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# Introduction to the Growth and Modelling of Biofilms in Ultrafiltration and Reverse Osmosis Plants

**In the environment, there is actually no surface without the potential for adhesion of biofilms. Especially in membrane processes, biofilms have a negative effect on the performance, resulting in higher energy costs, higher efforts for cleaning and a lower durability of membranes. Within a research project, the possibilities of a process water production from brewery waste water will be explored. A part of this research project is the examination of biofouling for the purpose of process optimization. This essay gives an overview about biofilms and their effects on membrane processes as well as an introduction to biofilm modeling. In the next part of this article series, first results of the research project will be presented.**

Descriptors: membranes, biofilm, biofouling, biofilm modelling, wastewater treatment

## 1 Introduction

Biofilms are one of the most successful life forms and can be found in almost every environment. Biofilms are beneficial in natural aquatic systems and their ability to remove toxic materials is utilized in wastewater treatment plants. On the other hand, biofilms or biofouling – defined as a performance reducing accumulation in technical systems [1] – have desirable effects on the water quality.

Within a research project, the treatment of brewery waste water with a membrane bioreactor, followed by an ultrafiltration (UF) and a reverse osmosis (RO) will be explored. It is the goal of this project to improve the utilisation of water by means of reliable process technology without or with only minimal use of chemicals in order to improve the environmental record of an enterprise in the food industry. A part of this research project is the examination of biofouling on the membranes for the purpose of process optimization.

In the first part of this essay, the theoretical basics of the growth of biofilms will be given and appropriations for the modelling of biofilms will be shown. Therefore a well known model by Wanner and Gujer was selected to explain the principles of Biofilm modelling.

The second part presents the used sensor technology as well as first results of the research project. The sensors, installed in the inlet of the UF and RO, detect online the growth of the biofilm. In combination with the detection of the technical parameters (membrane permeability, pressure, recovery, etc.) and the water

parameters (COD, pH, etc.) new possibilities for the characterization of the membrane performance will be offered.

## 2 Biofilms and biofouling in membrane processes

In the field of membrane processes, an essential part of operational costs can directly or indirectly be traced back to biofouling and associated counteractive measures. In case of biofouling, microorganisms deposit on the membrane surface, building extracellular polymeric substance (EPS) and embed themselves into it [1]. Biofilms are unavoidable in all non-sterile systems and therefore a decrease of permeate flux up to 10 % must be accepted [1].

Biofilms create a gel shift on the membrane surface, which acts as a secondary membrane and increases the hydraulic resistance. The additional trans-membrane pressure drop, caused by the biofilm, causes a decline of the permeate flux (at fixed feed pressure) or an increasing feed pressure (at fixed permeate flux) [2].

The consequences of biofouling on membranes are listed below [2]:

Higher membrane resistance:

- reduction of permeate recovery;
- higher demand of energy;
- higher trans-membrane pressure drop.

Gel phase between membrane surface and water:

- increase of pressure drop between feed and brine;
- degradation of salt rejection.

Damnation of the membrane modules:

- microbiological attack on membranes;

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Figures see Appendix

- Shortening of life-time of modules, caused by frequent cleaning procedures;
- Passage of microorganisms with a contamination of the permeate.

Higher costs:

- lowered facility capacity;
- worse product quality;
- higher energy input;
- higher effort for cleaning and longer downtime;
- lower durability of membranes.

For the removal of biofilms, the mechanical stability must be weakened first by chemical substances (oxidants as chlorine, ozone, peracetic acid) or alkaline agents (tenside or enzymes). In the second step, the biofilm has to be removed mechanically by flushing [2]. A solely killing of the microorganisms in the biofilm can have a positive short term effect on the permeability, but it is an excellent basis for the growth of a new biofilm [1].

### 3 Formation of biofilms

A biofilm consists of 5 components [3]:

- water (60–98 % of moisture content);
- extracellular polymeric substances (EPS);
- microorganisms;
- in storage particular material;
- solutes.

The basic requirement for the formation of biofilms is the interaction between microorganisms, surfaces, nutrients and humidity. According to Flemming [3] the formation of biofilms can be divided into three sections (Fig. 1):

#### Initial settlement

During the initial settlement, a settling of microorganisms and macromolecules at the surface can be noticed [3].

When surfaces come in contact with water, they will be conditioned by a type of natural glue, that consists of humic acids, proteins and polysaccharide molecules. These substances come to the surface due to the degradation of organic matter and create a “conditioning film” [4].

It is the basis for the settlement of microorganisms and influences significantly the primary adhesion, the rapid allocation of surface

with the bacteria suspension within the first hours of contact. The transport of microorganisms from the surrounding media takes place by advection and turbulent diffusion. The period of the induction phase can vary from hours/days in systems with high concentrations of nutrients and microorganisms and months in heavily oligotrophic systems [3].

#### Exponential growth

This phase is denoted by adsorption of new microorganisms (passive aggregation) and the growth of already existing cells (active aggregation) [3, 5]. During this phase, the supply of nutrients and the temperature of the media are particularly important. This phase is controlled by the transport processes in the biofilm, especially by the resistance of diffusion in the gel-matrix. New cells, which accumulate to the biofilm, mostly don't get in contact with the original surface [3].

#### Plateau phase

The majority of biofilms exist in a dynamic balance (plateau phase) with a limited thickness. The height of the biofilm is a decisive factor, because the lowest shifts (at a depth of 100–200 µm) of the biofilm are not involved in the metabolism with the fluid phase [3].

The biofilm is in a balance between the regeneration by adsorption and accretion and the detachment by erosion and sloughing. The detachment is influenced by various factors. One factor is the physical strength of the biofilm. If the shear stresses are higher than the cohesion, an erosion of biofilms will happen. However, shear stresses have only an effect on the parts of the biofilm, which are out of the laminar boundary layer. Furthermore, parts of the biofilm can be removed by variation of temperature or pH-value such as the degradation by higher organisms or an active disengagement of single cells [6].

Higher shear forces don't prevent the creation of biofilms, but lead to creation of denser and thinner biofilms [3, 7].

### 4 Modelling of biofilms

A model is a simplified description of a part from the reality. The model can be either a cutout from reality, or a simplified model, expressed by mathematical formulas [6]. If simplified models are used, a choice of processes and parameters must be made, which are considered in the modelling.

In the case of membrane treatment plants, the following parameters should be regarded:

- flux parameters (velocity, turbulence, viscosity);
- water parameters (temperature, chemical composition);
- membrane parameters (design, material, operating time, pore size);
- biofilm parameters (composition, thickness, density).

The modelling of biofilm systems depends strongly on the goal setting of the model. There is a distinction between equation-based models and biological/rule based models. In equation-based models, relations are constructed between characteristic physical values by using algebraic and differential equations. Biological/rule based models are based on behavioral rules, e.g. the behavior of microorganisms [8].

A lot of biofilm models have been developed in the last thirty years, paralleled by a dramatic increase in experimentally gained knowledge and a fast-growing computational capacity. Some models are relatively simple and are used for technical applications, whereas some are rather complex and were developed as research tools to analyze experimental data or to test new hypotheses [9].

One-dimensional models are used more often than three-dimensional models, because of their simplicity and the lower requirements for a numerical simulation [8]. One-dimensional models assume that the biofilm is homogeneous in layers parallel to the substratum [10]. But complex structures with spatial model composition couldn't be expressed with such models [11].

Hereafter the model of Wanner und Gujer [12] is presented, which was introduced in 1986 and improved over the years, becoming the standard model for many real biofilms [10]. This model allows a calculation of the thickness of biofilms and the allocation of particular solute substances in biofilms and fluids in dependence of time and distance to the surface.

The biofilm system can be seen as a three-part complex, which consists of the parallel layers: surface of material or growth body, biofilm and free fluid (Fig. 2).

The biofilm consists of different phases, such as liquid including dissolved and suspended particles, extracellular polymeric substances and different solid phases. However, these single phases are not locatable in the one-dimensional model. The volume fraction  $\delta_s$  of each phase must be calculated and summarized.  $\delta_f$  is the volume fraction of the liquid phase.

$$\delta_f + \sum_s \delta_s = 1 \quad (\text{Eq. 1})$$

In the free liquid microbe clusters or inorganic micro particles are ignored:

$$\delta_f = 1 \quad (\text{Eq. 2})$$

Every phase  $s$  of the biofilm contains specific components  $i$  (e.g. pollutants, nutrients, bound particles or oxygen). The goal of the model is the prognosis of the concentration of components in the different biofilm phases, in dependence on time  $t$  and distance to the surface.

Because it is not feasible to integrate all phenomena observed in heterogeneous biofilms into the general model, the biofilm model by Wanner and Gujer is based on a number of simplifying assumptions [8, 10].

- The volume fraction  $\delta_f$  of the liquid phase of the biofilm is constant.

- The liquid phase contains only dissolved components.
- Transport of the dissolved components in the liquid phase is by molecular diffusion.
- The dissolved components in the liquid phase are electrically neutral and behave ideally: Fick's first law of diffusion describes molecular diffusion.
- The ratio  $D_i^{(f)}/D_i^{(b)}$  of diffusion coefficients in the biofilm and in pure water is constant.
- The density  $\rho$  of the constituent particulate components, phase  $s$ , is only dependent on the position  $z$ .
- Advective transport (displacement) of the solid phase is the result of volume changes of the constituent particulate components.
- The advective velocities  $v_s$  for all solid phases are equal ( $v_s = v \nabla s$ ).

With these assumptions it is possible to determine the volume fractions  $\delta_s$  of the solid components (e.g. microbial species, biomass).

$$\rho_s \frac{\partial \delta_s}{\partial t} = - \frac{\partial v \rho_s \delta_s}{\partial z} \quad \forall s \quad (\text{Eq. 3})$$

The advective velocity  $v$  is a result of displacement of particulate components caused by biomass production and described by the differential equation:

$$\frac{\partial v}{\partial z} = \frac{1}{1 - \delta_f} \sum_s \frac{r_s}{\rho_s} \quad (\text{Eq. 4})$$

with the production rate  $r_s$ .

The mass transport of the liquid phase inside of the biofilm is dominated by diffusion while convection is important for the overall mass transport towards the biofilm [13]. Conditions, where other transport effects can play a significant role are described in [14–16].

The concentrations  $c_{fi}$  of the components in the liquid phase inside of the biofilm are modeled by:

$$\frac{\partial c_{fi}}{\partial t} = f \cdot D_i \frac{\partial^2 c_{fi}}{\partial z^2} \quad (\text{Eq. 5})$$

The empiric factor  $f$  accounts for the tortuosity due to the complex geometry inside the biofilm. So the particles cannot move straight along the diffusion gradient.

To solve the biofilm model for concrete cases, the initial values for  $c_{fi}(t_0, z)$  and  $\delta_s(t_0, z)$  must be set. Further, the system-specific parameters  $\delta_s, \delta_p, r_s$  must be determined experimentally.

The biofilm model by Wanner and Gujer is only one of a large spectrum of possible biofilm models, developed in the recent years [6, 8, 9, 10, 13, 15–20]. Also the number of transport and growth processes incorporated in the model has increased with the consequence that dozens of parameters have to be determined. Following Hoesel and Walcher [10] an adding of further parame-

ters and components is not the promising strategy. Instead of one universal model a simple model, addressing interesting partial aspects, could be more favourable.

Thus, in the second part of this article first results of the biofilm measurement within the research project and the approach of an integration into a biofilm model will be presented.

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## 5 References

1. Melin, T. and Rautenbach, R.: Membranverfahren, Grundlagen der Modul- und Anlagenauslegung; 3<sup>rd</sup> ed., Springer-Verlag, Berlin Heidelberg, 2007, pp. 260, 336-338.
2. Flemming, H.-C.: Biofouling bei Membranprozessen, Springer-Verlag, Berlin Heidelberg, 1995, pp. 13, 118.
3. Flemming, H.-C.: Biofilme, Biofouling und mikrobielle Schädigung von Werkstoffen, Habilitationsschrift, Kommissionsverlag R. Oldenburg, 1994, pp. 24-59, 65.
4. Carbonit Filtertechnik GmbH: Biofilms – Friend or foe? Correct handling of these constant human companions, Internet: <http://www.lagotec.de/images/stories/biofilms%20friend%20or%20foe.pdf> (accessed 07 June 2011).
5. Marshall, K. C.: Microbial adhesion and aggregation, Springer-Verlag, Berlin Heidelberg, 1984, p. 424.
6. Hunze, M.: Simulation in der kommunalen Abwasserreinigung, Oldenburg Industrieverlag, München, 2005, pp. 27, 188.
7. Christensen, B.E. and Characklis, W.G.: Physical and chemical properties of biofilms, In: Characklis, W.G.; Marshall, K.C. (eds.): Biofilms, John Wiley, New York, 1990, pp. 93-130.
8. Mehl, M.: Ein interdisziplinärer Ansatz zur dreidimensionalen numerischen Simulation von Strömung, Stofftransport und Wachstum in Biofilmsystemen auf der Mikroskala, Dissertation, TU München, 2001, pp.24-29.
9. Wanner, O.: Modeling of biofilms. In: Encyclopedia of environmental microbiology, John Wiley, New York, 4 (2002), pp. 2083-2095.
10. Hösel, V. and Walcher, S.: On the mathematical modeling of biofilms, GSF-Forschungszentrum für Umwelt und Gesundheit, Neuherberg, 1999, p. 4.
11. Lasser, R.; Efendiev, M. and Demaret, L.: Mathematical Analysis of Dynamic Systems in Biofilm Modeling, In: Annual Report 2005, GSF Forschungszentrum für Umwelt und Gesundheit, 2005, pp. 27-32.
12. Wanner, O.; Gujer, W.: A multispecies Biofilm model, Biotechnology and Bioengineering, 28 (1986), pp. 314-328.
13. Picioreanu, C.; van Loosdrecht, M.C.M.; Heijnen, J.J.: Effect of Diffusive and Convective Substrate Transport on Biofilm Structure Formation: A Two-Dimensional Modeling Study, Biotechnology and Bioengineering, 69 (2000), no.5, pp. 504-515.
14. Eberl, H.J.; Parker, D.F. and van Loosdrecht, M.C.M.: A new deterministic spatio-temporal continuum model for biofilm development, Journal of Theoretical Medicine, 3 (2001), pp. 161-175.
15. Wanner, O.; Eberl, H.J.; Morgenroth, E.; Noguera, D.R.; Picioreanu, C.; Rittmann, B.E. and van Loosdrecht, M.C.M.: Mathematical modeling of biofilms, IWA Publishing, London, 2006.
16. Eberl, H.J. and Sudarsan, R.: Exposure of biofilms to slow flow fields: The convective contribution to growth and disinfection, Journal of Theoretical Biology, 253 (2008), pp. 788-807.
17. van Loosdrecht, M.C.M.; Heijnen, J.J.; Eberl, H.; Kreft, J. and Picioreanu, C.: Mathematical modeling of biofilm structures, Antonie van Leeuwenhoek, 81 (2002), pp. 245-256.
18. Alpkvist, E.; Picioreanu, C.; van Loosdrecht, M.C.M. and Heyden, A.: Three-Dimensional Biofilm Model With Individual Cells and Continuum EPS Matrix, Biotechnology and Bioengineering, 94 (2006), no.5, pp. 961-979.
19. Chambless, J.D. and Stewart, P.S.: A Three-Dimensional Computer Model Analysis of Three Hypothetical Biofilm Detachment Mechanisms, Biotechnology and Bioengineering, 97 (2007), no.6, pp. 1573-1584.
20. Duddu, R.; Chopp, D.L. and Moran, B.: A Two-Dimensional Continuum Model of Biofilm Growth Incorporating Fluid Flow and Shear Stress Based Detachment, Biotechnology and Bioengineering, 103 (2009), no.1, pp. 92-104.

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Appendix

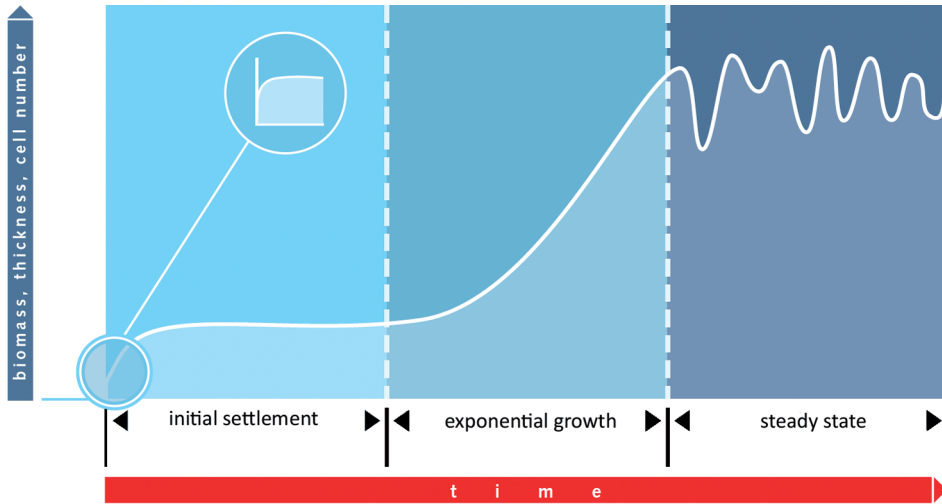


Fig. 1 Formation of biofilms [4]

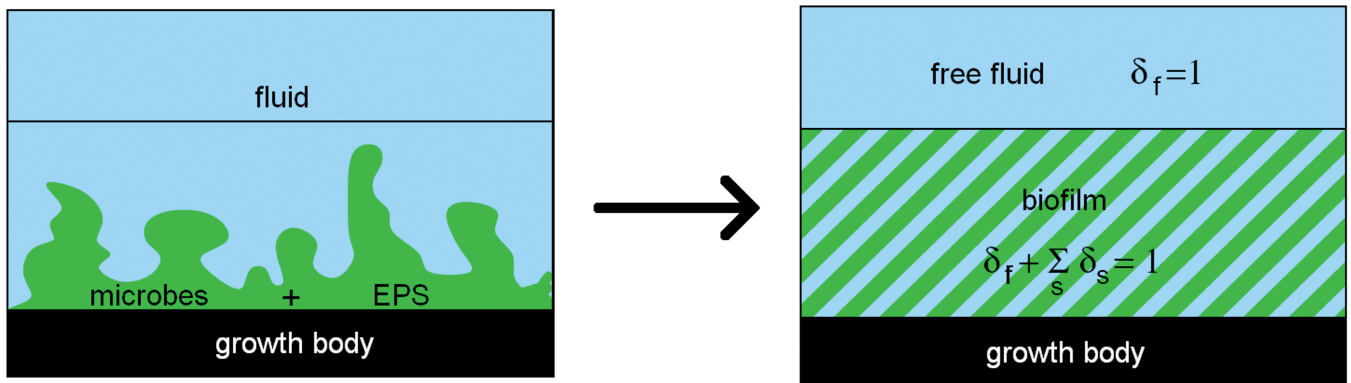


Fig. 2 Transition from reality to the layer model [8]