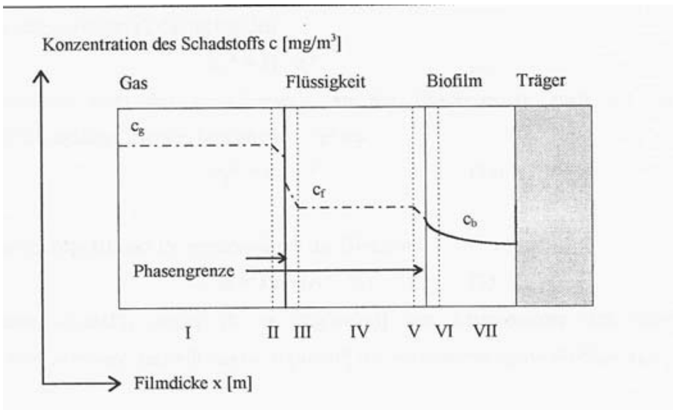
Basic information on the biodegradation of toluene in BTF system:

1. **Mass transfer in BTF system with polyurethane foam media.**

All dominant for the elimination in BTF is the transport of the VOC or compound from gas phase to the biological layer. In detail this procedure is divided in 7 single steps. See the following picture.



Gas = gas phase
Flüssigkeit = liquid phase
Biofilm = biological layer
Träger = media
Filmdicke = thickness of layer
Konzentration = concentration of pollutant

I = transport of pollutant from gas phase to phase interface
II = diffusion through boundary layer of gas phase
III = diffusion through boundary layer of liquid phase
IV = Diffusion through liquid phase
V = Diffusion through boundary layer to biological layer
VI = diffusion through boundary layer of biological layer
VII = biodegradation by micro organism in biological layer

To simplify the modelling in BTF systems the following assumptions were made:

- The system is running under steady state conditions

- The concentration in the gas phase is equal everywhere $c_g = c_g^*$

- At the boundary layer Henry`s law can be applied $c_g^* = H * c_l^*$

- The equilibrium can also be described with the help of the partition coefficient
$c_g^* = K * c1^*$

- Step III and IV can be combined with equation $m = k_l a * (c_l^* - c_l)$

- A limitation in transportation between liquid layer and biological layer will not be considered.

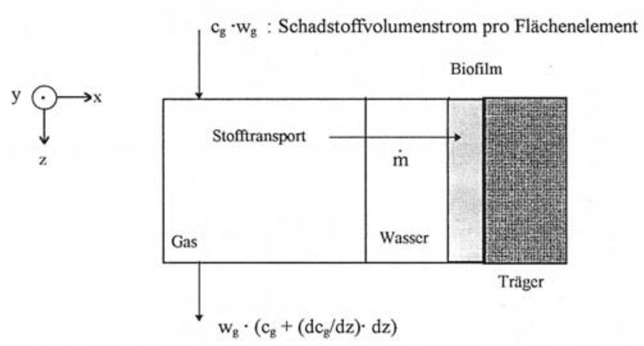
- The solubility in liquid is equal to the biological layer

- The diffusion through the biological layer is given by the 1st law of Fick

$$m = D_b * a * d_c / d_x$$

- the reaction rate of the biodegradation in the biological layer will be given by the equation of "Michaelis-Menten" $r_b = k * X_b * c_b / (K_m + c_b)$

With these simplifications the elimination of pollutants in BTF can be determined for some cases, after a balance of the mass flow rate.



Under steady state conditions the difference between mass flow rate before and after the volume element must be equal to the mass flow rate in the liquid phase and the biological layer.

The mass balance is given as following:

$$\Rightarrow m = -w_g * (dc_g/dz)$$

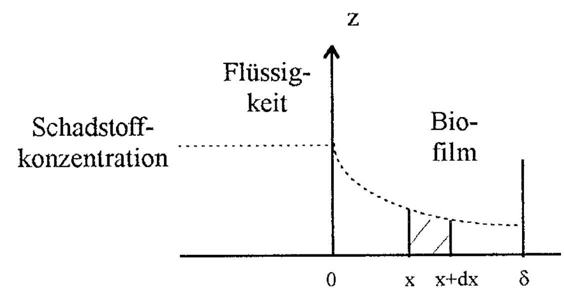
Now the following cases can be considered:

a) the transport through the liquid phase is limiting the reaction so that the concentration of the pollutant in the biological layer is nearly 0.

$$\Rightarrow c_{g,\,out} = c_{g,\,in} * e^{(-k_l a/H) * \tau}$$

This is a kinetics of 1. order and the elimination of pollutants is addicted to the inlet concentration.

b) Only the reaction in the biological layer will be considered.



The final differential equation can be calculated as following:

$$D_b \cdot \left.\frac{dc_b}{dx}\right|_{x+dx} - D_b \cdot \left.\frac{dc_b}{dx}\right|_{x} = r_b \cdot dx$$

$$\Rightarrow D_b \cdot \frac{d^2 c_b}{dx^2} - r_b = 0$$

$$\Rightarrow D_b \cdot \frac{d^2 c_b}{dx^2} - k \cdot X_b \cdot \frac{c_b}{K_m + c_b} = 0$$

This is an equation of 2. order and can only be solved numerically:

Case 1 : The concentration of the pollutants c_b in the biological layer is much less then the Michaelis Menten constant K_b. So a biological reaction of 1.order will follow.

$$r_b = k \cdot X_b / K_m \cdot c_b$$

For the following boundary conditions

für $x = \delta$; folgt: $dc_b(\delta)/dx = 0$;

für $x = 0$; folgt: $c_b(0) = c_g / H$;

you get:

$$c_b(x) = \frac{\cosh\left(\delta \cdot \sqrt{\frac{k \cdot X_b}{K_m \cdot D_b}} \cdot \left(1 - \frac{x}{\delta}\right)\right)}{\cosh\left(\delta \cdot \sqrt{\frac{k \cdot X_b}{K_m \cdot D_b}}\right)} \cdot \frac{c_g}{H}$$

The mass flow rate in the gas phase must be equal to the quantity of pollutants which are diffusing into the biological layer. In the bio layer the pollutant will be eliminated.

$$-w_g \cdot \left(\frac{dc_g}{dz}\right) = -D_b \cdot a \cdot \left(\frac{dc_b}{dx}\right)_{x=0}$$

$$-w_g \cdot \left(\frac{dc_g}{dz}\right) = \frac{D_b \cdot a \cdot c_g}{\cdot H} \cdot \sqrt{\frac{k \cdot X_b}{K_m \cdot D_b}} \cdot \tanh\left(\delta \cdot \sqrt{\frac{k \cdot X_b}{K_m \cdot D_b}}\right)$$

After the integration over the bed height you get:

$$\ln\left(\frac{c_{g,out}}{c_{g,in}}\right) = -\frac{D_b \cdot a}{H \cdot w_g} \sqrt{\frac{k \cdot X_b}{K_m \cdot D_b}} \cdot \tanh\left(\delta \cdot \sqrt{\frac{k \cdot X_b}{K_m \cdot D_b}}\right) \cdot Z$$

$$\text{mit} \quad K_1 = D_b \cdot \sqrt{\frac{k \cdot X_b}{K_m \cdot D_b}} \cdot \tanh\left(\delta \cdot \sqrt{\frac{k \cdot X_b}{K_m \cdot D_b}}\right)$$

$$\Rightarrow \ln\left(\frac{c_{g,out}}{c_{g,in}}\right) = -\frac{K_1 \cdot a}{H} \cdot \frac{Z}{w}$$

So the result is:

$$\Rightarrow c_{g,out} = c_{g,in} \cdot e^{-\frac{K_1 \cdot a}{H} \cdot \tau}$$

#Case 2: The concentration of the pollutant c_b in the bio layer is much higher then the Michaelis-Menten constant K_m:

- ⇨ you get a biological reaction of 0. order

$$r_b = k \cdot X_b$$

Using this equation in the differential equation so you get:

$$D_b \cdot \frac{d^2 c_b}{dx^2} - k \cdot X_b = 0$$

To solve this equation you have to look for different boundary conditions.

a) the biodegradation is limited by the biological reaction:

für $x = \delta$; folgt: $dc_b(\delta)/dx = 0$;

für $x = 0$; folgt: $c_b(0) = c_g / H$;

You get:

$$c_b(x) = \frac{c_g}{H} + \frac{\delta^2 \cdot X_b \cdot k}{2 D_b} \cdot \left(\frac{x^2}{\delta^2} - 2\frac{x}{\delta}\right)$$

In the mass balance you get :

$$-w_g \cdot \left(\frac{dc_g}{dz}\right) = -D_b \cdot a \cdot \left(\frac{dc_b}{dx}\right)_{x=0}$$

$$-w_g \cdot \left(\frac{dc_g}{dz}\right) = k \cdot X_b \cdot a \cdot \delta$$

After the integration over the BTF bed height Z you will get:

$$c_{g,out} - c_{g,in} = -\frac{k \cdot X_b \cdot \delta \cdot a \cdot Z}{w_g}$$

$$\Rightarrow c_{g,out} - c_{g,in} = -k \cdot X_b \cdot \delta \cdot a \cdot \tau$$

This means, that the difference between inlet and outlet concentration is independent of the gas concentration !

There will always be eliminated the same quantity of pollutants in each BTF element.

b) The elimination of the pollutants is limited by the diffusion through the bio layer. This means that the concentration can go to 0.

für $x = \lambda$; folgt: $dc_b(\lambda)/dx = 0$;

für $x = 0$; folgt: $c_b(0) = c_g / H$;

You get:

$$c_b(x) = \frac{c_g}{H} + \frac{\delta^2 \cdot X_b \cdot k}{2\,D_b} \cdot \left(\frac{x^2}{\delta^2} - 2\,\frac{x}{\delta} \cdot \frac{\lambda}{\delta}\right)$$

The depth of penetration of the pollutant λ can be given by $c_b(\lambda) = 0$

$$\Rightarrow \lambda = \sqrt{\frac{2\,c_g \cdot D_b}{H \cdot k \cdot X_b}}$$

The mass balance at the bio film border for $x = 0$ is as following:

$$-w_g \cdot \left(\frac{dc_g}{dz}\right) = -D_b \cdot a \cdot \left(\frac{dc_b}{dx}\right)_{x=0}$$

$$-w_g \cdot \left(\frac{dc_g}{dz}\right) = k \cdot X_b \cdot a \cdot \lambda$$

After the integration over the BTF bed height you will get:

$$\sqrt{c_{g,out}} - \sqrt{c_{g,in}} = -\frac{a}{w_g} \cdot \sqrt{\frac{k \cdot X_b \cdot D_b}{2\,H}} \cdot Z$$

$$\Rightarrow \sqrt{c_{g,out}} - \sqrt{c_{g,in}} = -a \cdot \sqrt{\frac{k \cdot X_b \cdot D_b}{2\,H}} \cdot \tau$$

Determination of the kinetics in BTF system with toluene as pollutant:

In a pilot test several media have been tested to determine the efficiency, residence time for several inlet concentration.

The following media have been tested:

- polyurethane foam
- polyurethane foam coated with activated carbon (to improve the mass transfer)
- synthetic fibres

The concentrations and residence times have been varied to get a summary on information due to the behaviour of the BTF system. The inlet concentration was

Minimum 65 mg toluene/m³
Maximum 400 mg toluene/m3

Residence time varied between 3 seconds to 30 seconds

For different situations the kinetics of the reaction was investigated based on the following reactions:

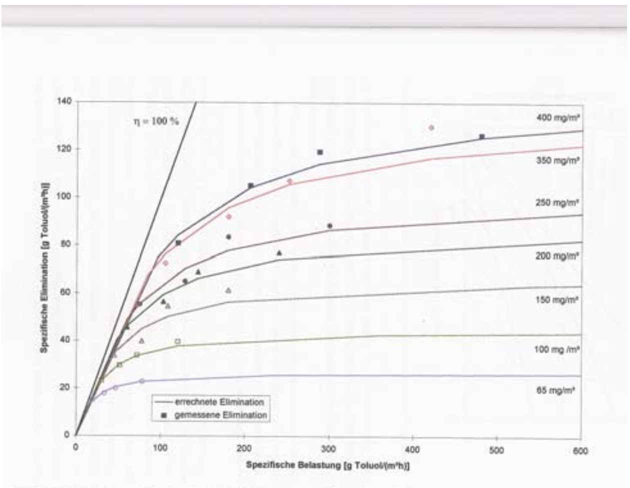
- 1. order reaction => $\ln(c_{in}/c_{out})$ over τ in a graphic shows to a straight line with a gradient k

- 0. order reaction , limited by reaction

  => $1-(c_{out}/c_{in})$ over τ shows a straight line with a gradient $k_{0,reac}/c_{in}$

- 0.order reaction, limited by diffusion

  => $1-\sqrt{c_{out}/c_{in}}$ over τ shows a straight line with a gradient $\sqrt{k_{0,diff}/c_{in}}$



Regarding the data in the given drawing, you can see the difference between calculated data and measured data in pilot tests.

It could also be seen that the evaluation with a 1.order reaction shows nearly a straight line. Due to the worse water solubility it is obvious that in the biological layer there could be a higher elimination but the transfer is not available.