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Model development and parameter estimation for a hybrid submerged membrane bioreactor treating Ametryn

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A B S T R A C T

A lab-scale membrane bioreactor (MBR) was used to remove Ametryn from synthetic wastewater. It was found that concentrations of MLSS and extra-cellular polymeric substances (EPS) in MBR mixed liquor fluctuated (*production and decay*) differently for about 40 days (*transition period*) after the introduction of Ametryn. During the subsequent operations with higher organic loading rates, it was also found that a low net biomass yield (*higher death rate*) and a higher rate of fouling of membrane (*a very high rate during the first 48 h*) due to increased levels of bound EPS (eEPS) in MBR mixed liquor. A mathematical model was developed to estimate the kinetic parameters before and after the introduction of Ametryn. This model will be useful in simulating the performance of a MBR treating Ametryn in terms of flux, rate of fouling (in terms of transmembrane pressure and membrane resistance) as well as treatment efficiency.

1. Introduction

Membrane bioreactor (MBR) technology, which is a combination of biological treatment and membrane filtration, is one of the most powerful (popular) domestic/industrial wastewater treatment and reuse technologies in the present world. In addition to these combined treatment processes in MBRs, various advanced physical, chemical and biological treatment tools are amalgamated to MBR systems (hybrid MBR systems) to further improve their performance. With the help of the research work carried out during the past decade, these MBR systems have been improved immensely to treat various types of domestic and industrial effluents to produce superior quality treated water to reuse and discharge into very sensitive environments. Therefore, apart from the research studies on sustainable operation (reduced cost, energy and human involvements); the present research works on MBRs are mainly focused on removal of toxic, bio-accumulated and persistent micro-pollutants from wastewater.

Fouling of membrane, which causes decrease in permeate flux and/or increase in trans-membrane pressure (TMP), has still been considered as the main obstacle to the widespread application of MBRs. This leads to higher demand of energy and consequently higher operating costs. Recent studies have shown a significant impact of biochemical process conditions such as sludge retention time (SRT), hydraulic retention time (HRT) and air supply (as aeration and membrane scouring) on fouling of membranes of MBR systems (Jiang et al., 2008). Changing these biochemical process conditions influences the production and decay of mixed liquor suspended solids (MLSS), free/suspended and bound extracellular polymeric substances (SMP and eEPS) and other foulants that frequently cause fouling of membranes.

In order to understand the fundamental behaviours and mechanisms of production and decay of fouling factors (MLSS, EPS, etc.), a significant number of modelling work has been carried out in past. Modelling of wastewater treatment systems (including MBRs) is mainly carried out focusing on their performance, operational improvements and cost effective designs. A significant quantum of the modelling work has been performed so far on MBRs and most of them are based on the well established activated sludge models (ASMs), which are modelled for activated sludge processes treating municipal wastewater. However, according to Peev et al. (2004), these models cannot be directly applied for complex industrially polluted wastewater consisting substances such as surfactants, phenolic compounds, pesticides, herbicides and other persistent polar/organic micro-pollutants. Fenu et al. (2010) reviewed the previous studies critically and comprehensively synthesized the differences of unmodified and modified modelling applications of ASM to MBR operations. Ng and Kim (2007) also carried out a mini review on modelling work related to MBRs treating municipal wastewater by categorising the models into biomass kinetic models (studies mainly based on basic empirical/mass balance model equations) – (Nagaoka et al., 1996, 1998, 2000;

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Nomenclature

EPS	eEPS concentrations in the bioreactor (g/L)
EPS_e	effluent eEPS concentrations (g/L)
EPS_i	influent eEPS concentrations (g/L)
g	the constant of gravity (9.81 m/s^2)
J	flux through the membrane (m/d)
k_{dm}	detachment rate of eEPS (day^{-1})
k_{dp}	decay rate of eEPS (day^{-1})
k_{dx}	death (endogenous decay) rate of MLSS (day^{-1})
k_α	rate constant concerning the consolidation process (day^{-1})
m	eEPS density on the membrane surface (kg/m^2)
m_0	initial eEPS density on membrane (kg/m^2)
P	trans-membrane pressure – TMP (Pa)
p	eEPS concentration in MBR mixed liquor (g/L)
Q_e	effluent (permeate) flow rate (L/day)
Q_i	influent (organic feed) flow rate (L/day)
Q_w	sludge waste flow rate (L/day)
R	the total filtration resistance (m^{-1})
R_d	MLSS decay rate (g/L/day)
R_g	MLSS growth rate (g/L/day)
R_m	membrane resistance (m^{-1})
S_e	effluent COD concentrations (g/L)
S_i	influent COD concentrations (g/L)
t	time (day)
V	hydraulic volume of the bioreactor (L)
x	MLSS concentration in the bioreactor (g/L)
x_e	effluent MLSS concentrations (g/L)
x_i	influent MLSS concentration (g/L)
x_{stdy}	steady state MLSS concentration (g/L)
x_w	waste MLSS concentration (g/L)
Y	MLSS yield due to influent COD (g-MLSS/g-COD)
Y_0	observed biomass yield (g-MLSS/g-COD)

Greek letters

α	specific resistance of EPS (m/kg)
α_o	specific resistance of EPS at $p = 0$ (m/kg)
α_p	constant (m/kg/Pa)
α_∞	the ultimate value of α (m/kg)
β	the ratio of produced EPS to increased MLSS (g-EPS/g-MLSS)
γ	constant (day^{-1} Pa^{-1})
δ	thickness of EPS biofilm on the membrane (m)
λ_m	static friction coefficient (–)
μ	viscosity of permeate (Pa s)
μ_s	specific MLSS growth rate (day^{-1})
ρ_g	density of air (kg/m^3)
ρ_{ML}	density of MBR mixed liquor (kg/m^3)
ρ_w	density of water (kg/m^3)
τ_g	shear stress (Pa)

Nagaoka, 1999; Nagaoka and Akoh, 2008; Chae and Shin, 2006; Peng and Xue, 2006; Yoon, 2003), fouling models (Khan et al., 2009) and integrated, hybrid or modified ASM models (Jiang et al., 2008). Several modelling works that have been carried out in past are tabulated in Table 1.

Modelling work, simulation and parameter estimation present in this paper is mainly based on the mathematical model expressions developed by Nagaoka et al. (1998). Previous to this, Nagaoka et al. (1996) modelled the membrane separation activated sludge process, which was later called as the MBR, for studying the influence of bacterial cellular polymers. Then they continued their study and modelled the biofouling process in a membrane separation activated sludge system in detail (Nagaoka et al., 2000). Subsequent to that they modelled the membrane separation activated sludge system for evaluation of the organic loading rate (Nagaoka et al., 2000) and for nitrogen removal (Nagaoka, 1999).

Comparatively, less number of biofouling modelling studies have been carried out for MBRs treating industrial wastewater. Peev et al. (2004) conducted a modelling work related to the degradation of low concentration pollutants in MBRs. Peng and Xue (2006) modelled their MBR for meat packing wastewater treatment and Munz et al. (2008) for a full scale microfitration MBR treating tannery wastewater. The objective of this study to understand the mechanism of the biofouling of membrane considering accumulation, detachment and consolidation of bound EPS (eEPS) on the membrane surface, and to develop a mathematical model for the prediction of operating performance of the submerged MBR treating Ametryn (a Photosystem II herbicide, which is widely used to control pre and post emergence of broadleaf and grass weeds in Australian farmlands and destroys the ecosystem – Navaratna et al., 2010). Ametryn shows a relatively higher solubility in water (185 mg/L) and it dissolves readily in solvents such as acetone and methanol. This paper compares the changes of kinetic parameters before and after the introduction of Ametryn to the MBR.

2. Model equations

Mathematical model expressions were developed to simulate the fluctuations of MLSS, EPS and TMP, and to estimate model parameters using experimental data.

2.1. Concentration of biomass (MLSS)

The biochemical function of activated sludge process (ASP) and MBR is compatible, and it includes a continuous generation of new sludge with the consumption of feed organic materials, while decaying some sludge mass due to endogenous respiration. Endogenous respiration involves consumption of cell-internal substrate, which leads to a loss of activity and slightly reduced biomass. Radjenović et al. (2008) stated that this biomass decay (includes cell lyses, maintenance, predation and death) due to endogenous respiration generally occurs during aerobic conditions (very slow during anoxic conditions). Endogenous respiration is more favourable in MBRs due their high biomass concentration. Theoretically, at an optimum MLSS, there is a stage where the supply of total energy via organic feed equals to the total demand of energy for the maintenance of biomass (just for their vial functions and not for producing additional biomass) in the bioreactor. Therefore, at a higher MLSS concentration, when the supplied organic feed is barely sufficient for the maintenance (very low food to microorganism – F/M ratio), additional growth of biomass is very small or no excess sludge is produced. To explain this phenomenon of biomass yield and decay, Nagaoka et al. (1998) modelled the following expression (7) and its derivation steps (Jang et al., 2004) are as follows.

Mass balance (biomass) equation for a MBR can be written as,

$$V\frac{dx}{dt} = Q_i x_i - Q_e x_e - Q_w x_e + R_g V + R_d V \quad (1)$$

where V is the hydraulic volume of the bioreactor (L), x is the MLSS concentration in the bioreactor (g/L), t is the time (days), Q_i, Q_e and