On the Drying Dynamics in Biofilters

Friedhelm Schönfeld[*1]
[1] Hochschule RheinMain - University of Applied Sciences,
FB Ingenieurwissenschaften
Am Brückweg 26, 65428 Rüsselsheim, friedhelm.schoenfeld@hs-rm.de

Abstract: To a large extent the performance of biofilters relies on the presence of suitable amounts of water in order to provide conditions needed for microbiological degradation of pollutants to take place. In many cases breakdown of filtration performance occurs due to inappropriate water contents in the filter material. The present study focuses on the drying dynamics within such filters, which are modeled as wetted porous media. Analyzing the governing equation of gas flow and water content reveals that such systems are prone to exhibit instable behavior. Small variations in the initial conditions e.g. slight inhomogeneities in moisture or porosity are likely to be amplified during operation until breakdown occurs. The time constants for such coupled drying processes are analyzed within a 1-D modeling approach. Furthermore, details of flow heterogeneity and drying are investigated by means of two and three dimensional models, which are solved by means of COMSOL Multiphysics.

Keywords: biofilter, porous media, drying

1. Introduction

Biofilters provide cost efficient means for removal of odors and other pollutants from air streams. The humidified air stream passes through the biofilter substrate, where pollutants are degraded by microbiological processes. Among others the filtration performance relies on the presence of the right amount of water in the biofilter material. One of the most frequent reasons for breakdown of biofilters lies in unfavorable water contents in the filter material. On the one hand too much ~~of~~ water causes agglomeration and clogging of the filter material, while on the other hand too little water leads to complete drying and breakdown (cf. Figure 1).

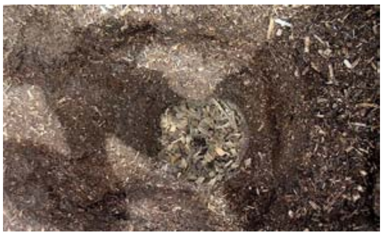

Figure 1. Partly dried out biofilter.
Courtesy of REINLUFT Umwelttechnik, Germany.

In spite of the importance of the water balance in the filter, details of the drying process have not been analyzed in depth so far, to the best of the author's knowledge. In the present study we formulate a minimum model taking flow distribution, evaporation and the water dependent permeability into account. We find that due to the strong interdependencies thereof, the operation of biofilters can suffer from inherent instabilities. A small variation in the initial moisture can lead to a complete breakdown of the filter as schematically shown in Figure 2.

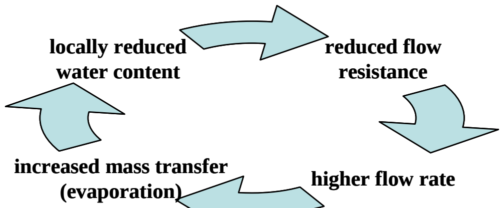

Figure 2. Processes involved in drying within biofilters, leading to a possible instable behavior, and breakdown.

2. Modeling approach

The present study focuses on the mathematical modeling of drying and gas flow. First, the time constants for such coupled drying processes are analyzed within a 1-D modeling approach. Second, details of flow heterogeneity and drying are investigated by means of two dimensional (2-D) and three dimensional (3-D) FEM models. For the formulation of a minimum model, we restrict ourselves to the most important aspects, *viz.* fluid dynamics of the gas stream in free an porous regions, evolution of the liquid water content in the filter medium and mass transfer from the liquid into the air stream. On the one hand the restriction to these phenomena helps keeping the model tractable, while on the other hand it allows identifying the basic mechanism for the formation of dry zones. Surely, the model is way too simple to allow predictive simulations of the complete biofilter performance, since metabolism and heat generation of micro organisms, the formation of biofilms, condensation, external influences and several further aspects are not incorporated. However, as will be shown the model is valuable to gain insight into the basic mutual dependence between gas flow and reduction in water content and allows analyzing the basic drying dynamics.

2.1 Governing equations 1-D Model

A generic model geometry is shown in Fig. 3. For writing down the basic equations in the one dimensional case we define $y(t)$ as the time dependent average volume fraction of liquid water within the filter material. The filter material is modeled as a porous medium, for the porosity of which we assume

$$\varepsilon = \varepsilon(y) = \varepsilon_0(1-y)\,. \quad (1)$$

$y=1$ denotes complete wetting with the filter medium being blocked for the gas stream ($\varepsilon(1)=0$), while $y=0$ denotes the dry state with the maximum porosity ε_0.
The pressure drop of the gas flow within the porous medium obeys a Forchheimer type of equation which according to Ergun [1] reads

$$\frac{\Delta p}{L} = 150\,\frac{(1-\varepsilon)^2}{\varepsilon^3}\,\frac{\mu_g}{d_p^2}\,u_0 + 1.74\,\frac{1-\varepsilon}{\varepsilon^3}\,\frac{\rho_g}{d_p}\,u_0^2\,. \quad (2)$$

Here, u_0, μ_g and ρ_g denote the superficial velocity, dynamic viscosity and density of the gas stream, respectively. d_p, denotes the equivalent particle diameter of the porous medium and L denotes the length of the packed bed in flow direction. For a given pressure drop the gas flow velocity depends on the porosity $\varepsilon(y)$ via Eq. (2).
In order to account for mass transfer from the wetted material into the gas stream we apply the correlation for the Sherwood number given by Ranz [2] (see also Levenspiel [3])

$$Sh(y) = 2 + 1.8\left(\frac{\nu_g}{D^g_{H_2O}}\right)^{1/3}\left(\frac{d_p}{\nu_g}\,\frac{u_0(y)}{\varepsilon(y)}\right)^{1/2}\,, \quad (3)$$

where $D^g_{H_2O}$ denotes the diffusion coefficient of vapor in the gas phase and ν_g the kinematic gas viscosity. The overall reduction in the mass density of liquid water in the porous medium is governed by

$$\dot{m} = Sh(y)\,\frac{D^g_{H_2O}}{d_p}\cdot A\cdot \Delta c^g_{H_2O}\,, \quad (4)$$

with A being the specific total wetted area $A = \frac{6}{d_p}(1-\varepsilon_0)$ and $\Delta c^g_{H_2O}$ being the difference between the equilibrium vapor concentration at the water interface and the vapor concentration in the gas stream. Casting Eq. (4) into the respective equation governing the reduction of the water volume fraction and inserting Eq. (3) we find

$$\dot{y} = -\alpha\left(2 + 1.8\beta\sqrt{\frac{u_0(y)}{\varepsilon(y)}}\right)\,, \quad (5)$$

where all material parameter have been lumped into the constants α and β, given in Appendix II. $u_0(y)$ denotes the superficial velocity given by Eqs. (1) and (2) for specific material parameters and a prescribed, constant pressure drop. Within the present study we restrict ourselves to low and moderate velocities in the filter medium and regard only the linear term in the Ergun equation (2). By inserting Eq. (1) and the linear term of (2) equation (5) translates to

$$\dot{y} = -\alpha\left(2 + 1.8\beta\,\delta\left(\frac{1}{1-\varepsilon_0(1-y)} - 1\right)\right)\,, \quad (6)$$

with α, β and δ given in Appendix II. The solution of the differential equation (6), which involves the product logarithm, is numerically computed by means of Mathematica [4].

2.2 Use of COMSOL Multiphysics

2-D and 3-D models have been set up using the modules ‘Free & Porous Media Flow’ of COMSOL [5] for simulating the air/vapor flow in the whole filter and the ‘PDE’ module has been applied for the simulation of the water content in the filter material. The model specifications together with a generic 2-D geometry are sketched in Fig. 3.

As a first step, simulation data have been compared to the 1-D model (Eq. (6)), solved by means of Mathematica, in order to validate the FEM approach. To this end a homogeneous porosity and water volume fraction was specified as initial guess and a slip boundary condition has been applied to the walls of the porous matrix. It was found that the differences between the results of both approaches are below 1%.

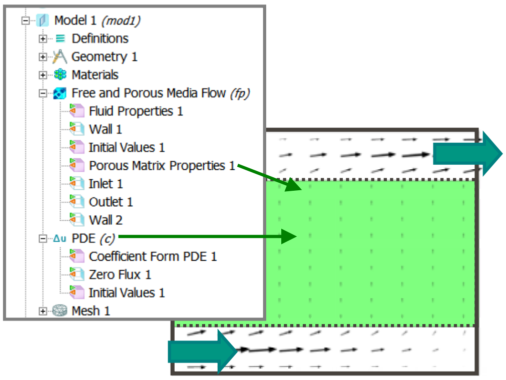

Figure 3. Generic geometry of a 2-D biofilter simulation and COMSOL model tree showing the applied modules.

4. Results

4.1 1-D Model

Results for the homogeneous average volume fraction of water within the pores of the filter material $y(t)$ are shown in Fig. 4, for initial water contents $0.8 \le y_0 < 1$. The complete set of parameters used in the simulations is given in Appendix III. Large volume fractions close to one imply slow flow velocities due to the high pressure drop leading to relatively low drying rates. Whereas a lower water content causes an accelerated flow and higher drying rates. Note, that a strong dependence of the drying time on the initial water content is observed, e.g. reducing the initial water content from almost one by 5% leads to a reduction in the drying time of about 30%.

With respect to real biofilters these simulations show that the drying dynamics, in particular the time for completed drying, strongly depends on the initial amount of water in the filter medium.

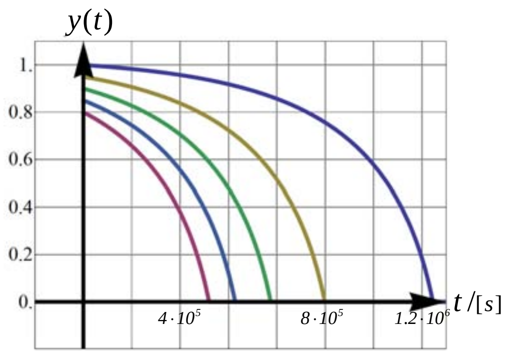

Figure 4. Homogeneous model: time dependent water volume fraction for various initial values $0.8 \le y_0 < 1$.

The sensitivity of the drying rate on the initial condition is also highlighted in Fig. 5 showing the absolute initial drying rate, i.e. absolute of the right hand side in Eq. 6., as function of the initial water content.

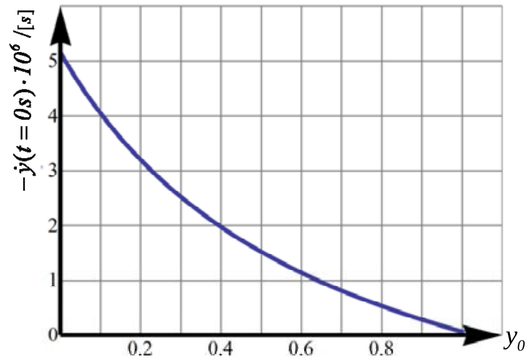

Figure 5. Absolute drying rate vs. water content (cf. Eq. 6).

Moreover, the 1-D model approach, Eq. (6), can be used to investigate the dependence of drying on the porosity of the dry filter material, ε_0. Corresponding results for y_0 =0.8 and four different porosities are shown in Fig. 6.

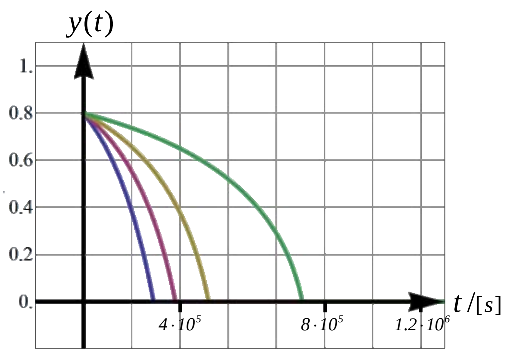

Figure 6. Homogeneous model: water volume fraction results for various porosities, ε_0 = *0.2, 0.4, 0.6* and *0.8* (from left to right).

Again a strong sensitivity of the drying time, here on the dry material porosity, is observed.

4.2 2-D Model

In order to investigate the consequences of the analyzed drying dynamics with respect to biofilters a 2-D FEM model has been set up. This time, the initial volume fraction of water was randomly distributed ($0.95 \leq y_0 < 1$) in a patch-like manner (cf. Fig. 7), while the porosity of the dry material was set to 0.6. Moreover no-slip boundary conditions have been applied at all walls. Fig. 7 shows snapshots of the water volume fraction and velocities for different time steps. It is observed that initially small inhomogeneities are more and more amplified until complete drying occurs. Because of the low flow resistance in the dry zones such channels cause a by-pass of the wet filter medium.

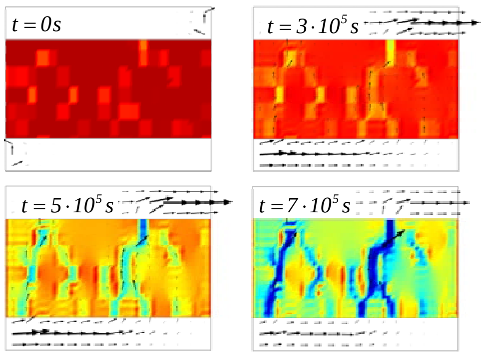

Figure 7. Results of 2-D FEM model: evolution of the water volume fraction with imposed random fluctuations of the initial water load.

Within the 2-D the approach the consequences of the drying dynamics, depending strongly on the initial conditions become obvious. While, the time scales in the various regions are basically governed by Eq. (6), here, different parts of the model are coupled by the flow distribution. With respect to real applications, the assumption of a constant, prescribed pressure drop is not realistic. As soon as dry passages have developed, the pressure drop will decrease and the gas flow is focused to the these dry regions, by-passing the still active parts of the filter medium.

4.3 3-D Model

Within the FEM framework the model can be easily expanded to three dimensions taking realistic geometries of biofilters into account. Exemplarily, simulations results for a twin-chamber biofilter are shown in Fig. 8.

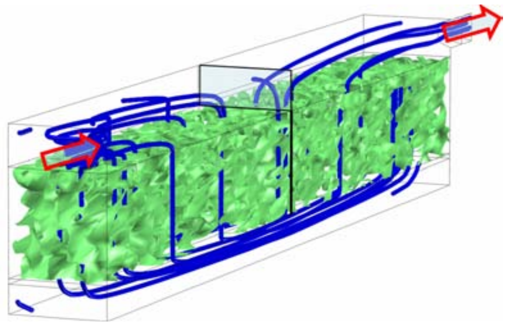

Figure 8. Results of a 3-D FEM simulation of a twin-chamber biofilter: Iso-surfaces of water volume fraction are shown in green. The blue streamlines show the gas flow passing through the filter medium.

5. Conclusion /Outlook

Having formulated models for 1-D, 2-D and 3-D simulations of gas flow and drying in porous media we are able to show that fundamental instabilities in the operation of biofilters can occur. Small inhomogeneities in the initial state (porosity of dry filter medium and / or initial water load) can be amplified during operation leading to complete dried out channels by-passing the wet biofilter material. The developed model approach allows in-depth investigations on the interplay between gas flow and water content and allows to identify the governing time scales for drying in biofilters. Although the present model approach is not appropriate to predict overall performances of biofilters it helps to understand drying and allows to investigate practical aspects such as the role of pre-conditioning of the gas stream, wall effects and possible flow mal distribution caused by inappropriate geometries of feeding and outlet pipes, to name a few. Future work will be dedicated to these aspects and to experimental studies for parameter identification and model validation.

6. References

[1] S. Ergun, Fluid flow through packed columns, *Chem. Eng. Prog.* **48**, 9-94 (1952).
[2] W. E. Ranz, W. R. Marshall, Jr., Evaporation from drops, Parts I & II, *Chem. Eng. Program.* **48**, 141-146 & 173-180 (1952).

[3] O. Levenspiel, *Chemical Reaction Engineering*, 3rd ed, p. 401, Wiley, NY (1999).
[4] www.wolfram.com
[5] www.comsol.com

Acknowledgements

The work has been funded by the German Ministry of Research and Education (BmBF) in the framework of the 4th IngenieurNachwuchs program.

Appendix

I. Notation

A	specific wetted surface area
$\Delta c^g_{H_2O}$	difference between equilibrium vapor concentration and vapor concentration in the gas stream
$D^g_{H_2O}$	diffusion coefficient of vapor in the gas phase
d_p	equivalent particle diameter
ε_0	porosity of dry filter medium
$\varepsilon, \varepsilon(y)$	porosity of wet filter medium
L	filter length | thickness
$\dot{m}$	reduction rate of mass density of liquid water
μ_g	dynamic gas viscosity
ν_g	kinematic gas viscosity
Δp	pressure drop across packed bed
ρ_g	gas density
ρ_l	liquid density
Sh	Sherwood number
u_0	superficial gas velocity
$y(t)$	average volume fraction of liquid water within the filter material

II. Model constants

$$\alpha = 6\,\frac{1-\varepsilon_0}{\varepsilon_0}\,\frac{D^g_{H_2O}}{d_p^2}\,\frac{\Delta c^g_{H_2O}}{\rho_l}$$

$$\beta = \left(D^g_{H_2O}\right)^{-1/3} d_p^{1/2}\,\nu_g^{-1/6}$$

$$\delta = d_p \left(\frac{\Delta p}{150\,L\,\mu_g}\right)^{1/2}$$

III. Values

Simulations have been exemplarily performed with following values:

$$\Delta c^g_{H_2O} = 17\,\frac{g}{m^3}$$

$$D^g_{H_2O} = 10^{-9}\,\frac{m^2}{s}$$

$$d_p = 1\,mm$$

$$\mu_g = 18\,\mu Pas$$

$$\rho_g = 1.2\,\frac{kg}{m^3}$$

$$\rho_l = 10^3\,\frac{kg}{m^3}$$

$$\Delta p / L = 208\,\frac{Pa}{m}\,.$$

The values are only partly motivated by real biofilters used in industrial applications, furthermore by pre-tests by means of model lab-systems. The investigation of realistic material parameters is the subjected to ongoing work.