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Development of a cost model for membrane bioreactors including sludge handling costs

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ABSTRACT

Membrane bioreactors (MBRs) are state of the art in municipal wastewater treatment. One of their main disadvantages is the high energy demand for air scour of the membrane. However, due to more stringent legal restrictions, sludge handling costs will increase and therefore they are becoming more and more significant for the total operating cost of the MBR. In this study, a novel cost model approach for immersed MBRs treating municipal wastewater incorporating the energy demand for aeration and fouling prevention as well as the related sludge handling costs subject to local conditions is presented. The model is consciously kept simple to be easily applicable for end users and is based on a few easily accessible input parameters like operational (hydraulic retention time, sludge retention time) and bio-kinetic parameters (yield, decay coefficient) and feed conditions. Information on bio-kinetic parameters and oxygen transfer efficiency varies strongly in the literature; therefore, the correct choice of these parameters is essential for an applicable model to avoid the over- or underestimation of the impact of aeration on the system. In first simulation and sensitivity studies, the derived framework was found to be appropriate to predict the total costs of an immersed MBR.

Keywords: Membrane bioreactor modelling; Dewatering; Aeration; Costs

1. Introduction

In the last decade, membrane bioreactor (MBR) technology has advanced from a pure research topic to a substantial alternative for conventional wastewater treatment plants. However, one of the main disadvantages of MBRs is the high energy demand for air scour of the membrane, but due to more stringent legal restrictions, sludge handling costs will increase [1] and they are therefore also becoming more and more important for the total operating cost of the MBR. Consequently, the currently assumed optimal MLSS concentration will shift to higher values and a new optimisation is necessary. The costs for sludge disposal vary strongly depending on the method used, on local conditions, like plant size, plant equipment, local regulations, transportation costs and sludge characteristics like dewaterability. Therefore, the operating conditions of each individual MBR should be selected carefully to minimise the overall costs.

Most of the cost models found in literature just consider the energy demand for aeration of the biology, fouling prevention, pumping etc. as the main factor influencing the operational costs. Just the model by Yoon et al. [2] include the sludge handling costs using a fixed value for the sludge treatment, however, this model does not include a sub-model for fouling prevention.

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To set up a model for the whole MBR process the following sub-models are needed:

(i) model for sludge growth
(ii) aeration model for biological processes
(iii) aeration model for fouling prevention
(iv) sludge treatment model including excess sludge properties models and disposal models

Biological modelling of MBR processes was investigated intensely in the last years. Normally, these models are based on the ASM models [2–5] and are sometimes extended by SMP concepts for a better description of simultaneous fouling and higher sludge retention time (SRT) operation [6–8]. The applicability of ASMs for modelling MBRs and the set of parameters used, however, still needs to be verified to further understand the effects of higher SRTs and MLSS concentrations on biomass growth [9].

The energy demand for aeration is comprised of the aeration demand for biotreatment by fine bubble aeration and the membrane aeration for fouling prevention typically by coarse bubble aeration which is calculated separately [10,11]. Furthermore, according to Krause and Cornel [10], the coarse bubble aeration already provides a portion (4–25%) of the dissolved oxygen for the biotreatment. They assumed that on average 15% of the oxygen demand for biotreatment can be attained through coarse bubble aeration.

Sludge handling models are very rare in literature [12]. Normally just a fixed cost value is assumed for sludge treatment including all treatment steps like dewatering, transport and incineration.

Additionally, several case studies on the optimisation of full scale MBRs are reported in literature [13–15]. These optimisations are done for particular local conditions at each plant and thus cannot be transferred easily to other MBRs, and also do not consider sludge handling and treatment.

In this study, a cost model for submerged MBRs treating municipal wastewater incorporating energy demand for aeration and fouling prevention as well as sludge handling costs subject to local conditions is presented, which will enable for each individual MBR the identification of the best operational parameters in terms of total operating costs.

2. Model development

The idea of this study is to set up cost model for municipal MBRs that are consciously kept simple to be easily applicable for end users. It is based on a few easily accessible input parameters like operational hydraulic retention time (HRT), SRT and bio-kinetic parameters like yield, decay coefficient and feed conditions. In Fig. 1 the scheme of the cost model with the different sub-models and their interrelation is shown.

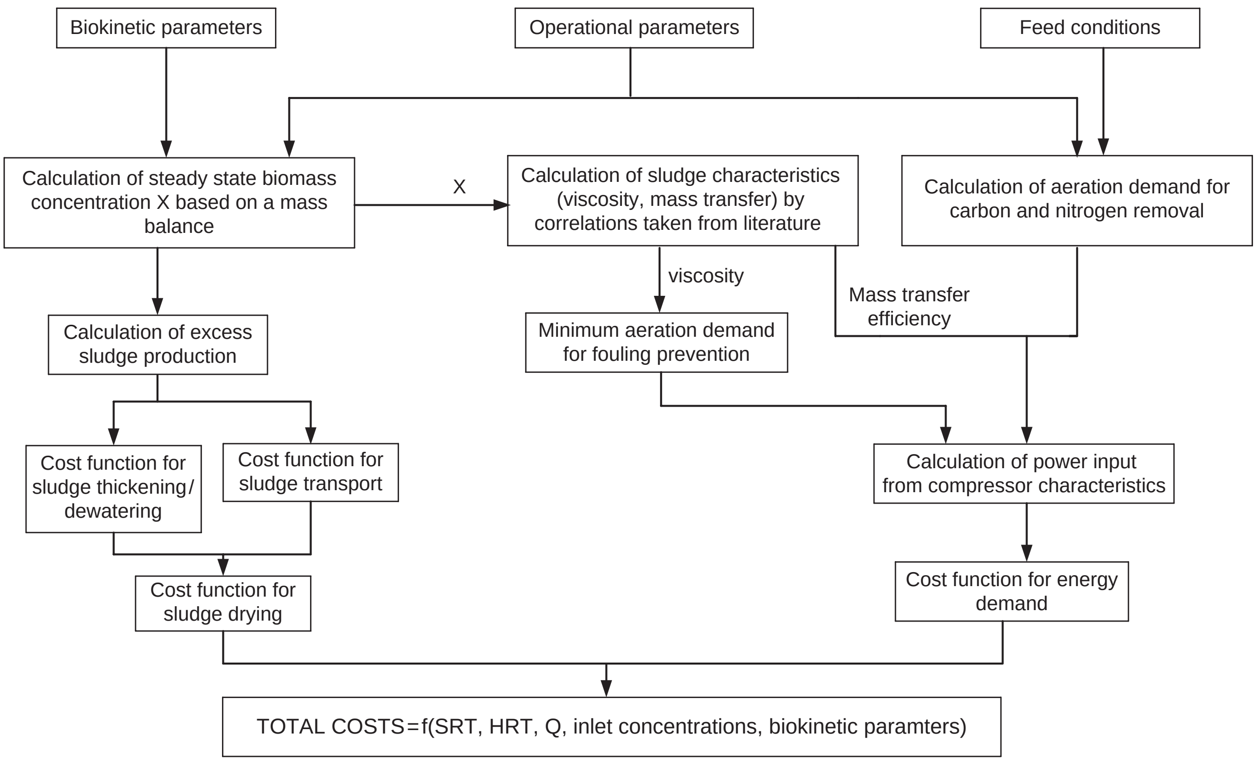

Fig. 1. Scheme of the cost model.

2.1. Sludge production model

The steady state biomass concentration in the MBR is calculated from a mass balance on sludge and substrate in the reactor (ASM1) [4, 5].

$$V\frac{dX}{dt} = Y\frac{\mu_{\max}\cdot S}{K_s + S}\cdot X\cdot V - b\cdot X\cdot V - Q_w\cdot X \quad (1)$$

$$V\frac{dS}{dt} = -\frac{\mu_{\max}\cdot S}{K_s + S}\cdot X\cdot V + Q\cdot S_0 - Q\cdot S \quad (2)$$

Assuming that the bioreactor is completely mixed, the biomass concentration at steady state conditions can be derived by rearranging Eq. (1) and (2) and solving for X.

$$X = \frac{1}{HRT}\cdot(S_0 - S)\cdot\frac{Y\cdot SRT}{1 + b\cdot SRT} \quad (3)$$

i.e., biomass concentration in the MBR is just a function of operating parameters (SRT, HRT), inlet conditions (S_0) and bio-kinetic parameters (Y, b). Operating parameters and inlet conditions are well known, so only the bio-kinetic parameters have to be determined experimentally or taken from literature.

With a known sludge age SRT and the biomass concentration X, the excess sludge production can be calculated using Eq. (4):

$$ESP = \frac{V\cdot X}{SRT} = \frac{Y\cdot Q}{1 + b\cdot SRT}\cdot(S_0 - S) \quad (4)$$

2.2. Aeration model

The theoretical aeration demand to maintain the biological process is calculated according to ATV-DVWK-A 131 [16] considering the oxygen requirement for carbon and nitrogen removal. To keep a constant oxygen concentration C_{set} of 2 mg L^{-1} in the reactor, the real aeration demand is then calculated considering the oxygen transfer efficiency and the blower efficiency.

$$Q_{air,\,real} = \frac{C^*}{C^* - C_{set}}\cdot Q_{air,\,theoret.}\cdot\frac{1}{\alpha\cdot\eta} \quad (5)$$

The oxygen transfer efficiency is a function of MLSS concentration and can be calculated according to different correlations found in literature [17–19]. The blower efficiency can be taken from data sheets. The power demand is then calculated using the correlation established by Krause and Cornel [10] with E_{pot} = 5.44 Wh m^{-3} m^{-1} and the depth h of the aeration device.

$$P_{biology} = E_{pot}\cdot Q_{air,\,real}\cdot h \quad (6)$$

According to Cornel and Krause [20], the aeration demand for fouling prevention varies between 0.4 and 1 kWh m^{-3} for immersed membranes. In a first approach, a linear relationship between power demand for fouling prevention and the constant viscosity μ_∞ at a high shear rate of 2300 s^{-1} was assumed in this study.

$$P_{fouling} = 0.0375\cdot\mu_\infty + 0.325 \quad (7)$$

The coefficients of Eq. (7) were determined by correlating own measurements of the viscosity μ_∞ at a given MLSS concentration with the power input. Furthermore, the coarse bubble aeration already provides a portion (15%) of the dissolved oxygen for the biotreatment [10].

2.3. Sludge handling model

The cost models for sludge thickening and transport are specific for each plant, due to different on-site sludge handling availabilities, and thus they must be adapted for each case. In a first approach, constant sludge treatment costs of 200–800 t_{DS}^{-1} are assumed [21]. This sub-model has to be refined in a next step.

3. Sensitivity analysis

In order to evaluate the derived model, simulation studies and sensitivity analyses were carried out. In a first step, a plausibility check with the different sub-models was realised. According to Eq. (3), biomass concentration in the MBR can be calculated. Information about operating conditions and the influent parameters are easily accessible for each plant, but information about bio-kinetic parameters are less precisely known because they are strongly dependent on operating conditions and have to be determined experimentally or taken from literature. Therefore, the effect of a varying yield coefficient on steady state biomass concentration is shown in Fig. 2 , initially assuming that the yield coefficient is independent of SRT. Yield coefficients obtained

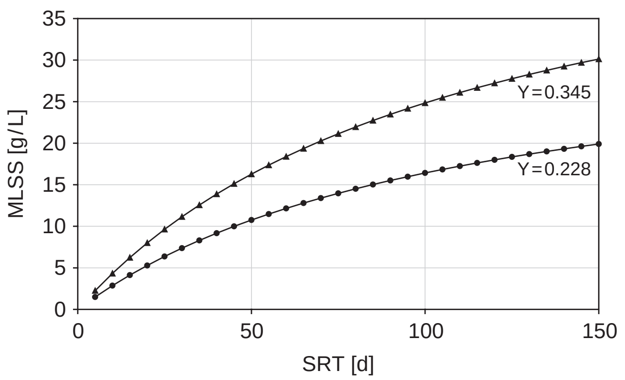

Fig. 2. Biomass concentration in the reactor depending on sludge age assuming a constant yield coefficient (b = 0.009 d^{-1}, HRT = 10 h, S_0 = 600 mgCOD L^{-1}, S = 30 mgCOD L^{-1}).

from literature [3, 22] vary between 0.38–0.13 mgVSS $mgCOD^{-1}$ for sludge ages from 5–110 days. Own measurements for a sludge age of 75 days resulted in a yield coefficient of 0.228 mg MLSS $mgCOD^{-1}$. It is obvious that an inaccurate yield coefficient can result in an error of up to 50% in the determination of MLSS. Therefore, a correlation for bio-kinetic parameters as a function of operating conditions needs to be implemented in the model.

According to Eq. (3) MLSS concentration changes linearly with yield coefficient and influent substrate concentration ($S_0 >> S$) and it is inversely proportional to HRT.

Further simulation studies were performed with the values given in Table 1. The operational conditions and the bio-kinetic parameters were taken from a bench–scale MBR for carbon and nitrogen removal operated in our laboratory at a SRT of 75 days with a complex synthetic wastewater [23]. The influent concentration S_0 and TN are average values from the plant and the effluent concentration was calculated assuming 95% removal efficiency.

In Fig. 3, the real aeration demand to maintain the biological process was determined using different correlations taken from literature [17–19] and assuming a blower efficiency of 50%. With increasing SRT, the difference between the aeration demands increases up to 60%. It is obvious that the big differences in the calculated aeration demand especially for high sludge age result in a significant difference in aeration costs. Therefore, oxygen transfer for higher MLSS concentrations should be investigated more intensively to get an improved knowledge of the parameters influencing oxygen transfer.

Table 1
Parameters of a bench–scale MBR used for the simulation.

Operational parameters	
Q [m^3 d^{-1}]	0.096
HRT [h]	10
F/M [kgCOD d^{-1}]	0.0576
T [°C]	14
C_{set} [mg L^{-1}]	2
ρ_{air} [kg m^{-3}]	1.225
Influent conditions	
S_0 [mg L^{-1}]	600
S [mg L^{-1}]	30
TN [mg L^{-1}]	80
Bio-kinetic parameters	
Yield [mgVSS $mgCOD^{-1}$]	0.228
b [d^{-1}]	0.009

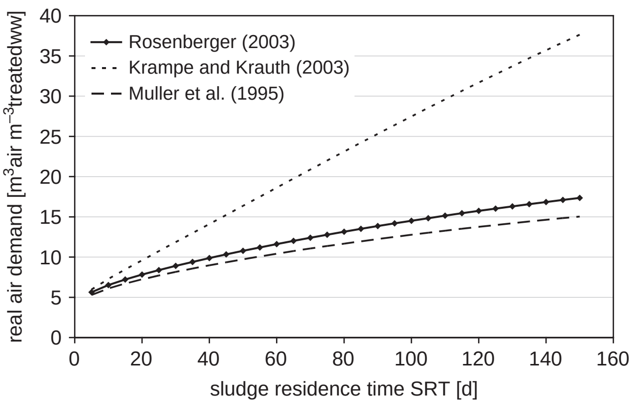

Fig. 3. Calculated aeration demand to maintain the biological process with different α correlations assuming a blower efficiency of 50%.

4. Cost considerations

The costs of an MBR process vary strongly depending on local conditions due to differences in the electricity tariff and sludge treatment depending on the method used and on local conditions like plant size, equipment, local regulations, transportation costs and sludge characteristics.

In Fig. 4, the total aeration costs for the biology and fouling prevention as well as the sludge treatment costs per m^3 treated wastewater versus sludge age are shown, assuming different electricity tariffs and sludge treatment cost, respectively. The total aeration costs were calculated with the parameters given in Table 1, the correlation found by Rosenberger [19], a blower efficiency of 50% and the assumption that the coarse bubble aeration for fouling prevention provides 15% of the aeration demand to maintain the biological process (see above). Total costs in the range of 10 c/m^3 have been reported which shows that the model yield realistic values [24].

Increasing the sludge treatment costs by 40% from 500 € t_{DS}^{-1} to 700 € t_{DS}^{-1} at constant electricity costs of 10 € cents kWh^{-1} will result in an increase of the total operation cost by 10–25% depending on sludge age. The strongest increase is observed for decreasing sludge ages. An increase in the electricity tariff by 25% at constant sludge treatment costs results in an increase of 10–18% of total operating costs. The increase is more pronounced for higher sludge ages. At a given combination of sludge treatment costs and energy costs the total costs per m^3 treated wastewater do not vary significantly. Nevertheless, a minimum of total costs can still be observed at different sludge ages depending on local costs. In the three combinations shown in Fig. 4, the optimal SRT varies

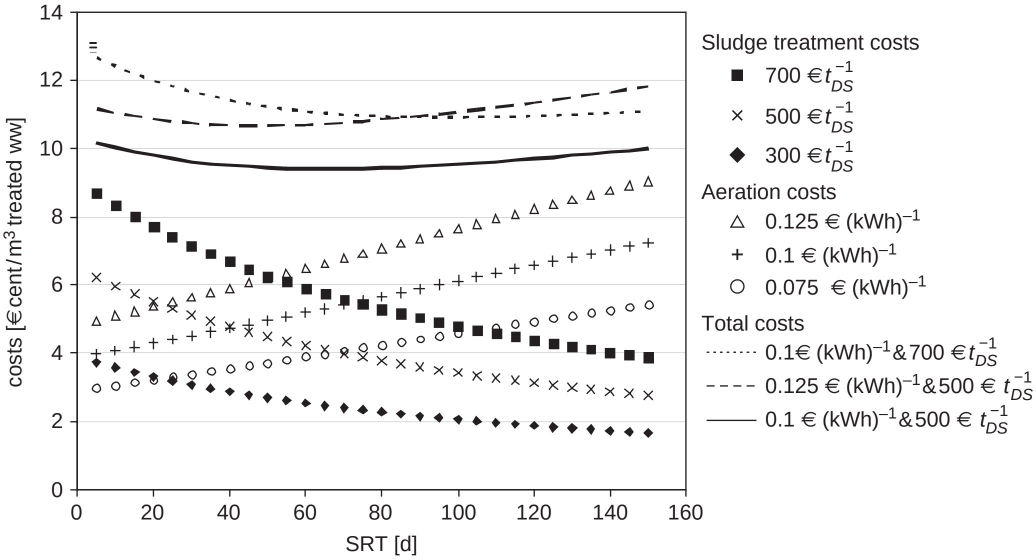

Fig. 4. Calculated costs per m^3 treated wastewater for aeration and sludge treatment versus sludge age assuming different electricity tariffs and sludge treatment cost, respectively.

between 50 and 100 days. Therefore, the model can be used to optimise the sludge age for a given MBR plant.

5. Conclusion

In this study, a novel cost model approach for immersed MBRs treating municipal wastewater is presented which incorporates energy demand for aeration and fouling prevention as well as the related sludge handling costs subject to local conditions. The model presented is consciously kept simple. It is suitable for MBR users and is based on a few easily accessible input parameters like operational (HRT, SRT) and bio-kinetic parameters (yield, decay coefficient) and feed conditions. The information on bio-kinetic parameters and oxygen transfer efficiency vary strongly in literature, therefore the correct choice of these parameters is essential for an applicable model.

The different sub-models were validated and a sensitivity analysis was performed to determine significant parameters on operating costs. In first simulation studies, the model was found to be appropriate to predict the total costs of an immersed MBR. It was shown that depending on local sludge treatment costs and electrical costs the optimal sludge age varies strongly between 50 and 100 days. Therefore the model can be used to identify the best SRT for each individual MBR.

Nevertheless, some improvements need to be made for the model to be more universally valid. Especially the information of bio-kinetic parameters as a function of sludge age is needed to yield a reliable prediction of the biomass concentration. Furthermore, the sludge treatment costs have to be modelled in greater detail splitting them into costs for transport, sludge thickening and dewatering and maybe also other sludge treatment routes like anaerobic digestion.

Nomenclature

ASM	Activated sludge model
b	decay coefficient [d^{-1}]
C^*	oxygen saturation concentration [mg L^{-1}]
C_{set}	Oxygen concentration in aerated tank [mg L^{-1}]
E_{pot}	Potential energy [Wh]
ESP	Excess sludge production [g h^{-1}]
h	Depth of aeration device [m]
HRT	Hydraulic retention time [h]
K_s	Half saturation constant [mg L^{-1}]
P	Power demand [kW]
Q	Influent flow rate [m^3 h^{-1}]
Q_w	Sludge flow rate [m^3 h^{-1}]
Q_{air}	Air flow rate [m^3 h^{-1}]
S	COD concentration influent [mgCOD/L]
S_0	COD concentration effluent [mgCOD/L]
SRT	Sludge retention time [d]
t	Time [d]
T	Temperature [°C]
V	Volume [m^3]
X	Biomass concentration [mg L^{-1}]
Y	Yield coefficient [mgVSS $mgCOD^{-1}$]
α	Dimensionless oxygen transfer coefficient [-]
η	Blower efficiency [-]
μ_{max}	Maximum specific growth rate [d^{-1}]
μ_{∞}	Infinite viscosity [mPas]
MLSS	Mixed liquour suspended solids [g/L]

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