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The Fouling phenomena in membrane bioreactors: a comparison of different mathematical modelling approaches

Mannina, G. *
* Dipartimento di Ingegneria Civile, Ambientale, Aerospaziale, dei Materiali - Università di Palermo, Viale delle Scienze, 90128 Palermo, Italy (E-mail: giorgio.mannina@unipa.it)

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Summary of key findings

Eight different modelling approaches for membrane fouling modelling have been compared and the uncertainty has been assessed. Overall the eight approaches provided satisfactory results in terms of model fitting with the measured data. Different results have been obtained in terms of uncertainty bounds showing a different reliability of the model approaches. The study allowed to gain insights about the mechanisms which control fouling in membrane bioreactors.

Background and relevance

Membrane fouling can be considered as the Achilles' hill in the application of MBR for wastewater treatment. Membrane fouling leads to a progressively decrease of filtration performance over time. The key mechanisms, biological and physical, have been partially encoded thus leading to uncertainty (Fenu et al., 2010). In order to fill this gap, the reliability of MBR fouling modelling was assessed. Specifically, eight fouling modelling approaches were compared and their uncertainty was evaluated to determine their robustness and suitability for applications. Fouling is simulated by different algorithms using several approaches that range from the well known model derived by the Darcy's law to more complex ones. In this study, the uncertainty associated with eight different models has been assessed. To accomplish this, the models were integrated in a home-made integrated MBR model that was developed in a previous study (Mannina et al., 2011).

The integrated model is divided into two sub-models: a biological and a physical sub-model. The biological sub-model is a modified version of ASM1 (Henze et al., 2000) according to the ASM-SMP approach. The physical sub-model consists in four steps, jointly correlated each other: (i) cake layer formation during the membrane filtration; (ii) COD removal by biological membrane (i.e. cake layer); (iii) COD removal by physical membrane and (iv) modelling of the membrane resistances. The physical sub-model describes the cake layer formation during the suction phase and the partial removal of the cake layer during the backwashing phase, taking into account the irreversible fouling of the membrane (Mannina et al., 2011). Regarding the fouling phenomena, as discussed above, eight different modelling approaches (see Table 1) have been implemented. The first modelling approach (namely, Mod0) is derived by the MBR model as proposed by Mannina et al. (2011) and models the pore fouling resistance as proportional to the amount of permeate produced. Such a resistance is calculated through the specific pore fouling resistance in terms of the filtrate volume in order to have a realistic and correct approach. The second model (Mod1) assumes that the membrane has straight cylindrical pores that decline in radius as solid matter accumulates on the pore walls (Bolton et al., 2006). The resistance is calculated as a function of the volume processed and considers the increment of the resistance as a function of the initial flux (J_0). Mod2 assumes the resistance due to solute adsorption is recognized to be time dependent and tends towards a steady value corresponding to adsorption equilibrium (Juang et al., 2008). Differently to previous fouling modelling approaches, according to Mod3, the membrane is assumed to have straight through cylindrical pores (Orsello et al., 2006). Initially, pore constriction occurs through all the open pores while the membrane surface is blocked gradually by protein aggregate to form an inhomogeneous blocked area. Once a pore is blocked by an aggregate deposited on the surface, no further pore constriction can occur. Subsequently, a cake layer will build up within the blocked area. The resistance of the cake layer is not uniform, and is dependent on the time when the pores are first blocked by particle protein aggregates. Similarly to Mod2, Mod4 assumes that the fouling resistance depends on the total permeate volume produced in a filtration interval under consideration, e.g. between two chemical cleanings (Wintgens et al., 2003). It is important to highlight that differently to Mod-2, Mod-4 assumes that the resistance increases depend on the filtrated volume. Differently to previous modelling fouling approaches, Mod-5 assumes that the increase of cake layers can act as a prefilter for soluble component, therefore reducing its pore constriction effect (Wu et al., 2011). According to Mod5 approach, introduces the influence of the cake layer formation on the pore constriction mechanism having a more realistic schematization of the phenomena. Another implemented erosion model approach regards the model Mod-6 according to Wu et al. (2012) where the membrane fouling is divided into cake layer formation and pore fouling. The cake layer is assumed to be formatted by mixed liquor suspended solids (MLSS) and consolidated by the entrapment of colloidal components, resulting in the decreasing in cake porosity and increasing in specific cake resistance. Finally, the most complex approach (Mod7), used in the present study for the evaluation of the membrane fouling, is derived by Wu et al. (2013). According to such an approach, the removal mechanisms include physical sieving and/or adsorption by the bio-cake, back transport, adsorption by membrane and biodegradation by the biomass within the cake layer (Wu et al., 2013).

Table 1. Main model algorithms for membrane fouling modelling

Modelling approach	Main adopted equations	Number of parameters	Reference
Mod0: cake filtration	$R_p = r_{po} \cdot \sum J_{tot} \cdot t_{filtr}$	11	Mannina et al., 2011
Mod1: pore constriction	$R_p = R_m \left(1 + \frac{K_s \cdot J_0 \cdot t_{filtr}}{2}\right)^2$	12	Bolton et al., 2006
Mod2: pore constriction	$R_p = R_{a,ss}\left(1 - e^{-b \cdot t}\right);$	13	Juang et al., 2008
Mod3: pore constriction	$R_p = R_m\left(1 + \beta \cdot Q_0 \cdot C_b \cdot t_b\right)^2$	12	Orsello et al., 2008
Mod4: pore fouling	$R_p = S_f \left(1 - e^{-k_f \cdot \int_0^t F(t) \cdot dt}\right)$	13	Wintgens et al., 2008
Mod5: pore constriction	$R_p = R_m \left(1 + \beta \cdot Q \cdot C_s \cdot t \cdot \frac{n}{n + R_{ca}}\right)^2$	13	Wu et al., 2011
Mod6: pore fouling	$R_m + R_p = K_m \frac{\left(1 - \varepsilon_m\right)^2}{\varepsilon_m^{\ 3}};$ $\varepsilon_c = \varepsilon_{c(o)} - \frac{M_{sf}}{\rho_c \cdot \delta_{c(i)}};$ $\frac{dM_s}{dt} = J \cdot C_s \frac{r_S}{r_S + M_{sf} + M_{pc}}$	13	Wu et al., 2012
Mod7: cake filtration	$R_{cd,i}(t) = \delta_d \frac{(1 - \varepsilon_d)^2}{(\varepsilon_d)^3} K_c$	19	Wu et al., 2013

R_p: is the pore fouling resistance; ***r_{p0}***: is specific pore fouling resistance in terms of the filtrate volume; **J_{tot}** is the total flux; **t_{filtr}** is the filtration; **R_m** is the membrane resistance; ***t_p*** is the time at which the pore region is first blocked. **Ks** is a coefficient; ; **$R_{a,ss}$** is the resistance due to solute adsorption; **b**: is a coefficient; **J_0**: initial flux; ***C_b*** bulk concentration; **Q_0** initial flow rate; β filtration coefficient; **Q:** is the filtration flow rate; **Cs** is the soluble component concentration; **$R_{cd,i}$** is the resistance of the ith permanent bio-cake layer; **n**: is a coefficient; **S_f**: is the model parameter fouling saturation; **k_f**: is model parameter fouling; F: is trans-membrane flux; **Δt** : is the time step; **R_{ca}**: is the cake resistance; **M_{sf}**: is the mass of dynamic cake layer; **K_m** is a membrane related constant; **ε_m** is the membrane porosity at time t; **ε_c**: is the cake porosity at time t; **ρ_c**: is density of the deposited colloidal components **δ_c**: the cake thickness; **ρ_s**: is density of the deposited soluble components; **M_s**: is the amount of soluble mass within membrane pores; **M_{sf}**: is the mass of dynamic cake layer formed by particles with diameter d_i; **M_{pc}** is the total mass of the previously formed permanent cake layers; **r_s**: is the cake pre-filter effect coefficient; **ε_s** is the membrane porosity at time t; **ε_d** is the porosity of the dynamic cake layer.

Results and Discussion

Ten-thousand Monte Carlo simulations were run for each of the eight models evaluated here. In Figure 1, the measured irreversible resistances along with the best efficiency simulation and the uncertainty bounds obtained by 5% and 95% percentiles are presented. Figure 1 shows results for the eight fouling modelling approaches adopted in the present studies; some interesting consideration can be drawn. All presented approaches have a very good ability to fit the experimental data giving the impression that all adopted models are equivalent. The good calibration results are most likely due to the overall modelling approach employing the MBR integrated model (Mannina et al., 2011). Despite such a fact, some differences can be noticed especially looking at the uncertainty bounds, statistical indices (i.e., ARIL, NS, posterior distributions of model parameters etc.). Although the best modelling efficiencies are high (NS>0.7), modelling results present quite different pattern especially with respect to uncertainty bounds. The MBR resistances present a different distribution ranging from Mod0 to Mod7. In particular, while the dynamic reversible resistance differs of only 2% for the eight modelling approaches, the irreversible resistance (pore fouling) shows an overall variability around 15%. The Mod-1 shows an overall better performance and model results are much more consistent.

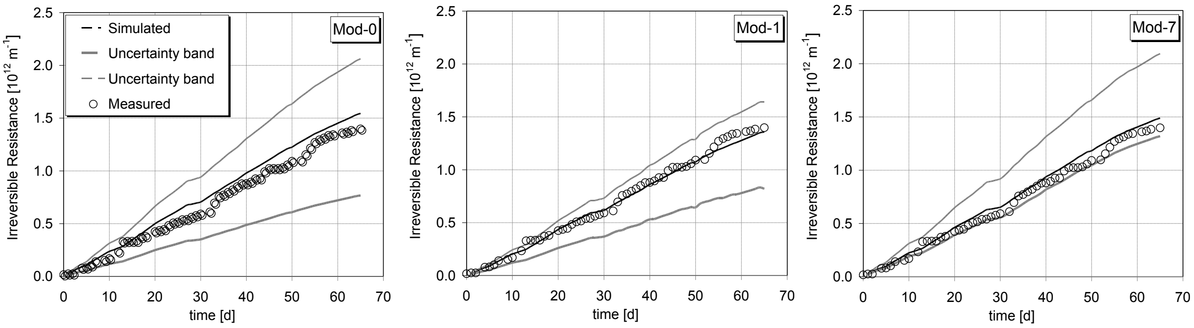

Figure 1.1 Measured, modelled and uncertainty bounds of the irreversible resistance of the fouling modelling approaches, Mod0; Mod1 and Mod7, left, centre and left, respectively.

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