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Integrated benchmark simulation model of an immersed membrane bioreactor

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ABSTRACT

This paper presents a new integrated model of an immersed membrane bioreactor (iMBR) for wastewater treatment. The model is constructed out of three previously published submodels describing the bioreactor, the membrane, and the interface between them. The bioreactor submodel extends a conventional activated sludge model with soluble and bound biopolymers which have been found to cause irreversible and reversible fouling. The membrane model describes fouling as a function of biopolymer concentrations, permeate flow, and shear stresses on the membrane surface. The interface describes the dependency of oxygen transfer rate on suspended solids concentrations and calculates shear stresses on the membrane surface from air-scour rates. The paper serves three purposes. First, the integrated model is simulated on a plant layout of a previously published MBR benchmark model which did not consider any interactions between the submodels. Hence, this paper presents a new and upgraded MBR benchmark model. Secondly, the simulation results showcase how simulations with an integrated model can be used to optimise plant performance and minimise energy consumption. Finally, the paper introduces new measures of fouling which can be used for benchmarking different MBR plant layouts and control strategies.

1. Introduction

MBR systems are widely applied in municipal and industrial wastewater treatment thanks to superior effluent quality, better process stability and smaller footprint compared to, so called, conventional treatment processes such as activated sludge or trickling filters. Despite of widespread use of membrane bioreactors (MBRs) in wastewater treatment this technology is currently missing bespoke dynamic process models that would allow simulation of MBR-based plants in commercial wastewater treatment plant (WWTP) simulation packages along with conventional processes such as activated sludge reactors, trickling filters, or sedimentation tanks. None of the commercial packages, to authors' knowledge, contain a MBR model which is able to predict bulk liquid concentrations of the most dominant biofoulants, i.e. soluble microbial products (SMP) and extracellular polymeric substances (EPS) despite the fact that SMP and EPS have been found to have a direct impact on the rates of such membrane fouling mechanisms as pore constriction, pore blocking, and cake filtration (Hoa et al., 2003; Broeckmann et al., 2006; Nuengjamnong, 2006; Wang et al., 2009). Additionally, MBR models in commercial software packages do not provide a detailed mechanistic description of membrane fouling and fouling control mechanisms. As long as the mathematical models for MBR systems do not become more comprehensive and the main interactions between the bioreactor and the membrane are not described, simulation-based process design and optimisation or control strategy development will not be possible on MBR-based plants.

Luckily, recent years saw a number of dynamic mathematical models of membrane bioreactors created and described in the scientific literature. These publications are briefly summarised in Janus and Ulanicki (2014, 2015). Although the MBR

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Nomenclature

$AE_{bioreactor}$	energy demand for fine-bubble aeration (kWh d^{-1})
$AE_{membrane}$	energy demand for coarse-bubble aeration (kWh d^{-1})
AE_{total}	total energy demand for aeration (kWh d^{-1})
A_{mem}	total membrane area (m^{2})
$BOD_{5,95}$	95%-ile of effluent biological oxygen demand (gO_2 m^{-3})
COD_{95}	95%-ile of effluent chemical oxygen demand (gO_2 m^{-3})
E.Q.	effluent quality index (kgPU d^{-1}) – see Copp (2002) for definition
FI_i	Irreversible fouling index (m^{-1} m^{-3})
FI_r	Reversible fouling index (m^{-1} m^{-3})
$f_{EPS,dh}$	fraction of X_{EPS} produced during heterotrophic biomass decay (gO_2 gO_2^{-1})
$f_{EPS,h}$	fraction of X_{EPS} produced during heterotrophic biomass growth (gO_2 gO_2^{-1})
f_{EPS}^{inf}	EPS content in the influent biomass (–)
f_{nr}	fraction of S_{UAP} and S_{BAP} ending up in the permeate (–)
f_{SMP}^{inf}	S_{BAP} content in the influent soluble inert organic matter S_I (–)
g	gravity constant (9.81 m s^{-2})
h_g	geometric head difference (m H_2O)
h_l	head loss due to friction (m H_2O)
i_{XB}^{inf}	N content of the influent biomass (–)
i_{XEPS}^{inf}	EPS content in the influent biomass (–)
i_{XBAP}^{inf}	N content in BAP (–)
I.Q.	influent quality index (kgPU d^{-1}) – see Copp (2002) for definition
J	permeate flux (L m^{-2} h^{-1})
K_p	PI controller's proportional gain (depending on application)
k_i	irreversible fouling strength (m kg^{-1})
k_r	cake detachment constant (kg m^{-2} s^{-1})
ME	energy for mixing of mixed liquor (kWh d^{-1})
m_i	mass of irreversible foulant per membrane area (kg m^{-2})
m_r	mass of reversible foulant per membrane area (kg m^{-2})
$\dot{m}_r^{back}$	back-flux of reversible foulant from the membrane (kg m^{-2} d^{-1})
OCI	operational cost index (–)
q_a	airflow rate (m^{3} d^{-1})
q_{ave}	average flow rate (m^{3} d^{-1})
$q_{a,1}$	airflow rate into the first aerobic tank (m^{3} d^{-1})
$q_{a,2}$	airflow rate into the second aerobic tank (m^{3} d^{-1})
$q_{a,3}$	airflow rate into the membrane tank (m^{3} d^{-1})
q_b	backflush flow (m^{3} d^{-1})
q_{eff}	effluent (permeate) flow rate (m^{3} d^{-1})
q_{inf}	influent flow rate (m^{3} d^{-1})
q_{ir}	internal recirculation flow rate (m^{3} d^{-1})
q_{ave}	average flow rate (m^{3} d^{-1})
q_{min}	minimum flow rate (m^{3} d^{-1})
q_{max}	maximum flow rate (m^{3} d^{-1})
q_{rec}	sludge recirculation flow rate (m^{3} d^{-1})
q_w	waste activated sludge flow rate (m^{3} d^{-1})
$PE_{permeate}$	energy associated with permeate pumping (kWh d^{-1})
$PE_{q_{back}}$	energy associated with back-flushing (kWh d^{-1})
$PE_{q_{eff}}$	energy associated with effluent pumping (kWh d^{-1})
$PE_{q_{int}}$	energy associated with internal recirculation (kWh d^{-1})
PE_{q_r}	energy associated with sludge recirculation (kWh d^{-1})
PE_{q_w}	energy associated with WAS pumping (kWh d^{-1})
PE_{sludge}	energy associated with sludge pumping (kWh d^{-1})
PE_{total}	total pumping energy (kWh d^{-1})
R_i	resistance due to irreversible fouling (m^{-1})
R_m	clean membrane resistance (m^{-1})
R_r	resistance due to reversible fouling (m^{-1})
R_t	total membrane resistance (m^{-1})
S_{ALK}	alkalinity (molHCO_3^- m^{-3})
S_{BAP}	concentration of biomass associated products (gO_2 m^{-3})
S_{ND}	concentration of soluble organic nitrogen (gN m^{-3})
S_{NH}	concentration of ammoniacal nitrogen (gN m^{-3})
$S_{NH,95}$	95%-ile of effluent ammoniacal nitrogen concentration (gN m^{-3})
S_{NO}	concentration of nitrites and nitrates (gN m^{-3})
S_I	concentration of soluble inert organic matter (gO_2 m^{-3})
S_O	dissolved oxygen concentration (gO_2 m^{-3})
SP_{disp}	amount of sludge for disposal (kgTSS d^{-1})
SP_{tot}	total sludge production (kgTSS d^{-1})
S_S	concentration of readily biodegradable substrate (gO_2 m^{-3})
S_{SMP}	concentration of soluble microbial products (gO_2 m^{-3}). $S_{SMP} = S_{UAP} + S_{BAP}$
S_{UAP}	concentration of utilisation associated products (gO_2 m^{-3})
t_f	filtration cycle duration time (s)
t_I	integral time of the PI controller (d)
T_l	liquid temperature (°C)
TN_{95}	95%-ile of effluent total nitrogen concentration (gN m^{-3})
t_{simu}	simulation time (d)
TSS_{95}	95%-ile of effluent total suspended solids concentration (gN m^{-3})
t_0	simulation start time (d)
v_{sg}	superficial gas velocity (cm s^{-1})
v_{sl}	superficial liquid velocity (cm s^{-1})
$V_{ax,1}$	first anoxic tank volume (m^{3})
$V_{ax,2}$	second anoxic tank volume (m^{3})
V_{mem}	membrane tank volume (m^{3})
V_{eff}^{net}	net volume of permeate discharged from the plant (m^{3})
$V_{ox,1}$	first aerobic tank volume (m^{3})
$V_{ox,2}$	second aerobic tank volume (m^{3})
X_A	concentration of autotrophic biomass (gO_2 m^{-3})
X_{EPS}	concentration of extracellular polymeric substances (gO_2 m^{-3})