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DEVELOPMENT OF A SIMULATION MODEL FOR HOLLOW-FIBER AND FLAT SHEET MEMBRANE WASTEWATER TREATMENT PLANTS

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ABSTRACT

The innovative technology of membrane wastewater treatment plants (MWWTPs) shows numerous advantages compared to classical purification techniques. Key for its commercial success is the reduction of energy consumption, enabled by the optimization of filtration using a dynamic simulation model. This paper is focused on the development of a robust and flexible membrane bioreactor simulation model for reactors with submerged flat sheet or hollow-fibre modules. Model calibration is based on standard values usually measured on MWWTPs, which increases the practical usability substantially. This is demonstrated by calibrating and validating it for a full-scale MWWTP achieving a good performance. The model is developed in Matlab [1] where it can be easily combined with Activated Sludge Models (ASM) [2].

Index Terms **-** membrane; modeling; optimization; relaxation; microfiltration; wastewater; ASM

1. INTRODUCTION

In comparison to conventionally designed wastewater treatment plants (WWTPs), membrane bioreactors offer several advantages, such as smaller installation size and lower effluent concentrations. However, the number of operating membrane plants in Germany is relatively small due to their significantly higher energy consumption with 75-80kWh per population equivalent and year [3] in comparison to conventional WWTPs with 30-50kWh [4]. This fact is closely connected with the energy used for the membrane installation amount, which is about 60% of the total energy use [5]. Thus, one possible strategy is to reduce energy consumption and costs by optimizing plant operation using a dynamic simulation model. In line with the research project EnAM “Development of a universally usable automation system for membrane bioreactors” (Entwicklung eines allgemein nutzbaren Automatisierungssystems für Membranbelebungs-anlagen), financed by the Ministry for the Environment and Conservation, Agriculture and Consumer Protection of the state of North Rhine-Westphalia, such a model is developed.

At the current state of research in membrane simulation development many different models have been developed in order to optimize the relaxation and filtration strategies to reduce the energy consumption [6, 7]. Unfortunately, some of these models rely partially on quantities which are neither measurable online nor with standard laboratory equipment. An example are extracellular polymeric substances (EPS) [8, 9]. For the practical usage on municipal MWWTP these resource-demanding models are not very manageable. This is why the local sewage treatment associations need a reliable model, which can be implemented easily into the existing plant operation using standard measurement values.

This work focuses on model development and simulation of flat sheet and hollow-fibre filtration processes to improve plant efficiency and thus to minimize plant energy consumption as well as to reduce costs for membrane cleaning. The developed universally applicable model, is calibrated as well as validated successfully for a full-scale membrane WWTP with submerged flat modules.

2. MATERIALS AND METHODS

The developed simulation model for the membrane unit of a municipal MWWTP is calibrated and validated for the MWWTP Seelscheid (NRW, Germany). Plant and model development as well as its calibration are described in detail in the following section. The model algorithm is implemented using the commercial software package Matlab, in particular the simulation toolbox Simulink.

2.1. Full-scale municipal membrane WWTP

The full-scale municipal membrane WWTP at Seelscheid with over 11,000 equivalent inhabitants is operated by the local sewage treatment association, called Aggerverband. It is equipped with 12,480m² Kubota EK400 submerged membranes [10], whose nominal pore size is 0.4µm, whereas its effective pore size during operation is considerably lower and maybe already in the ultrafiltration (UF) range as proven by Henze [11].

The 800m³ large membrane bioreactor (MBR) is divided into three tank divisions where each tank is split up into two membrane units “top” and “bottom”.

Table 1. Plant parameters

Parameter	**Value**
Relaxation	1min
Filtration	9min
Membrane area	12,480m²
Reactor volume	800m³
Reactor divisions	3
Set point reactor level	85%
Crossflow air flow rate	3x180m³/h
Permeate pumps flow	3x50m³/h
X_{TSS}	9-12g/l

The most important plant parameters are summarized in table 1.

2.2. Dynamic Simulation Model

The dynamic simulation of WWTPs offers the possibility for intelligent optimization of the plant's operating strategy. For MWWTPs one of the most crucial parts of plant operation is crossflow aeration control. On the one hand the airflow has to be minimized to save energy but on the other hand the crossflow aeration is mandatory for cleaning membrane surfaces.

With the developed dynamic simulation model it is possible to predict the needed pressure, called transmembrane pressure (TMP), to pump a given permeate flux through the membrane. Having a reliable predictor for TMP it becomes possible to estimate the needed crossflow aeration as shown below. To ensure practical usability of the model it only dependends on process values, which are commonly measured on MWWTPs. Relevant measurements are:

- total suspended solids (TSS)
- permeate flow
- suction pressure
- water temperature
- fill level of membrane tank
- crossflow aeration
- chemical cleaning protocol

The main equation of the TMP predictor is Darcy's law, which connects the permeate flow and the TMP by introducing a dynamic resistance for the membrane unit. A commonly used model is the “resistance-in-series-model” introduced by Choi [12]:

$$F(t)=\frac{\Delta p_{TM}(t)}{\left(R_M+R_{DS}(t)+R_F(t)\right)\cdot\eta\left(T(t)\right)} \tag{1}$$

where the transmembrane pressure $\Delta p_{TM}(t)$ is obtained from the measured suction pressure $p(t)$ via eq. 2:

$$p(t)=-\Delta p_{TM}(t)+p_{water}(t) \tag{2}$$

$\Delta p_{TM}(t)$	transmembrane pressure	mbar
$\eta\left(T(t)\right)$	dynamic viscosity [13]	$kg\cdot m^{-1}\cdot s^{-1}$
$F(t)$	permeate flux	$l\cdot m^{-2}\cdot h^{-1}$
$R_{DS}(t)$	cake layer resistance	m^{-1}
R_M	intrinsic membrane resistance	m^{-1}
$R_F(t)$	fouling resistance	m^{-1}
$p(t)$	suction pressure	mbar
$p_{water}(t)$	pressure of the water head on the pressure sensor	mbar
$X_{TSS}(\tau)$	total suspended solids	$g\cdot l^{-1}$
$Q_{cross}(\tau)$	crossflow aeration	$m^3\cdot d^{-1}$

Therefore, the internal state of the model consists of the sum of three resistances R_M, $R_{DS}(t)$ and $R_F(t)$ representing the dynamic behavior of the membrane. The advantage of using the “resistance-in-series-model” is the flexibility, where newly discovered effects regarding the membrane behavior can be extended by adding further resistances.

2.2.1. The membrane resistances

The intrinsic membrane resistance R_M is a constant resistance, which is modeling the intrinsic non-varying physical property of a membrane.

The cake layer resistance $R_{DS}(t)$ is modeling the additional resistance of the membrane caused by the sludge accumulated on the membrane surface. The so called cake mass is assumed to be affected by the amount of total suspended solids $X_{TSS}(\tau)$, the permeate flux $F(\tau)$ and the dynamic viscosity $\eta\left(T(t)\right)$ of the water, eq. 3.

$$\begin{aligned}R_{DS}(t)=\int_0^t & r_{DS}\cdot F(\tau)\cdot\eta\left(T(\tau)\right)\cdot X_{TSS}(\tau)\\ & -k_r\cdot Q_{cross}(\tau)-k_p\cdot P(\tau)\,d\tau\end{aligned} \tag{3}$$

The cake layer is decreased by the shear force induced by the crossflow aeration $Q_{cross}(\tau)$ and by cake mass erosion due to water movement, like turbulence, which is modeled by $P(\tau)$.

The cake layer resistance depends on three parameters $r_{DS}>0$, $k_r>0$ and $k_p>0$, which are estimated during model calibration.

The fouling resistance $R_F(\tau)$ is modeling the degradation of the membrane due to the amount of permeate flux $F(\tau)$, which is pumped through the membrane over the years [14], $S_F>0$, $k_F>0$:

$$R_F(t)=S_F\cdot\left(1-\exp\left(-k_F\cdot\int_0^t F(\tau)d\tau\right)\right) \tag{4}$$

r_{DS}	cake mass accumulation rate	m·bar·g^{-1}
k_r	specific crossflow aeration efficiency	m^{-4}
k_p	specific erosion rate	m^{-1}·d^{-1}
S_F	fouling resistance in saturation	m^{-1}
k_F	fouling coefficient	m^{-1}

2.3. State-machine

In order to indicate a unique state in which the MWWTP system resides, a finite state-machine is implemented with the following states:

1. filtration
2. relaxation / backwash
3. pause
4. fine chemical in-situ cleaning
5. main chemical cleaning

Depending on the state of the plant, modelled by the state-machine, different parts of the formulas are active. For example there is only permeate flux in the filtration state and only crossflow aeration in the filtration and relaxation phase.

The chemical in-situ cleaning period, which is done repetitively on hollow-fibre membrane WWTPs, is modelled by reducing the cake layer resistance. After that, the main chemical cleaning period resets the cake layer and reduces the fouling resistance [14].

2.4. Calibration Method

To calibrate the model for a specific MWWTP the parameters in the equations of the model, eq. 1 - 4, are determined solving a constrained linear least-squares problem. In order to do this, the equations are written linearly with respect to the open parameters, e.g. r_{DS}, k_r, k_p and S_F. To give an example the cake layer resistance in eq. 3 can be written like this:

$$R_{DS}(t)=\begin{bmatrix} \int_0^t F(\tau)\cdot\eta\left(T(\tau)\right)\cdot X_{TSS}(\tau)d\tau \\ -\int_0^t Q_{cross}(\tau)d\tau \\ -\int_0^t P(\tau)d\tau \end{bmatrix}^T\cdot\begin{pmatrix} r_{DS} \\ k_r \\ k_p \end{pmatrix} \tag{5}$$

To solve the problem numerically the integrals are discretized with a time-grid, $0\leq\tau_i\leq t$, $i=1,\ldots,N$, given by the available measurement time series gotten from the plant, each having N measurements. So that, the discrete integrals in the equations are evaluated at each time-step $i=1,\ldots,N$ by inserting the needed measurement values until time τ_i. These evaluated integrals are concatenated vertically to give, for $R_{DS}(t)$, three N dimensional column vectors. These column vectors are used as basis functions for a to be defined least-squares curve fitting problem.

The model to be fit is Darcy's law, which, using eq. 1 and 2, can be written as:

$$p(t)=p_{water}(t)-\Delta p_{TM}(t) \tag{6}$$

with

$$\Delta p_{TM}(t)=F(t)\cdot\left(R_M+R_{DS}(t)+R_F(t)\right)\cdot\eta\left(T(t)\right) \tag{7}$$

Inserted eq. 6 in eq. 7 the resulting one is written linearly in dependence of the model parameters using the calculated basis functions.

This is done for each time-step τ_i, what leads to a linear system of equations, whose residual has to be minimized by solving the constrained linear least-squares problem:

$$\hat{\boldsymbol{p}}=\underset{\boldsymbol{p}}{arg\,min}\left|\boldsymbol{A}\cdot\boldsymbol{p}-\boldsymbol{b}\right| \qquad \text{subject to} \quad \begin{matrix}\boldsymbol{LB}\leq\boldsymbol{p}\leq\boldsymbol{UB} \\ \boldsymbol{C}\cdot\boldsymbol{p}\leq\boldsymbol{d}\end{matrix} \tag{8}$$

Here $\boldsymbol{p}\in\mathbb{R}^p$ is the parameter vector of $p\in\mathbb{N}^+$ parameters, $\boldsymbol{LB}\in\mathbb{R}^p$ and $\boldsymbol{UB}\in\mathbb{R}^p$ are the lower resp. upper bound vectors for the parameters, $\boldsymbol{A}\in\mathbb{R}^{N\times p}$ is the measurement matrix, $0\leq\tau_i\leq t, 1\leq i\leq N$:

$$\boldsymbol{A}=\begin{bmatrix} p_1-F\eta_1\cdot\boldsymbol{R}(1,1) & \ldots & p_1-F\eta_1\cdot\boldsymbol{R}(1,p) \\ \vdots & \vdots & \vdots \\ p_i-F\eta_i\cdot\boldsymbol{R}(i,1) & \ldots & p_i-F\eta_i\cdot\boldsymbol{R}(i,p) \\ \vdots & \vdots & \vdots \\ p_N-F\eta_N\cdot\boldsymbol{R}(N,1) & \ldots & p_N-F\eta_N\cdot\boldsymbol{R}(N,p) \end{bmatrix} \tag{9}$$

with $p_i := p_{water}(\tau_i)$ and $F\eta_i := F(\tau_i) \cdot \eta\left(T(\tau_i)\right)$. $\boldsymbol{b} = \left(p(0), p(\tau_i), p(t)\right)^T \in \mathbb{R}^N$ is the target vector, which here is the vector of the measured suction pressures. The matrix $\boldsymbol{R} \in \mathbb{R}^{N \times p}$ stands symbolically for the matrix gotten from the membrane resistances; eq. 5 shows an example of a part of the matrix. The $m \in \mathbb{N}^+$ linear inequality constraints $\boldsymbol{C} \cdot \boldsymbol{p} \leq \boldsymbol{d}$, with matrix $\boldsymbol{C} \in \mathbb{R}^{m \times p}$ and vector $\boldsymbol{d} \in \mathbb{R}^m$, assure that e.g. all resistances $R_{DS}(\tau_i)$, $R_F(\tau_i)$ are positive for every $i = 1, \ldots, N$.

The optimal parameter vector $\hat{\boldsymbol{p}} \in \mathbb{R}^p$ is obtained by solving the optimization problem in eq. 8.

2.5. Validation

Since the optimization problem minimizes the mean squared error (MSE) between the measured $\boldsymbol{p}(\tau_i) \in \mathbb{R}^N$ and simulated $\hat{\boldsymbol{p}}(\tau_i) \in \mathbb{R}^N$ suction pressure the performance measure $v \in \mathbb{R}$ is defined as the RMSE between the values of both pressure time series:

$$v = \sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} \left(\boldsymbol{p}(\tau_i) - \hat{\boldsymbol{p}}(\tau_i)\right)^2} \tag{10}$$

3. RESULTS AND DISCUSSION

As a matter of principle the simulation model is developed in order to match the behavior of hollow-fibre and flat sheet membrane wastewater treatment plants. With the purpose to obtain good results for the simulation, the model parameters have to be adjusted by the calibration using measured values from the plant. In order to do this the simulation model is calibrated and validated for the flat sheet full-scale municipal membrane WWTP at Seelscheid.

3.1. Simulation model calibration and validation

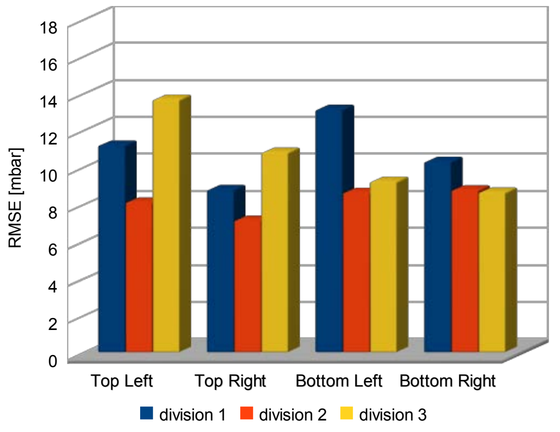

Figure 1. Calibration from 2009-03-05 to 2009-04-11

The simulation model calibration using the method of constrained linear least-squares has been proven to provide good calibration results. In order to compare the simulated model with the full-scale plant, the simulated and measured pressure is investigated from 2009-03-05 to 2009-04-11. Figure 1 illustrates the RMSE for the calibration period in a bar plot. As it can be seen, division two has the lowest RMSE, which means that the calibration is better than for the other ones. Table 2 explains the RMSE results in detail.

Table 2. Calibration RMSE overview from 2009-03-05 to 2009-04-11

Position	Division 1 *mbar*	 2 *mbar*	 3 *mbar*
Top Left	11.17	8.09	13.64
Top Right	8.76	7.11	10.78
Bottom Left	13.09	8.61	9.20
Bottom Right	10.28	8.74	8.62
Mean	10.38	8.14	10.56

In order to determine that the calibrated simulation model is an accurate representation of the real system, a validation with measured data from 2009-04-11 to 2009-04-28 is done.

Table 3. Validation RMSE overview from 2009-04-11 to 2009-04-28

Position	Division 1 *mbar*	 2 *mbar*	 3 *mbar*
Top Left	15.79	8.75	13.64
Top Right	14.43	8.15	9.42
Bottom Left	17.77	9.43	8.09
Bottom Right	15.38	8.94	8.86
Mean	15.84	8.82	9.92

Figure 2 illustrates the RMSE for the calibration period in a bar plot and table 3 shows the RMSE validation results in detail. In comparison to the

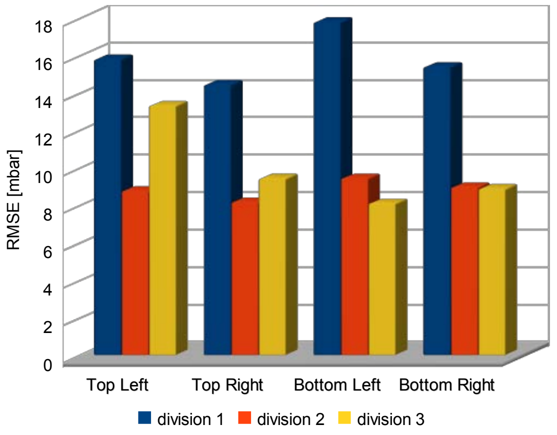

Figure 2. Validation from 2009-04-11 to 2009-04-28

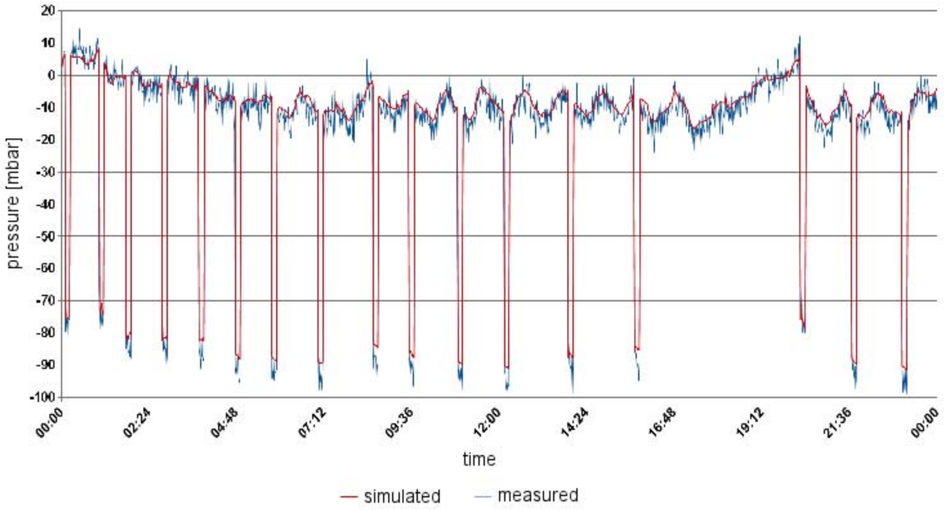

Figure 3. Measured against validated pressure of the third MBR division on 2009-04-27

calibrated RMSE results the behavior of the validation results of each division is similar. Only the RMSE of division one is higher than on the other divisions, which comes from the TMP range where the maximum TMP is 250mbar. The maximum TMP on the other divisions is varying from 150mbar to 200mbar. In order to see this in detail, figure 3 illustrates the measured pressure against the simulated of the third MBR division on 2009-04-27.

Based on these results it can be stated that a simulation model is developed, calibrated and validated successfully by focusing on its practical usability.

4. CONCLUSION

A fully calibrated and validated membrane simulation model of a full-scale municipal membrane WWTP with submerged flat modules is developed. The model combines the simulation behavior of membranes with the practical utilizability for local associations for sewage treatment. Because of the seven input measurement variables TSS, permeate flow, suction pressure, water temperature, fill level of membrane tank, crossflow aeration and chemical cleaning protocol the simulation model can be used on any municipal MWWTP, where standard measurement equipment is installed.

Another advantage of this developed dynamic simulation model is the adaptability to existent WWTP simulation models, where an ASM, for instance ASM1, is used. In this kind of models the common variables TSS, temperature or permeate flow are utilized and can be easily connected with the membrane simulation model.

Based on the good simulation results for the MWWTP Seelscheid, it can be concluded that the model is able to simulate the behavior of MWWTP with flat sheet modules. Currently the simulation model is adapted to a hollow fiber WWTP in line with the research project EnAM. Furthermore a control strategy, which is based on this model is under development.

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