002), for example, investigated the relationship between the inert COD in the influent and that in the effluent of a submerged MBR (sMBR). They reported that the inert COD in the effluent was higher than that in the influent wastewater which was ascribed to the production of inert compounds by the microorganisms and their progressive accumulation within the bioreactor.

With the growing interest of identifying membrane foulants, it is important to identify the constituents of inert compounds such as SMP/EPS or colloidal compounds which may have direct or indirect impact on biomass viability and membrane fouling as well. Although amount of SMP is negligible compared to the total suspended solids in the mixed liquor, the SMP attached to the suspended solids has a great influence on specific resistance (Lee et al. 2002). The colloidal content in the feed and mixed liquor plays a dominant role in controlling the membrane fouling (Gao et al. 2013). However, a direct correlation between these potential biomass parameters concerning the biomass viability and membrane fouling has yet to be developed. Therefore, this paper aims to propose a conceptual model of the biomass viability considering the potential effects of the SMP and colloidal particles which may also have strong correlation with the model of membrane fouling. The ultimate objective is to develop new conceptual mathematical models of biomass viability and membrane fouling which can be used in an integrated way for the operational control of an MBR.

2. Methods of the Development of Conceptual Models

2.1 Background and State-of-the-art

The mixed liquor volatile suspended solids(MLVSS) and the SOUR have been conventionally used as simple indicators of the biomass viability as the accumulation of inert (non-biodegradable) matter within the bioreactor was commonly observed to increase the MLVSS with time resulting in a reduction of the oxygen uptake rate within the system (Hasar et al. 2002; Hasar and Kinachi 2004). Hasar and Kinachi (2004) proposed an empirical model of the viability of microbial activity in a submerged MBR (sMBR) where the accumulation of inert compounds within the bioreactor was identified affecting the biomass viability with operation time. They proposed empirical mathematical expressions (Eq.1 and Eq. 2) to represent the exponential decay or loss of microbial activity (viability). Hasar and Kinachi (2004) also established important correlations between the microbial viability and the increasing ratio of inert COD in the effluent (Cs) to that in the influent (C_0), and also the ratio of volatile suspended solids to the mixed liquor suspended solid’s concentration (MLVSS/MLSS).

Power function:

$$\mathrm{SOUR}= 1.811*(C_s/C_0)^{-3.12}*(\mathrm{MLVSS/MLSS})^{-1.389} \qquad \text{Eq. 1}$$

Exponential function:

$$\mathrm{SOUR}= 1.33 + \exp\,(7.245-4.832*(C_s/C_0)-2.526*(\mathrm{MLVSS/MLSS}) \qquad \text{Eq. 2}$$

The empirical model, however, did not consider the relative contributions of the individual fractions of inert compounds (e.g. microbial products, colloidal components) to the biomass viability. Although the parameters presented in the model are useful indicators of the biomass viability, these cannot be linked directly to the physical sub-model of the membrane fouling.

Many researchers acknowledged the inhibitory effect of SMP on microbial activity (Table 1), and the SMP has also been identified as one of the major foulants responsible for irreversible membrane fouling. However, there is no unambiguous method of measurement of SMP/EPS to characterize the biomass and the available methods are too complex to be adopted in general practice. Hence, the trend in many scientific studies is to investigate DOC (dissolved organic carbon), COD or TOC (total organic carbon) in the mixed liquor supernatant to represent SMP and EPS concentrations. Soluble COD in the supernatant (COD_{ss}) which was likely to be SMP had significant impact on cake formation rate, and the significant difference between COD_{ss} and COD_{sp} (soluble COD in the permeate) suggested that membrane retained some of the high molecular weight SMP (Lin et al. 2010). The authors concluded that the SMP in the COD_{ss} might have served as the binding sites for sludge cake formation. Wu et al. (2012) modelled specific cake resistance as the cake consolidation process due to the entrapment of colloidal material within the cake layers which could explain the acceleration of cake resistance and the increase of transmembrane pressure (TMP) in the MBR. The cake layer was assumed to be formatted by MLSS and consolidated by the entrapment of colloidal components, resulting in a decrease in cake porosity and subsequent increase in specific cake resistance.

Table1. Studies on the effect of SMP on microbial activity

In the following section, the new proposed conceptual model of biomass viability presents effective correlations of SOUR with MLSS/MLVSS and total/soluble

COD in the bioreactor's supernatant and effluent. The model of biomass viability is subsequently linked to the predicted rejection efficiency of the membrane at the actual fouling state using the parameters such as MLSS and SMP/EPS concentration in the supernatant and TMP.

2.2 New Conceptual Model of Biomass Viability

The literature review in the previous section suggests that the accumulation of colloidal and soluble products developed from microbial metabolism may develop progressive effects on biomass viability and membrane fouling as well. As already discussed in the review, the SMPs were commonly observed to inhibit microbial growth in the activated sludge processes. The proposed model, therefore, includes SMP in the bioreactor as the main parameter affecting the biomass viability. The model also considers that the accumulation of colloidal inert compounds in the mixed liquor also affects the biomass viability. Both of these fractions of inert compounds are considered in the proposed conceptual model of biomass viability including as well the common indicators such as the ratio of MLVSS/MLSS and the SOUR. The proposed models consider soluble COD in the effluent (COD_{sp}) as a reflective parameter of SMP (within the bioreactor) part of which is retained on the membrane surface contributing to the membrane fouling. The colloidal COD in the effluent(COD_{cp}) is assumed to be reflective of the concentration of colloidal inert components in the bioreactor which is known to be major foulants and thus may be given as function of the rejection efficiency of the membrane at the actual fouling state (Galinha et al. 2012).

The new proposed model of biomass viability is based upon two major assumptions, a fraction of the inert COD present in the bioreactor will pass the membrane unchanged and the biodegradable COD in the permeate is negligible.

Following the basic structure of the empirical model given by Hasar and Kinachi (2004), the new conceptual model of biomass viability is given in Eq. (3) and Eq. (4).

Exponential function:

$SOUR = a_1 + \exp[b_1 * (COD_{sp} / COD_i) + b_2 * (COD_{cp}/COD_i) + b_3 * (MLVSS/MLSS)]$ Eq.3

or

Power function:

$SOUR = a_1 * b_1 * (COD_{sp} / COD_i) * b_2 * (COD_{cp}/COD_i) * b_3 * (MLVSS/MLSS)$ Eq.4

where COD_i is the total inert COD in the influent, a_1, b_1, b_2 and b_3 are constants to be estimated during model calibration.

In summary, the model considers that the following criteria are influential for the biomass viability:

i) The progressive change in the concentration of SMP is assumed to cause changes in the composition of the microbial communities (Chipasa and Medrzycka 2008) which mainly inhibit the microorganisms' activity for other nutrients' treatment/removal. The SMP/EPS concentration in the supernatant of the bioreactor is the controlling parameter for biomass viability and also for the progressive built-up of irreversible membrane fouling. The progressive development of SMP/EPS within the bioreactor can be traced by monitoring the soluble COD concentration in the effluent which is accounted in the model by a parameter of its ratio to the total inert COD of the influent.

ii) The effects of collodal microbial products is perhaps more significant for membrane fouling. Fraction of this can also be traced in the effluent and therefore, is introduced into the model of biomass viability by the ratio of the colloidal COD of effluent to the total inert COD of the influent.

2.3 Conceptual Mathematical Model of Membrane Fouling

Membrane fouling is not a discrete physical phenomenon rather is highly linked with the dynamic biochemical process occurring within the bioreactor. The recent trend of mathematical modelling of MBR is therefore to develop bioprocess model of MBR integrated with the model of membrane fouling. Hence, a conceptual model of the membrane fouling is given in this section which incorporates some of the bioprocess parameters of the model of biomass viability proposed in the previous section. The proposed model of the membrane resistance at the actual fouling state is based upon the basic resistance-in-series model. The total membrane resistance given in Eq. (5) is made up of membrane's intrinsic resistance, pore fouling resistance and cake layer resistance.

$$R_t = R_m + R_c + R_p \qquad \text{Eq.5}$$

R_m is the non-varying intrinsic resistance of the membrane typically determined by Darcy's law. R_p is the pore fouling resistance caused by solute deposition inside the membrane pores, and this can be calculated by the Eq.6 as followed by Li and Wang (2006). R_c (cake layer resistance) can be calculated according to the Eq.7 proposed by Lee et al (2002) where r_c implies for specific cake resistance (in mbar g^{-1}), V_p is the total volume filtered, A_m is the membrane filtration area, X_{TSS} is the total suspended solids, and k is a coefficient value of which ranges from 0 to 1. Cho et al. (2005) found relationship among specific cake resistance, MLSS, bound EPS, TMP, and expressed the specific cake resistance as a funtion of bound EPS, TMP(Δp), MLVSS and viscocity(μ) (Eq.8).

$$R_p - r_p V_p \qquad \text{Eq.6}$$

$$R_c = \frac{r_c . k . V_p . X_{TSS}}{A_m} \qquad \text{Eq.7}$$

$$r_c = \frac{\Delta P}{\mu^2}\left(9.3 * 10^{12} + 1.803 \times 10^4\left(1 - \exp\left(-115.2\left(\frac{EPS}{MLVSS}\right)\right)\right)^{36.66}\right) \quad \text{Eq.8}$$

Later, Zarragoitia-Gonzalez et al. (2008) modified the equation assuming bound EPS is associated with SMP and expressed the bound EPS in terms of SMP concentration in the bioreactor(S_{SMP}) with appropriate coefficient, and the modifed equation is as follows:

$$r_c = \frac{TMP^p}{\mu^2}\left(a + b\left(1 - \exp\left(-c\left(\frac{S_{SMP}}{0.8X_{TSS}}\right)\right)\right)^d\right) \quad \text{Eq.9}$$

In order to maintain the link with the proposed mathematical model of biomass viability through the parameters of COD_{sp} and COD_{cp}, the proposed equation for the specific cake resistance is given as follows:

$$r_c = \frac{TMP^p}{\mu^2}\left(a + b\left(1 - \exp\left(-c\left(\frac{(COD_{sp} + COD_{cp})}{dMLVSS}\right)\right)\right)^e\right) \quad \text{Eq.10}$$

where TMP^p is the transmembane pressure, and a,b,c,d,e are the constants. According to the proposed modification of the equation for specific cake resistance (Eq.9), it is implied that the accumulation of both the soluble and colloidal inert compounds within the bioreactor contributes to the cake resistance. By the integration of these easily measurable parameters in the equation, the researchers could find a way to measure membrane resistance avoiding the measurement of controversial SMP parameters. However, it may be possible to establish a correlation between the concentration of SMP in the bioreactor, and the soluble COD in the permeate by establishing analogy between Eq.9 and Eq.10. Finally, all the parameters could be integrated in the basic Darcy's law for estimating the rejection efficiency of the membrane at the actual fouling state, and the equation is as follows:

$TMP = = \mu * j_t * R_t$, where j_t is the total flux Eq.11

3. Conclusion

The proposed new conceptual models presented in the paper consist of parameters to represent the soluble and colloidal inert compounds of wastewater that potentially affect biomass viability and membrane resistance of an MBR. The measurements of soluble and colloidal COD of the effluent can be effectively used to establish empirical correlations to estimate the SMP/EPS concentration of the supernatant. Hence, the proposed model of biomass viability can also be effectively linked to the model of membrane fouling. The development of such empirical correlation would help integrate models of biomass viability and membrane fouling for a better operational control of MBR.

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Table1. Studies on the effect of SMP on microbial activity

Reference	System studied	Findings
Zhang and Yamamoto (1996)	Wastewater reuse system of an existing building was investigated using membrane separation activated sludge process.	The accumulated microbial products might be one of the limiting factors to bacterial activity and viability.
Huang et al. (2000)	A submerged membrane bioreactor treating synthetic wastewater was studied during long term operation	The accumulation of SMP in the supernatant of the bioreactor proved to be inhibitory towards the metabolic activity of the activated sludge, as well as contributing to the poor membrane permeability of the mixed liquor
Shin and Kang (2003)	Experiments were performed in lab-scale sMBR fed with synthetic wastewater.	Microbial inhibition was not observed by the accumulation of SMP during operation time
Chipasha and Medrzycka (2004)	A modified UCT process was studied where activated sludge was used from a local municipal wastewater treatment plant. Variations in pH, dissolved oxygen concentration, soluble biological and chemical oxygen demands (sBOD5 and sCOD) as a measure of microbial activity in synthetic wastewater were monitored.	Biomass developed in the presence of SMP degraded the substrates irregularly, suggesting that some microbes were dependent on the metabolic products of those that could utilize the feed components.
Li et al.(2006)	Crossflow dynamic membrane bioreactor (CDMBR) kinetics was investigated by treating caprolactam wastewater over a period of 180 days.	The sludge activity was possibly inhibited by the accumulated SMP or affected by the pump shear stress
Germain et al. (2007)	Both municipal and industrial pilot and full scale sMBRs with mixed liquor suspended solids concentrations (MLSS) ranging from 7.2 to 30.2 g L^{-1} were studied	The presence of SMP_{COD} had a negative effect on oxygen transfer suggesting that SMP affected microbial activity.
Chipasha and Medrzycka (2008)	A modified UCT process was studied where activated sludge was used from a local municipal wastewater treatment plant	Results suggested that accumulation of SMP was one of the intrinsic regulatory mechanisms that control viability and dormancy of microbial communities in activated sludge