CONTROL OF VOC AND ODOURS BY BIOFILTRATION: DESIGN CRITERIA

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INTRODUCTION

Types of Biological Air Pollution Control Systems

APPLICATION	BIOMASS	WATER PHASE
Biofilter	Fixed	Fixed
Biotrickling filter	Fixed	Flowing
Bioscrubber	Flowing (suspended)	Flowing

INTRODUCTION

- A biofilter consists of bed of soil or compost beneath which is a network of perforated pipe. Contaminated air flows through the pipe and out the many holes in the sides of the pipe thereby being distributed throughout the bed.
- The microorganisms are the same that degrade organic wastes in nature and in wastewater treatment plants.

INTRODUCTION

- In soils the pores are smaller and less permeable than in compost. Therefore, soil requires larger areas for biofiltration.
- This technology has been used in Europe for many years and is considered to be a Best Available Control Technology (BACT) for treating contaminated gaseous streams.
- Biofilters function efficiently and economically for removing low concentrations (less than 1,000 to 1,500 ppm as methane) of VOCs, air toxics, and odor.

ADVANTAGES VS DISADVANTAGES

ADVANTAGES

- low installation and operation **costs** (No fuel costs, microbes do oxidation for free at low temperatures)
- used in Europe for many years and it is considered to be a Best Available Control Technology (**BACT**) for treating contaminated gaseous streams
- low **maintenance** requirements
- **environmentally safe** (few byproducts compared to incineration e.g., CO and NOx)
- economically applied to **dilute** gas stream where the removal efficiency is good

  \- For odorous compounds 98 to 99% removal has been reported

  \- For VOCs generally in the range of 65 to 99% removal

DISADVANTAGES

- Microbes are **SLOW** ➔ need a large area for long residence
- High VOC concentrations can be **toxic** to microbes
- Sensitive **moisture** controls – must keep microbes happy☺
- Need to keep **porous** – growth can clog the system
- Biofilters can also remove particulates and liquids from gas streams. However, care must be taken because particulates or greasy liquids can function to **plug** the biofilter

THEORY OF BIOFILTER PROCESS: KEY PRINCIPLES

- **Biotransformations** act along with **adsorption**, **absorption**, and **diffusion** to remove contaminants from the gaseous stream.
- The contaminants in the gas are either adsorbed onto the solid particles of the media or absorbed into the water layer that exists on the media particles.
- Diffusion occurs through the water layer to the microorganisms in the slime layer on the surface of the media particles.
- The media of the filter functions both to supply inorganic nutrients and as a supplement to the gas stream being treated for organic nutrients.
- The sorbed gases are oxidized by the microorganisms to end products, including carbon dioxide, water, nitrogen, mineral salts (ex. calcium salts), and energy to produce more microorganisms.
- The biofilters are actually a mixture of different media (compost, activated carbon, etc.) combined with a microbial population that enzymatically catalyzes the oxidation of the sorbed gases.
- The sorption capacity is relatively **low**, but the oxidation **regenerates** the sorption capacity.
- Overloading of the biofilter results when adsorption is occurring faster than oxidation and the efficiency decreases.

BIOFILTER TYPOLOGIES

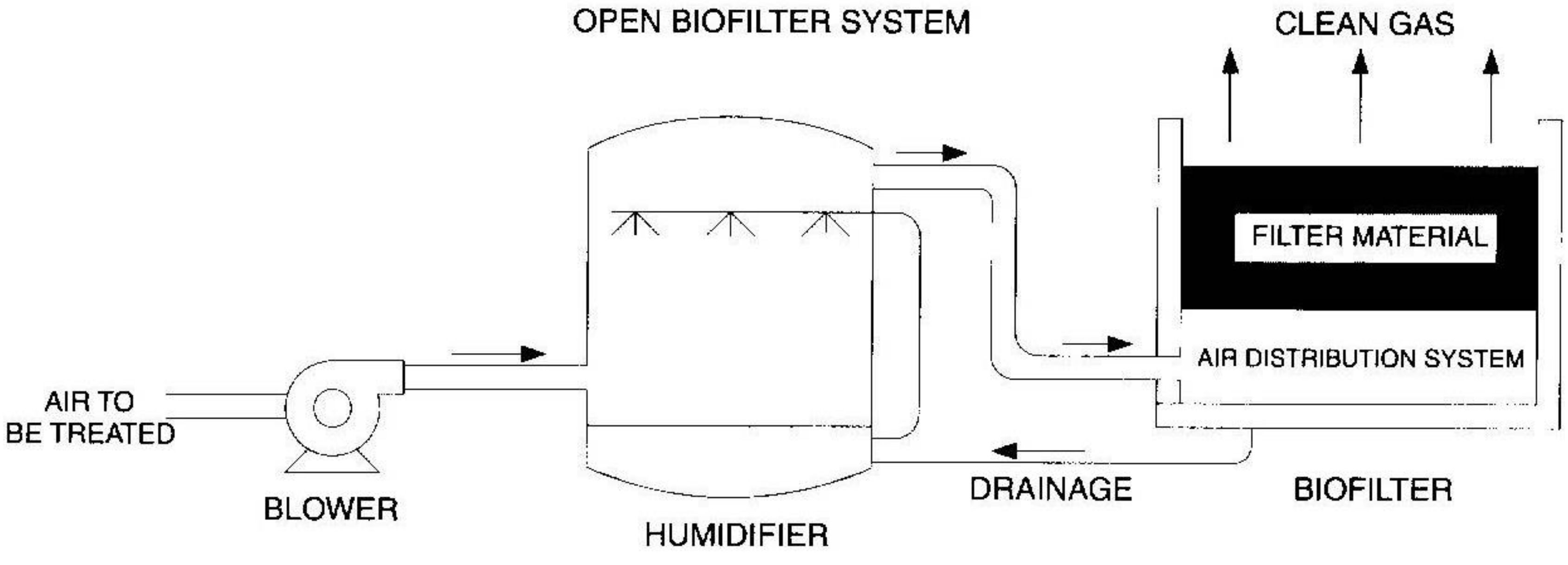
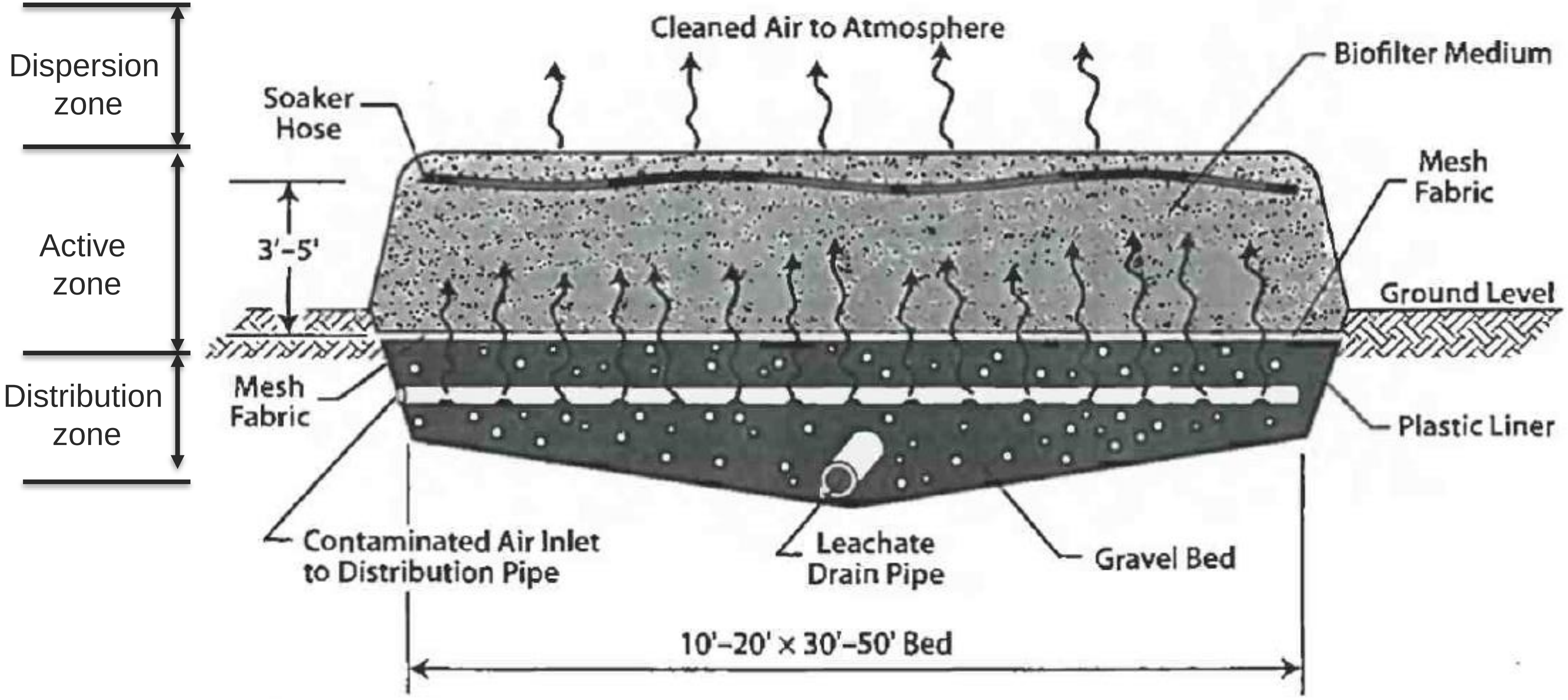


FIGURE 15.1 Typical open biofilter configuration.

- A biofilter can be **open** or **enclosed**, it can be built directly into the ground or in a reactor vessel, and it can be single or multiple bed.
- A typical biofilter configuration (see above). Optional components include a heat exchange chamber to cool or heat the gas stream to optimal temperature for the filter bed and a water sprinkler system to apply moisture directly to the filter media surface.

BIOFILTER TYPOLOGIES

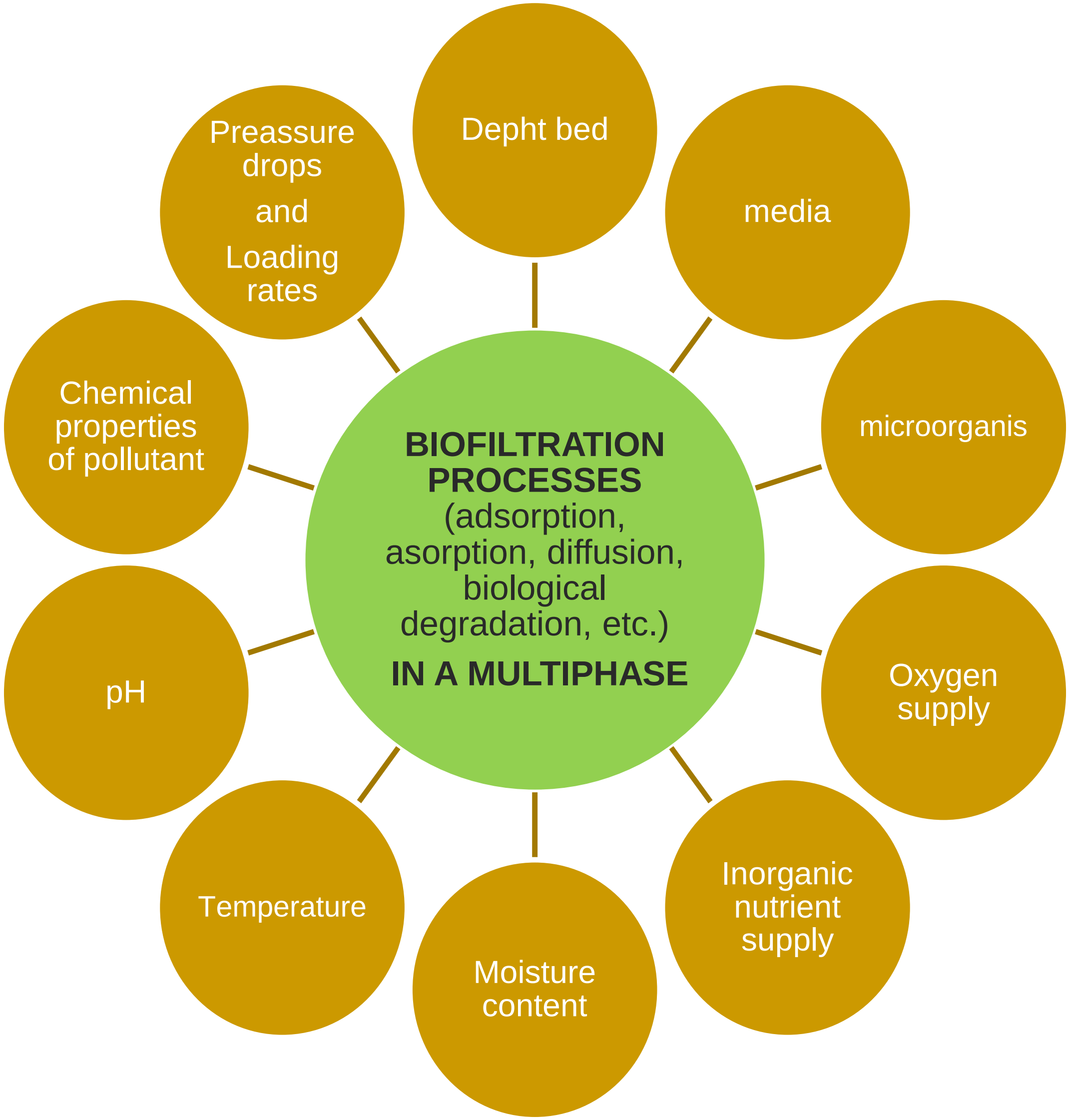


Dispersion zone

Active zone

Distribution zone

PROCESSES AND CONDITIONAL VARIABLES



BIOFILTRATION PROCESSES
(adsorption, asorption, diffusion, biological degradation, etc.)

IN A MULTIPHASE

Depht bed

media

microorganis

Oxygen supply

Inorganic nutrient supply

Moisture content

Temperature

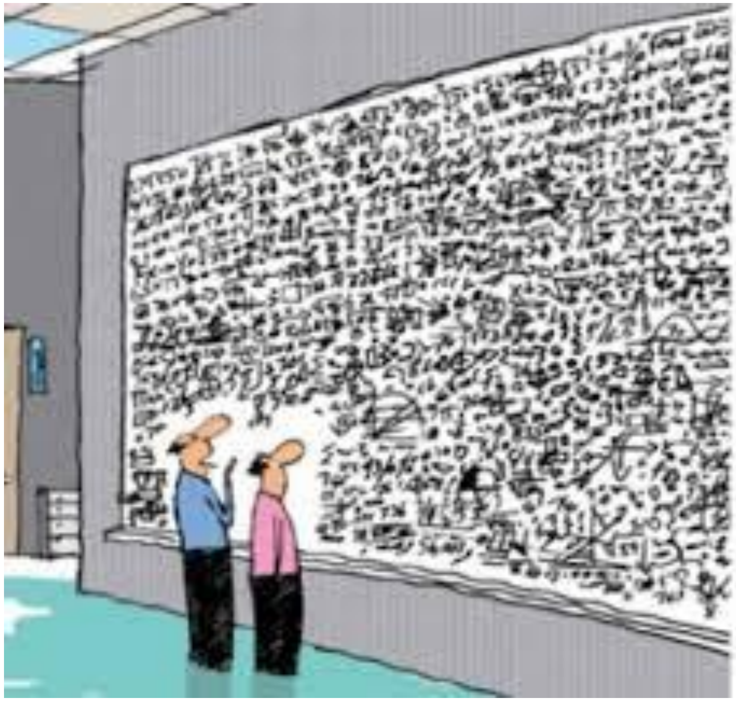
pH

Chemical properties of pollutant

Preassure drops

and

Loading rates

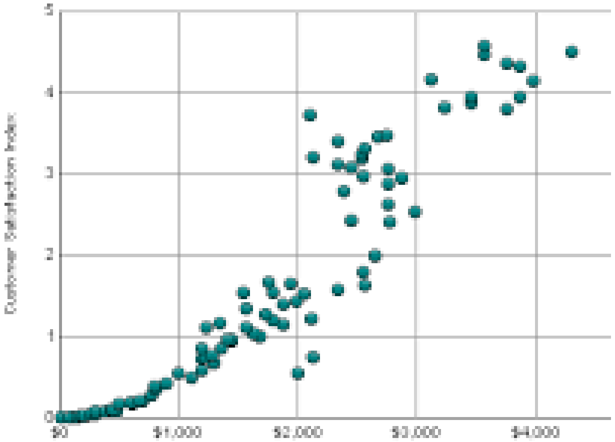


Which design approach in a so complex system?

DESIGN APPROACHES

Rule of thumbs
(ex. retention time)

- 👍 Easy to use
- 👎 scarce scientific explanation



Empirical relationships
(ex. Removal efficiency
VS gas superficial)

- 👍 Easy to use
- 👎 Generaly limited to one variable
- 👎 Scarce adatability for different configurations

Mathematical modelling
(ex. the biofilm theory)

- 👎 Difficult to use
- 👍 Good adatability for different configurations
- 👍 Coupling with results from pilot scales

DEPTH AND MEDIA OF BIOFILTER BED

- The medium is the solid porous material that is used to support the biomass.
- The used materials should have the following characteristics: large surface area for microbial adhesion, high porosity to reduce pressure drops, high moisture retention and low cost.
- The depth of biofilter media range for 0.5 to 2.0 m, with 1 m being the typical depth of a biofilter.
- Many different media types include soil, compost, sand, shredded bark, peat, heather, volcanic ash, and a mixture of these components have been used.

DEPTH AND MEDIA OF BIOFILTER BED

- Often polystyrene spheres or peat granules may be added to increase the structural support of the system and to increase the adsorptive capacity of the media.
- The two most commonly discussed media in the literature are **soil** and **compost**.
- Typical parameters include a neutral pH, pore volumes of greater than 80%, and a total organic content of 55% or greater.

DEPTH AND MEDIA OF BIOFILTER BED

- Soil is a **stable** choice for media in that it does not degrade. However, it contains fewer and less complex microorganisms than compost media.
- Compost has **higher air and water permeability**. The buffering capacity of compost is also very good. However, with time compost decomposes, and the average particle sizes of the filter media decrease.

DEPTH AND MEDIA OF BIOFILTER BED

- The useful life of the media is typically up to 5 years.
- Fluffing, or turning, of the media material in the biofilter may be required at shorter intervals to prevent excessive compaction and settling.

MICROORGANISMS

- Three types of microorganisms are generally present in a biofilter. These include fungi, bacteria, and antinomycetes. Antinomycetes are organisms which resemble both bacteria and fungi.
- The growth and activities of the microorganisms is dependent <u>on ample oxygen supply</u>, absence of toxic materials, ample inorganic nutrients for the microorganisms, optimum moisture conditions, appropriate temperatures, and neutral pH range.

MICROORGANISMS

- Start up of a biofilter process requires some acclimation time for the microorganisms to grow specific to the compounds in the gaseous stream.
- For easily degradable substances, this **acclimation period** is typically around 10 days.
- The acclimation process also allows the microorganisms to develop tolerance or acceptance for compounds they may find to be toxic in nature.

MICROORGANISMS

- Often, biofilters are not used continuously in the treatment process. They may be employed intermittently or seasonally, depending on the treatment process.
- The biomass has been shown to be able to be viable for shut downs of approximately 2 weeks. If inorganic nutrient and oxygen supplies are continued, the biomass may be maintained for up to 2 months.

MICROORGANISMS

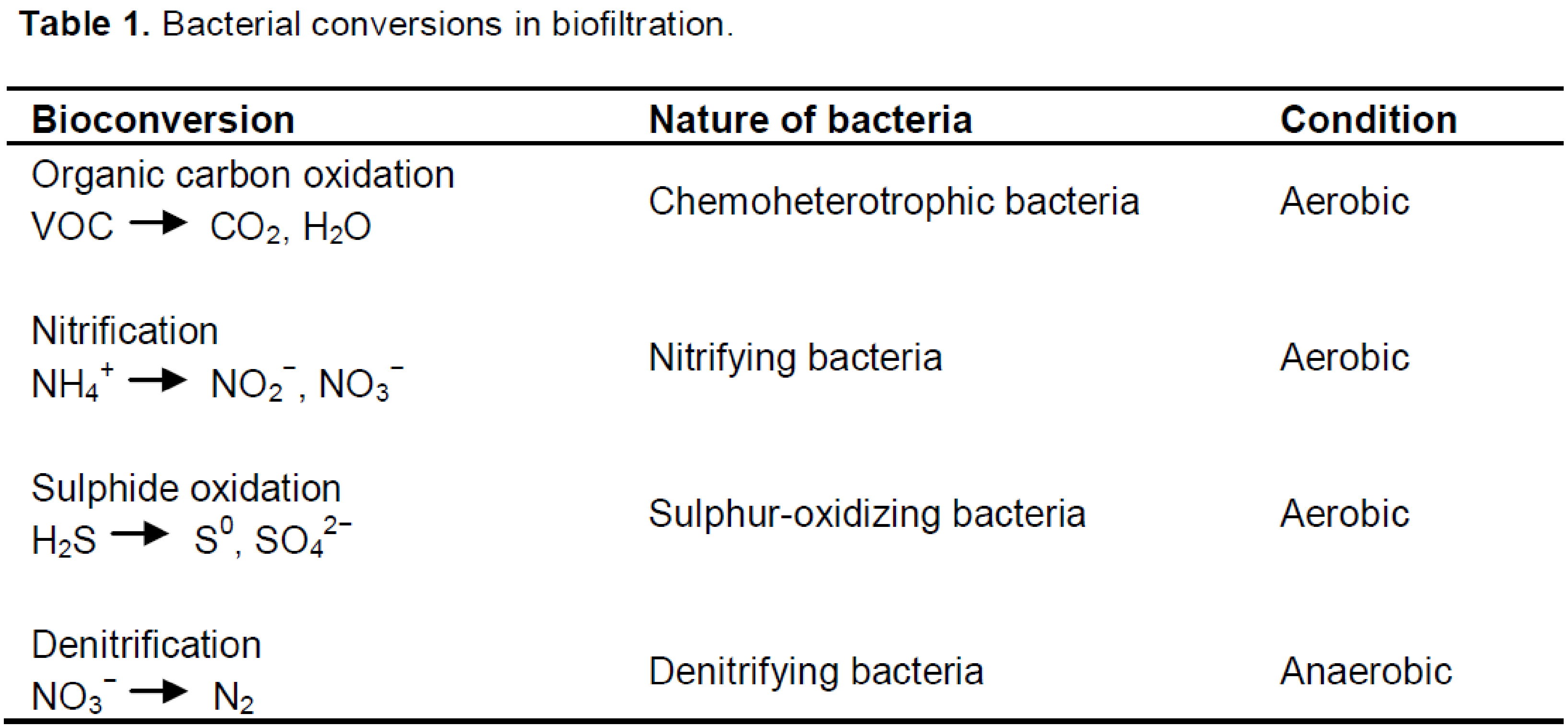


Table 1. Bacterial conversions in biofiltration.

Bioconversion	Nature of bacteria	Condition
Organic carbon oxidation VOC $\rightarrow$ CO_2, H_2O	Chemoheterotrophic bacteria	Aerobic
Nitrification $NH_4^+ \rightarrow NO_2^-$, NO_3^-	Nitrifying bacteria	Aerobic
Sulphide oxidation $H_2S \rightarrow S^0$, SO_4^{2-}	Sulphur-oxidizing bacteria	Aerobic
Denitrification $NO_3^- \rightarrow N_2$	Denitrifying bacteria	Anaerobic

Sonil Nanda, 2012. Microbial biofiltration technology for odour abatement: An introductory review. J. Soil Sci. Environ. Manag. 3, 28–35. https://doi.org/10.5897/JSSEM11.090

OXYGEN SUPPLY

- Typically, a minimum of 100 parts of oxygen per part of gas must be supplied.
- Anaerobic zones need to be avoided to ensure that the compounds are biotransformed and to prevent any anaerobic zone odors (primarily hydrogen sulfide) from forming.

INORGANIC NUTRIENT SUPPLY

- These are typically nitrogen, phosphorous, and some trace metals.
- Trace metals are almost always well supplied in the media material. Nitrogen and phosphorous may need to be added, depending on the media characteristics.
- For aerobic microorganisms, the O/N/P ratio is estimated as 100/5/1.
- A nutrient solution is sprayed regularly at the top of the filter and the excess solution is collected.

MOISTURE CONTENT

- Moisture content <u>is the most critical operational</u> parameter for the successful operation of a biofilter. The gaseous streams tend to dry out the biofilter media.
- Too little water will result in decreased activity of the microorganisms, and perhaps transfer of the adsorbed contaminants out of the filter and into the atmosphere.

MOISTURE CONTENT

- Too much water can also cause problems, such as anaerobic zones, with the potential of producing odors, and increases in the headloss of the system.
- Optimal water contents vary in the literature, but generally the range of 20 to 60% by weight is accepted.

MOISTURE CONTENT

- Moisture can be added to the system in two ways: humidification of the gas stream or direct application of water to the biofilter surface.
- Typically, the degree of saturation suggested is at least 95%, with saturation percentages of 99% and 100% quoted as the optimum.
- Typically, water droplet diameters of less than 1 mm for surface sprays are suggested, in order to prevent compaction of the biofilter.
- The maximum water loading rate suggested is 0.5 gal/ft^2. h.

TEMPERATURE

- The microorganisms' activity and growth is optimal in a temperature range of 10 to 40^{o}C. Higher temperature will destroy the biomass, while lower temperatures will result in lower activities of the microorganisms.
- In winter, heating of the off gas streams may be required. On the contrary, high temperature off gases may need to be cooled.
- The oxidation of organic compounds generates heat and that amount of heat can significantly affect both the temperature and the humidity of the air as it moves through the biofilter.

PH OF THE BIOFILTER

- The pH in the biofilter should remain near neutral, in the range of 7 to 8.
- When inorganic gases are treated, inorganic acids may be produced.
  For example, treated H_2S will produce H_2SO_4.
  Other inorganic acids which can be formed include HCl and HNO_3.
- These acids can cause lowered pH in the media over time.

PH OF THE BIOFILTER

- Carbon dioxide production by the microorganisms can also lower the pH over time.
- The media typically has some inherent buffering capacity to neutralize small changes in the pH. However, lime may need to be added if the buffering capacity is not sufficient.

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LOADING AND REMOVAL RATES

- Loading rates can be expressed in three ways: flow rates of gases through the bed, gas residence times, and removal rates.
- Flow rates of gas into the bed range from 0.3 to 9.5 $m^3/min\text{-}m^2$. The typical range is 0.3-1.6 $m^3/min\text{-}m^2$.
- Off gas rates are typically around 1,000 to 150,000 m^3/h.

LOADING AND REMOVAL RATES

- Gas residence time, the time the gas actually spends in contact with the biofilter material, is the time available for adsorption and absorption to occur.
- Suggested gas residence times are a minimum of 30 s for compost media and a minimum of 1 min for soil media.
- Sligtly longer residence times are suggested for inorganic gases.

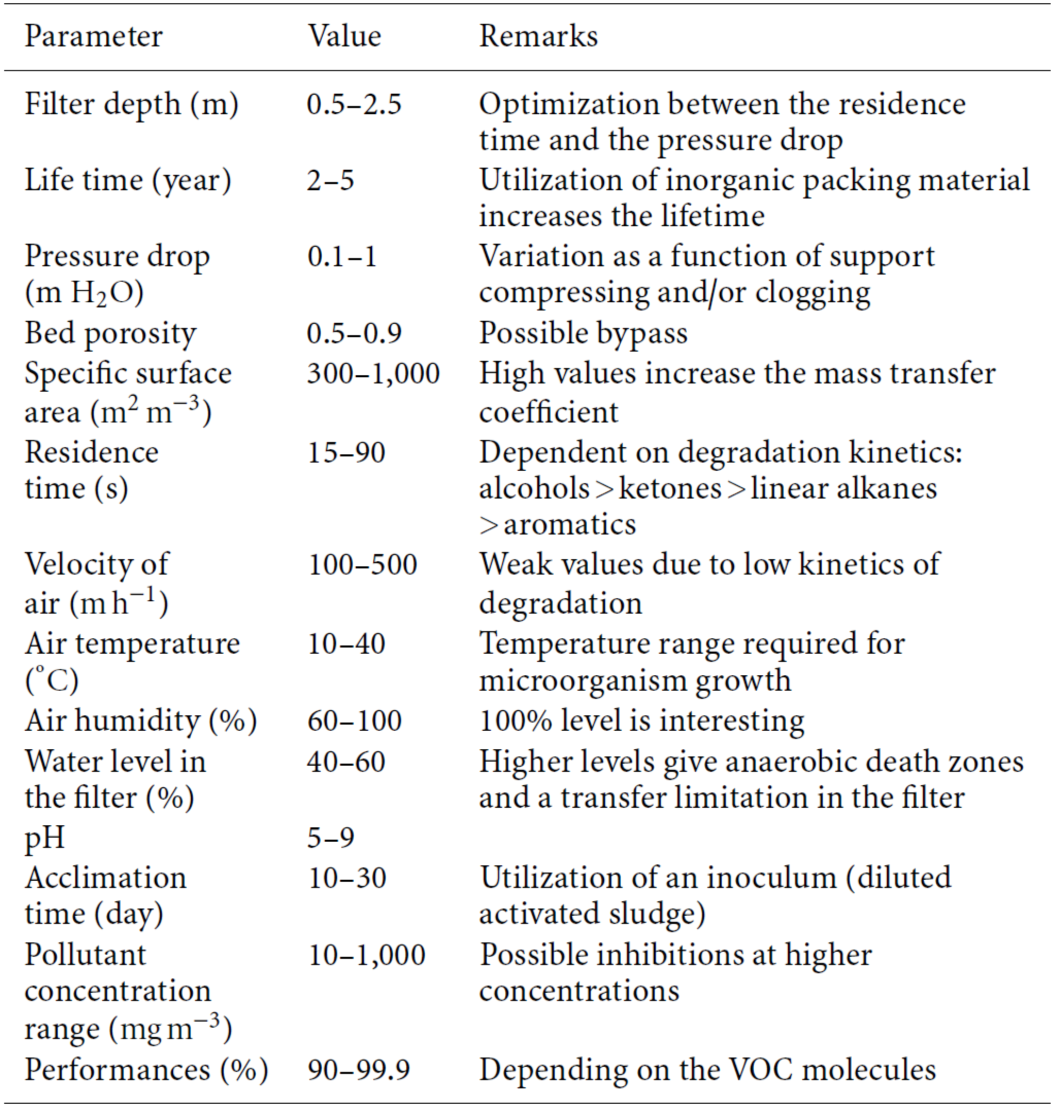
LOADING AND REMOVAL RATES

- Removal rates are typically reported in units of g/kg of dry media/day.
  Generally, the lower-molecular-weight, less-complex compounds are more easily degraded and more quickly removed in a biofilter.

PREASSURE DROPS

- The pressure drop through the filter bed depends on the superficial gas velocity, media type, porosity, moisture content, and compaction of the media.
- The total pressure drop in a biofilter will <u>increase linearly as the bed depth and as the square of the superficial gas velocity</u>.
- Fluffing or replacing the media over time can help to prevent compaction and higher pressure drops.
- Typical pressure drops range from 1 to 3 in. of water. Typical power consumption for a biofilter is in the range of 1.8 to 2.5 kWh/1,000m^3.

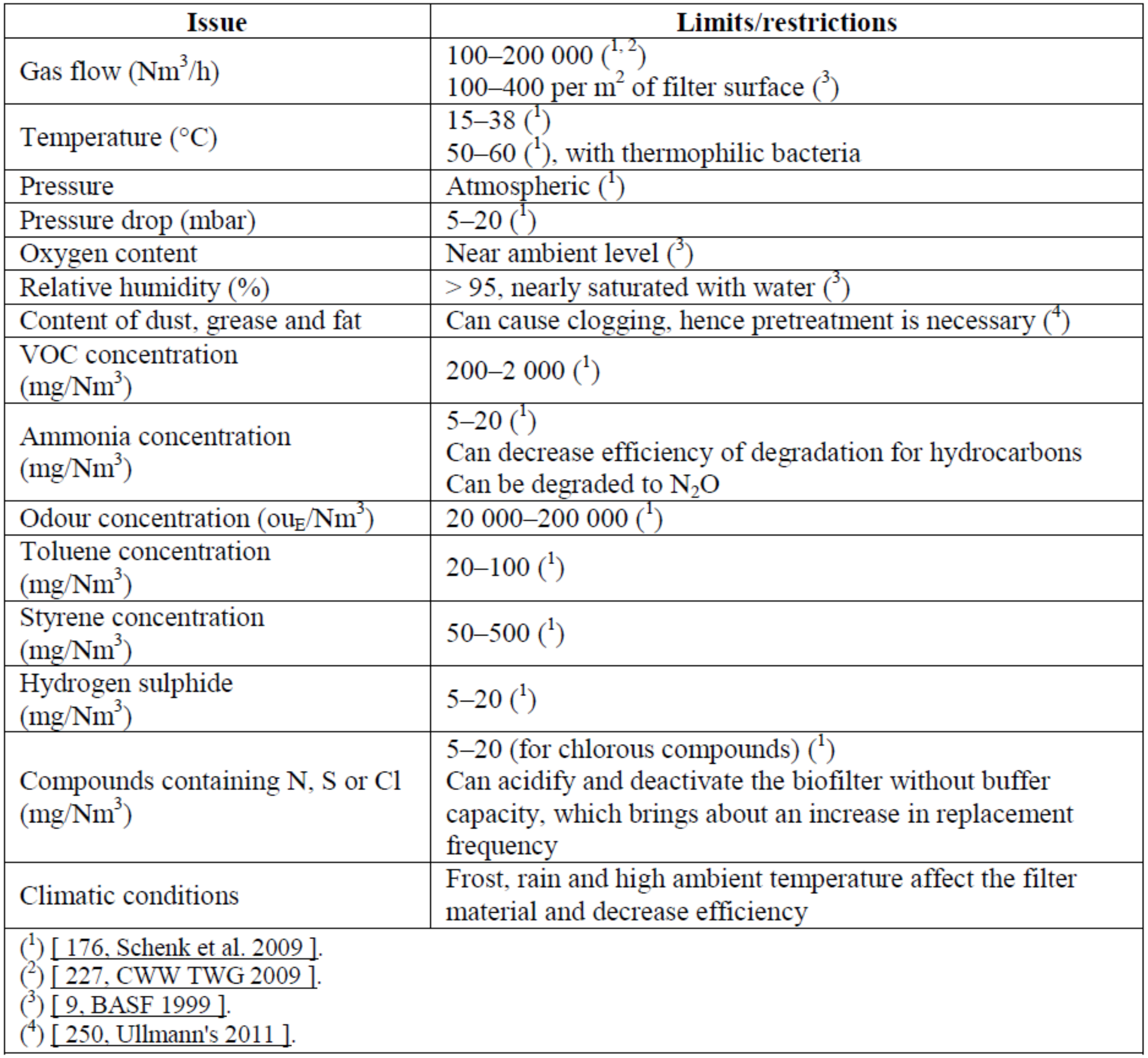
OPERATIVE DATA PARAMETERS (1)



Parameter	Value	Remarks
Filter depth (m)	0.5–2.5	Optimization between the residence time and the pressure drop
Life time (year)	2–5	Utilization of inorganic packing material increases the lifetime
Pressure drop (m H_2O)	0.1–1	Variation as a function of support compressing and/or clogging
Bed porosity	0.5–0.9	Possible bypass
Specific surface area ($m^2\,m^{-3}$)	300–1,000	High values increase the mass transfer coefficient
Residence time (s)	15–90	Dependent on degradation kinetics: alcohols > ketones > linear alkanes > aromatics
Velocity of air ($m\,h^{-1}$)	100–500	Weak values due to low kinetics of degradation
Air temperature (°C)	10–40	Temperature range required for microorganism growth
Air humidity (%)	60–100	100% level is interesting
Water level in the filter (%)	40–60	Higher levels give anaerobic death zones and a transfer limitation in the filter
pH	5–9	
Acclimation time (day)	10–30	Utilization of an inoculum (diluted activated sludge)
Pollutant concentration range ($mg\,m^{-3}$)	10–1,000	Possible inhibitions at higher concentrations
Performances (%)	90–99.9	Depending on the VOC molecules

Some operating conditions for biofilters used for VOC removal in air

OPERATIVE DATA PARAMETERS (2)



Issue	Limits/restrictions
Gas flow (Nm^3/h)	100–200 000 (1, 2) 100–400 per m^2 of filter surface (3)
Temperature (°C)	15–38 (1) 50–60 (1), with thermophilic bacteria
Pressure	Atmospheric (1)
Pressure drop (mbar)	5–20 (1)
Oxygen content	Near ambient level (3)
Relative humidity (%)	> 95, nearly saturated with water (3)
Content of dust, grease and fat	Can cause clogging, hence pretreatment is necessary (4)
VOC concentration (mg/Nm^3)	200–2 000 (1)
Ammonia concentration (mg/Nm^3)	5–20 (1) Can decrease efficiency of degradation for hydrocarbons Can be degraded to N_2O
Odour concentration (ou_E/Nm^3)	20 000–200 000 (1)
Toluene concentration (mg/Nm^3)	20–100 (1)
Styrene concentration (mg/Nm^3)	50–500 (1)
Hydrogen sulphide (mg/Nm^3)	5–20 (1)
Compounds containing N, S or Cl (mg/Nm^3)	5–20 (for chlorous compounds) (1) Can acidify and deactivate the biofilter without buffer capacity, which brings about an increase in replacement frequency
Climatic conditions	Frost, rain and high ambient temperature affect the filter material and decrease efficiency

(1) [176, Schenk et al. 2009].
(2) [227, CWW TWG 2009].
(3) [9, BASF 1999].
(4) [250, Ullmann's 2011].

Application limits and restrictions associated with biofiltration

(Reference: Brinkmann, T., Giner, G., Hande, S., Serge, Y., Sancho, R., Delgado, L., 2016. Best Available Techniques (BAT) Reference Document for Common Waste Water and Waste Gas Treatment /Management Systems in the Chemical Sector)

A

Rule of thumbs
(ex. retention time)

B

Empirical relationships
(ex. Removal efficiency
VS gas superficial)

C

Mathematical modelling
(ex. the biofilm theory)

ANALYTICAL SOLUTIONS

COMMON DESIGN PARAMETERS

In order to design a biofilter or to analyze its performance, the following parameters must be considered:

$$EBRT = \frac{V_f}{Q}$$

where

EBRT: Empty Bed Residence Time [min];
V_f: Volume of the empty filter bed [m^3]
Q: volumetric flow rate [m^3/min];

$$t = EBRT \cdot J$$

where

t: True Residence Time [min];
θ: bed porosity (volume of voids/volume of empty bed)

$$SL = \frac{Q}{A}$$

where

SL: Surface Loading (=U_G) [m^3/m^2hr] or [m/hr];
A: cross-sectional area of empty bed normal to the airflow rate [m^2];

$$VL = \frac{Q}{V_f} = \frac{1}{EBRT}$$

where

VL: Volume Loading [min^{-1}];

$$ML_V = VL \times C_i$$

where

ML_V: Mass Volume Loading [g/m^3 /hr];
C_i: concentration of pollutant in the inlet gas stream [g/m^3];

$$EC = \frac{Q(C_i - C_e)}{V_f}$$

where

EC: Elimination Capacity [g/m^3 /hr];
C_i, C_e: concentration of pollutant in the inlet and outlet gas stream, respectively [g/m^3];
It is the removed quantity per unit time referred to a unit volume of bed

⇓

$$EC = VL(C_i - C_e) \qquad EC = \frac{(C_i - C_e)}{EBRT}$$

Since $h = \frac{C_i - C_e}{C_i}$ ⇒ $EC = ML_V \times h$

EXAMPLE 1: EMPIRICAL RELATIONSHIP

A mixture of BTEX (benzene, toluene and xylene) vapors in air is to be controlled with a compost biofilters. A pilot plant with bed dimensions of 4 m * 1m * 0.75 m (deep) was operated with results as shown in the table. Other pilot-plant data include: gas flow = 5 m^3/min, T=30°C, P= 1 atm, ΔP= 4 cm of water. The average molecular weight of the BTEX mixture is 92.

Inlet BTEX conc.	Removal Efficiency
ppm	%
25	95
37.5	95
50	95
75	90
100	75
125	65
150	53
175	47
200	40

Prepare a graph showing the elimination capacity as a function of the mass loading rate. What are the maximum efficiency and the maximum elimination capacity of the system? What is the critical load?

$$EC = ML_v \times \eta$$

Is the efficiency constant if the inlet concentration increase?

EXAMPLE 1: EMPIRICAL RELATIONSHIP

$$C_{mass} = \frac{M_P}{V_t} = \frac{C_{ppm} * MW_P}{R * T/P} * 10^{-6}$$

C_{mass}= mass concentration, g/m^3

C_{ppm}= volume or molar concentration, ppm

M_p= mass of pollutant gas, µg

MW_p= molecular weight of pollutant gas, g/gmol

T= temperature, K

P = preassure, Pa (101325 Pa)

R= 8.314 Pa*m^3/gmol*K

EBRT= (4m * 1m *0.75)/ 5m^3/min=0.6 min

SL=5 m^3/min / (4 m* 1 m) =1.25 m/min

VL= 1/EBRT= 1.667 min^{-1}

MLv=VL* Ci

EC=MLv* η

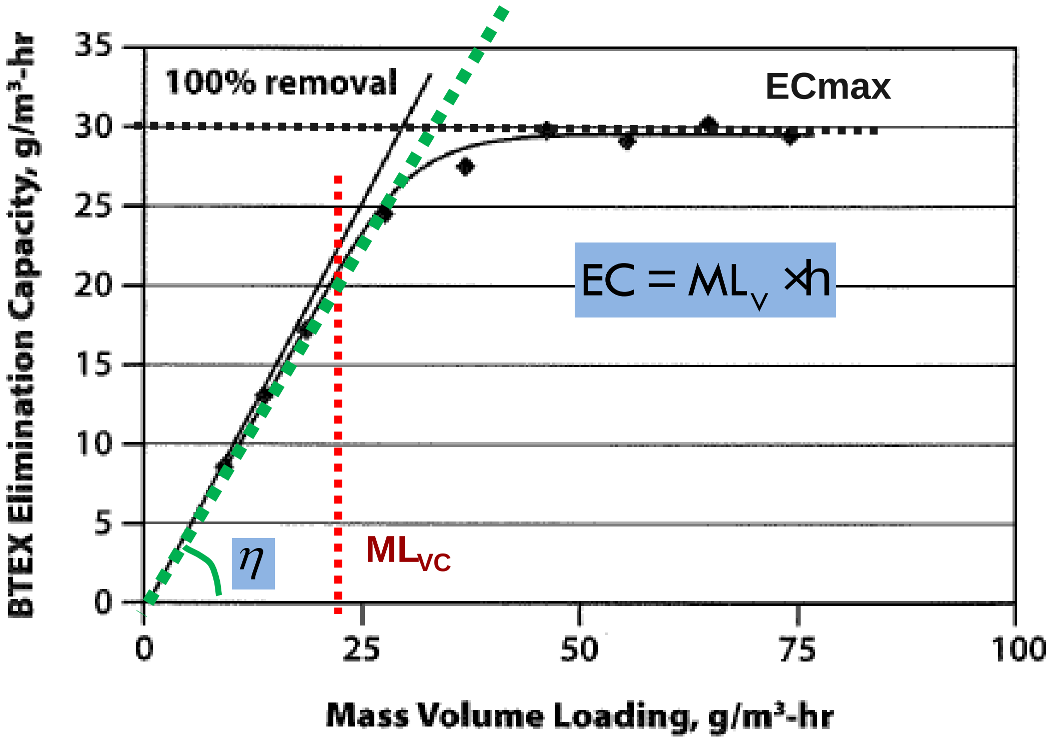
The maximum efficiency is 95%.
The maximum elimination capacity is 30 g/m3*h.
The critical load appears to be about 20 g/m3*h

Inlet BTEX conc.	Conc	Removal Efficiency	EBRT	MLV	EC
ppm	g/m3	%	min	g/m3*h	g/m3*h
25	0.09	95	0.6	9.25	8.79
37.5	0.14	95	0.6	13.88	13.18
50	0.19	95	0.6	18.50	17.58
75	0.28	90	0.6	27.75	24.98
100	0.37	75	0.6	37.00	27.75
125	0.46	65	0.6	46.26	30.07
150	0.56	53	0.6	55.51	29.42
175	0.65	47	0.6	64.76	30.44
200	0.74	40	0.6	74.01	29.60

EXAMPLE 1: EMPIRICAL RELATIONSHIP

DESIGN is based on result **from pilot plant** test aimed at experimentally measure the ***Elimination capacity*** (quantity removed per unit time and per filter unit volume) VS ***Mass volume loading*** (quantity fed per unit time and per filter unit volume).

E.g.: a mixture of BTEX vapors in air has been treated with a compost biofilter pilot plant, operated at different BTEX concentrations.



- At low loading rates EC varies linearly with MV_L ➔The efficiency stays constant
- There is a point at which the EC begins to level out (Inflection point) ➔The efficiency begins to drop off.
- The MVL at this point is called the **Critical Load ML_{VC}**.
- The graphs indicates what are the **maximum efficiency** (Slope of the initial linear trend) and the **maximum elimination capacity ECmax** of the specific system (plateau)

EXAMPLE 1: EMPIRICAL RELATIONSHIP

- Our target is to establish the optimal ML_V to be applied and accordingly, the Volume required for the filter (V_f).
- If we design for the maximum elimination capacity **ECmax**, the efficiency of the system could be very low. It is always suggestable to stay at the maximum efficiency, and thus below the **Critical Load ML_{VC}**

- In the reference example, we can fix MLv=18,5 g/m³/h <**ML_{VC}**

$$ML_V = VL \times C_i$$

- Since the Ci is known, VL can be derived

$$VL = \frac{Q}{V_f} = \frac{1}{EBRT}$$

- Since the VL is known, Vf can be derived

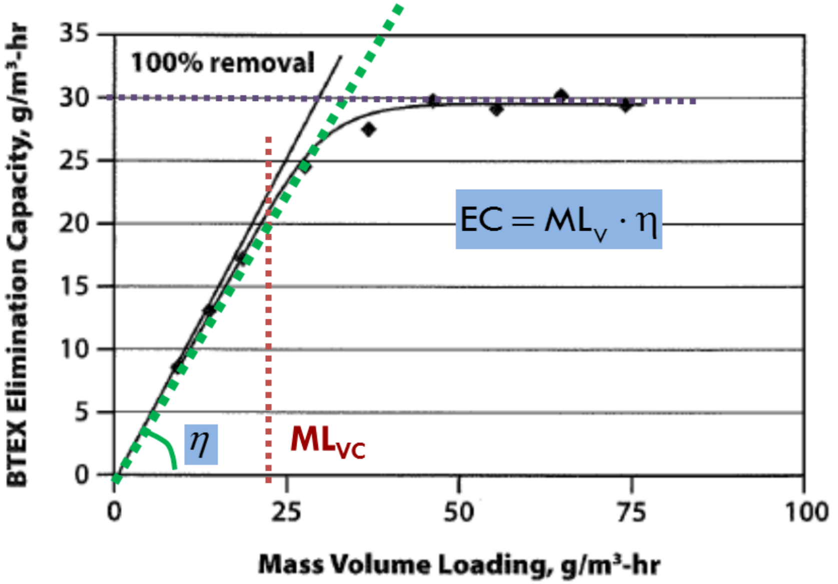
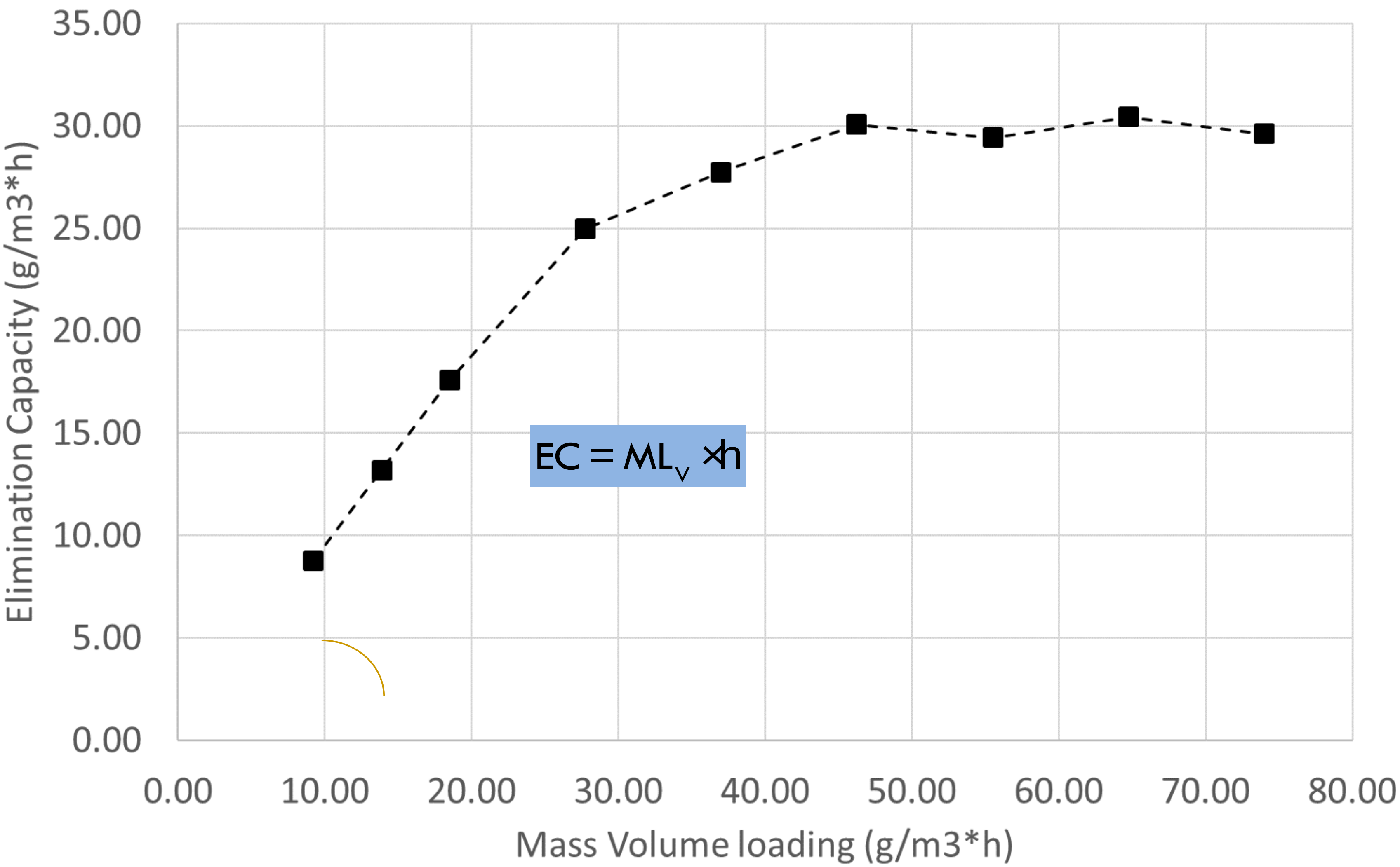


Figure 14.4
BTEX elimination capacity vs. mass volume loading from Example 14.3.

Vf=EBRT*Q= 0,6 min * 5 m³/min= 3 m³

EXAMPLE: EMPIRICAL RELATIONSHIP



$EC = ML_v \times h$

REMOVAL CAPACITY: THE BIOFILM THEORY

- **Stationary** state is supposed
- The resistance at the interface between the biolayer and the gas phase was negligible, therefore **Henry’s law** can be applied
- The nutrient transport in the biolayer was facilitated by diffusion mechanism
- The thickness of biofilm (δ^*) was negligible compared to the diameter of the packing particle and its value is constant along the biofilter.
- The substrate degradation kinetics was assumed: a) to follow a zero - order rate equation, in which the Michaelis-Menten constant was assumed to be very small compared to substrate concentration; b) to follow a first-order rate equation in which the Michaelis-Menten constant was assumed to be very large
- Oxygen is always in excess and does not affect kinetics.
- Two phases are considered: gas phase and (solid/biofilm) phase.
- Pollutant diffusion in (solid/biofilm) phase follows Ficks’s law.
- The flow of the waste gas through the filter media was assumed to follow plug flow with no axial dispersion.
- One pollutant only is considered.

REMOVAL CAPACITY: MONOD KINETICS

IN EXCESS OF OXYGEN

$$r_i = \frac{k_i \cdot c_{L,i}}{c_{L,i} + K_i}$$

In the case oxygen limits the biodegradation rate

$$r_i = \frac{k_i \cdot c_{L,i}}{c_{L,i} + K_i} * \frac{c_{L,ox}}{K_{ox} + c_{L,ox}}$$

Where:

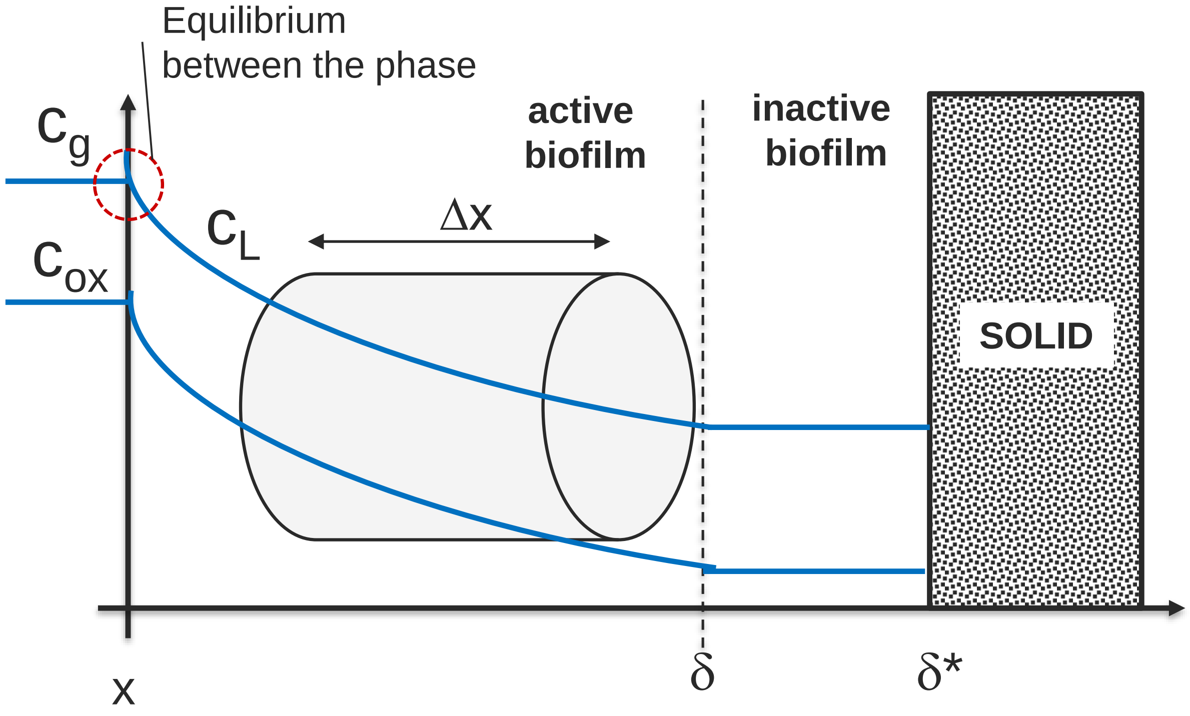
- r_i rate at which pollutant-i is consumed (g/h m^3)
- k_i is the maximum degradation rate of substance (g/h m^3)
- K_i is the Monod constant for substance-i (g/m^3)
- $C_{L,i}$ is the substance concentration in <u>liquid phase </u>(g/m^3)

IN EXCESS OF OXYGEN

If $C_{L,I} >> K_i$ then $r_i = k_i$ zero order kinetic

If $C_{L,I} << K_i$ then $r_i = \frac{k_i \cdot c_{L,i}}{K_i} = k_{0,i} \cdot c_{L,i}$ first order kinetic

REMOVAL CAPACITY: THE BIOFILM THEORY



The resistence to mass transfer in the gas phase is small (system diluted with substances as VOC not completely dissolved)

- x is the direction perpendicular to the gas-solid interface
- δ is the effective biofilm thikness
- δ^* is the total biofilm thikness

$C_{g,i} = H_{D,i} * C_{L,i}$

Where:

$H_{D,i}$ is the Henry's constant of compound-i, dimensionless, although the units really are (g/m^3 in air) / (g/m^3 in water)

The chemical to be removed should be soluble in water

REMOVAL CAPACITY: THE BIOFILM THEORY

Advective flux

Diffusive flux (Fick law)

$$N_i = \overbrace{C_i \cdot v^*}^{\downarrow} - \overbrace{D_i \frac{\mathrm{d}C_i}{\mathrm{d}x}}^{\downarrow}$$

The advective flux can be omitted for diluted system (c_i small) or low velocity (v*)

Where:

N_i = flux of the component-i in g/h (or mole/h)

C_i= concentration in the medium (g/m^3)

V* = mean velocity of the flux (m/h)

D_i = diffusivity coefficient (g/m*h)

Reference: Zarook, S.M., Shaikh, A.A., 1997. Analysis and comparison of biofilter models. Chem. Eng. J. 65, 55–61. https://doi.org/10.1016/S1385-8947(96)03101-4

REMOVAL CAPACITY: THE BIOFILM THEORY

We can apply a mass balance in the biolayer

A= E-U-C

$$\underset{\substack{\uparrow \\ \text{Stationary condition}}}{\frac{\partial c_{L,i}}{\partial t}} = -\underset{\substack{\uparrow \\ = 0}}{\frac{\partial (c_{L,i} * \mathrm{v})}{\partial x}} + \frac{\partial D_i * \frac{\partial (c_{L,i})}{\partial x}}{\partial x} - ri \Rightarrow \boxed{D_i \frac{\partial c_{L,i}}{\partial x^2} - ri = 0}$$

With boundary conditions:

x=0 → $c_{L,i} = \frac{c_{g,i}}{H_{D,i}}$

x=δ → $\frac{\partial c_{L,i}}{\partial x} = 0$

REMOVAL CAPACITY: THE BIOFILM THEORY

We can apply a mass balance in the **gas** phase:

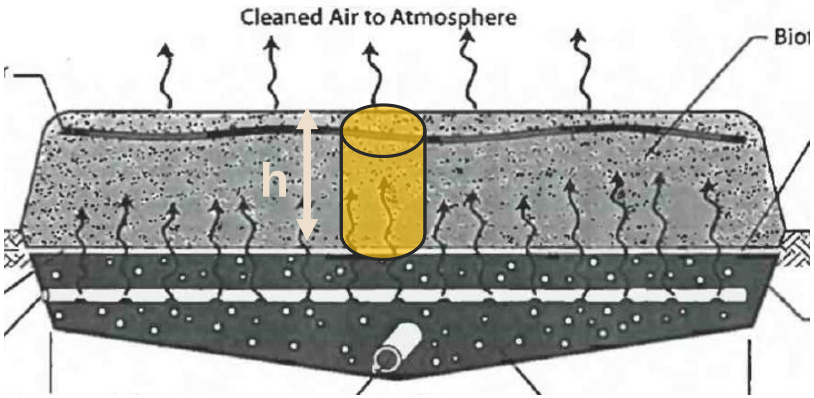
A= E-U-C

$$\frac{\partial c_{g,i}}{\partial t} = \frac{\partial \left(c_{g,i} * v^{*}\right)}{\partial h} - Output$$

Stationary condition

$N_{g,i}$
We consider only the advective contribution, the diffusive term is low

$N_{g,out}$
It is represented by the flux of substances from the gas to the biofilm



$$u_g * \frac{\partial c_{g,i}}{\partial h} = As * N_{g,out} = As * D * \left[\frac{\partial c_{L,i}}{\partial x}\right]_{x\,=\,0}$$

With boundary conditions:

h=0 → $c_{g,i} = c_{g,input}$

where:
$v^* = u_g$ = superficial gas velocity (face velocity) (m/h)
As= specific surface area, ratio of packing surface area to bed volume (m^2/m^3)

REMOVAL CAPACITY: THE BIOFILM THEORY

1° solution – zero order kinetic with reaction limitation

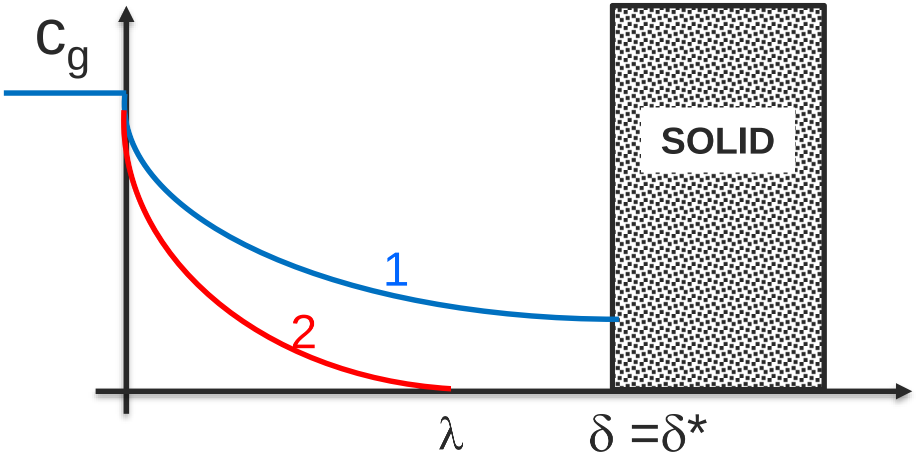
$$\frac{c_{g,out}}{c_{g,in}} = 1 - \frac{As * \delta * h * k_i}{c_{g,in} * u_g}$$

2° solution – zero order kinetic with diffusion limitation

$$\frac{c_{g,out}}{c_{g,in}} = \left\{ 1 - \frac{As * h}{u_g} * \sqrt{\frac{k_i * D_i}{2 * H_{D,i} * c_{g,in}}} \right\}^2$$

EBRT=Vf/Q=empty bed resident time

$$\lambda = \sqrt{\frac{2 * D_i * c_{g,out}}{k_i * H_{D,i}}}$$



Reaction limitation (curve 1)

X=0 $c_{L,i} = c_{g,i}/H_{D,i}$

X= δ =δ* $\frac{\partial c_{L,i}}{\partial x} = 0$

The total biofilm is fully active

Diffusion limitation (curve 2)

X=0 $c_{L,i} = c_{g,i}/H_{D,i}$

X= λ $\frac{\partial c_{L,i}}{\partial x} = 0$ $c_{L,i}$=0

The rate of diffusion is slow compared the chemical reaction rate in the biofilm.The depth of penetration in the biolayer is smaller than the layer thikness

REMOVAL CAPACITY: THE BIOFILM THEORY

3° solution – first order kinetic

If the degradation rate is assumed to be the first-order, one can not clearly distinguish between reaction and diffusion limited regimes.

$$\frac{c_{g,out}}{c_{g,in}} = exp\left\{-\frac{h * As * D_i * \phi * tan\phi}{\delta * H_{D,i} * u_g}\right\}$$

Where ϕ is the Thiele module
and represents the ratio of biodegradation
rate to diffusion rate.

$$\phi = \delta * \sqrt{\frac{K_{O,i}}{D_i}}$$

$$\eta = \frac{c_{g,in} - c_{g,out}}{c_{g,in}} = 1 - exp\left\{-\frac{h*As*D_i*\phi*tan\phi}{\delta*H_{D,i}*u_g}\right\} = 1 - exp\left\{-\frac{h*R}{H_{D,i}*u_g}\right\}$$

Where R is the reaction unit (min $^{-1}$)

$$\mathrm{R} = \frac{As * D_i * \phi * tan\phi}{\delta}$$

If it can be assumed that H_i and R do not change within a biofilter ($R_0 = R/H_{D,i}$)

$$\eta = 1 - exp\left\{-\frac{h * Ro}{u_g}\right\}$$

COUPLING THEORY AND PILOT SCALE

1° solution – zero order kinetic with reaction limitation

$$\frac{c_{g,out}}{c_{g,in}} = 1 - \frac{As * \delta * h * k_i}{c_{g,in} * u_g}$$

2° solution – zero order kinetic with diffusion limitation

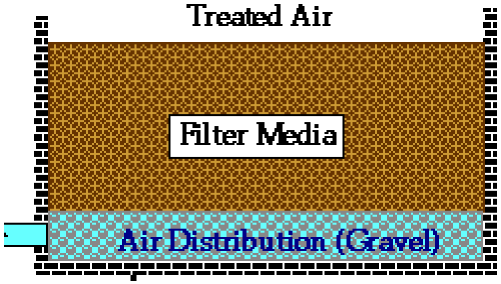
$$\frac{c_{g,out}}{c_{g,in}} = \left\{1 - \frac{As * h}{u_g} * \sqrt{\frac{k_i * D_i}{2 * H_{D,i} * c_{g,in}}}\right\}^2$$

3° solution – first order kinetic

$$\frac{c_{g,out}}{c_{g,in}} = exp\left\{-\frac{h * As * D_i * \phi * tan\phi}{\delta * H_{D,i} * u_g}\right\}$$

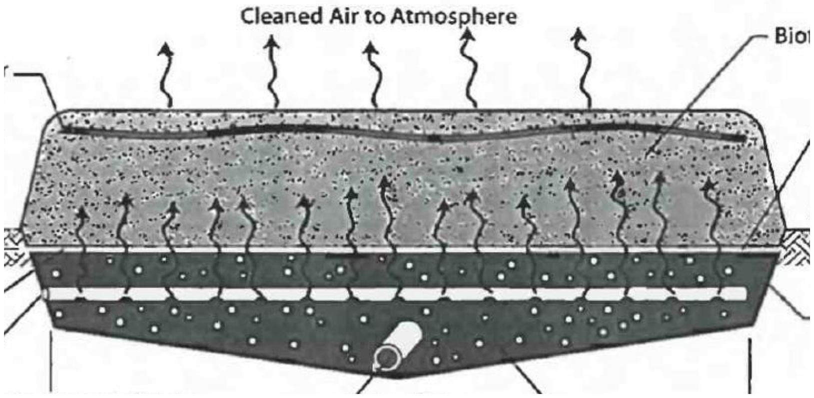
$$\eta = 1 - exp\left\{-\frac{h * Ro}{u_g}\right\}$$

PILOT SCALE



Scale factor «h»

INDUSTRIAL SCALE



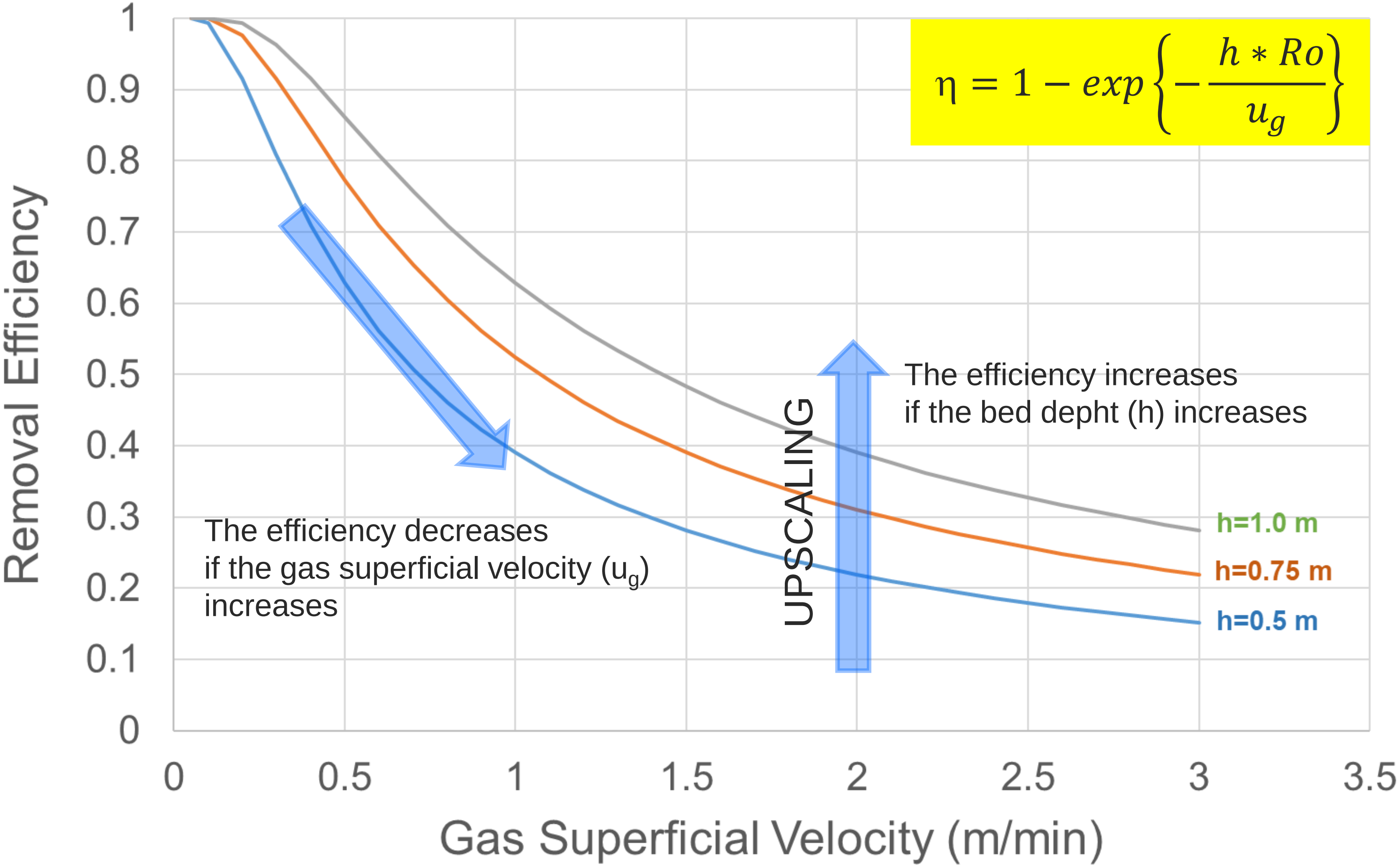
Example 2: Mathematical modelling

A pilot-plant biofilter to control styrene was built and operated to obtain data as follows: at superficial gas velocity of 0.5, 1.0 and 1.5 m/min, removal efficiencies of 63%, 39% and 28%, respectively, were observed. The bed depth was 0.5 m. Develop a set of graps that show how different efficiencies might be obtained by varying bed depht and gas velocity in the full-scale biofilter.

$$Ro = \frac{\ln(1 - \eta)}{-h/u_g}$$

Plugging in the measured values for each of the three data points and averaging the three answers yields a value fo R_0=0.99 min^{-1}.

Example 2: Mathematical modelling



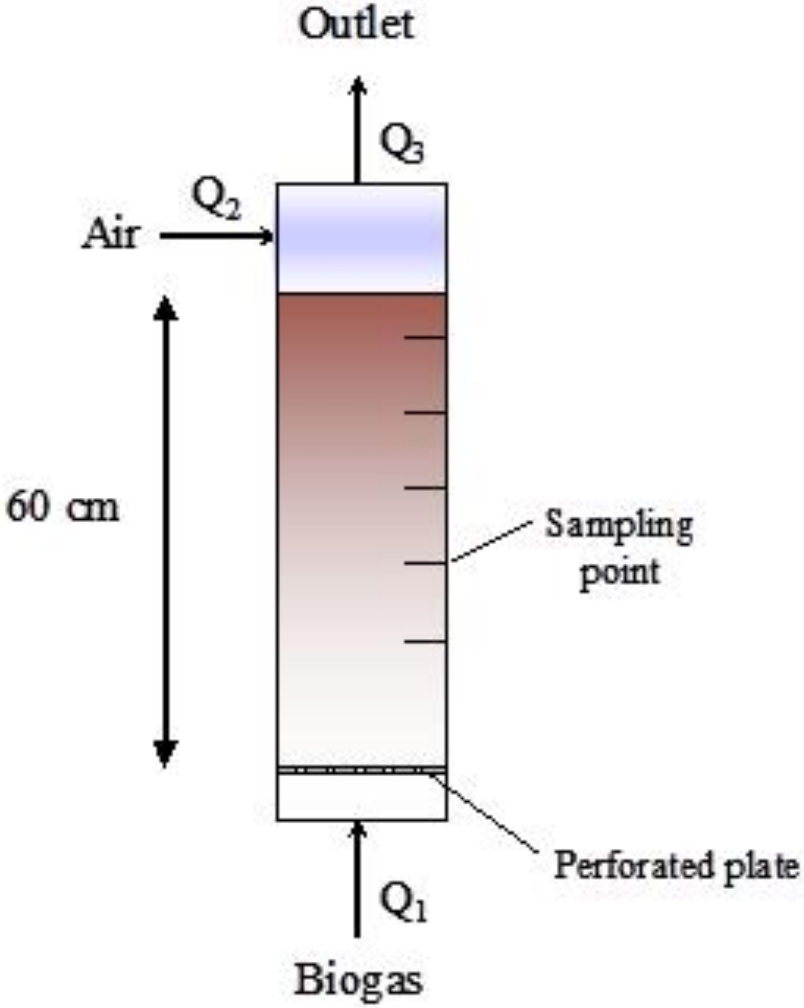
$$\eta = 1 - exp\left\{-\frac{h * Ro}{u_g}\right\}$$

The efficiency decreases if the gas superficial velocity (u_g) increases

UPSCALING

The efficiency increases if the bed depht (h) increases

COUPLING THEORY AND PILOT SCALE



Reference: Raga, R., Pivato, A., Lavagnolo, M.C., Megido, L., Cossu, R., 2017. Methane oxidation and attenuation of sulphur compounds in landfill top cover systems: Lab-scale tests. J. Environ. Sci. 65, 317–326. https://doi.org/10.1016/j.jes.2017.06.040

PRETREATMENT OF GAS STREAMS

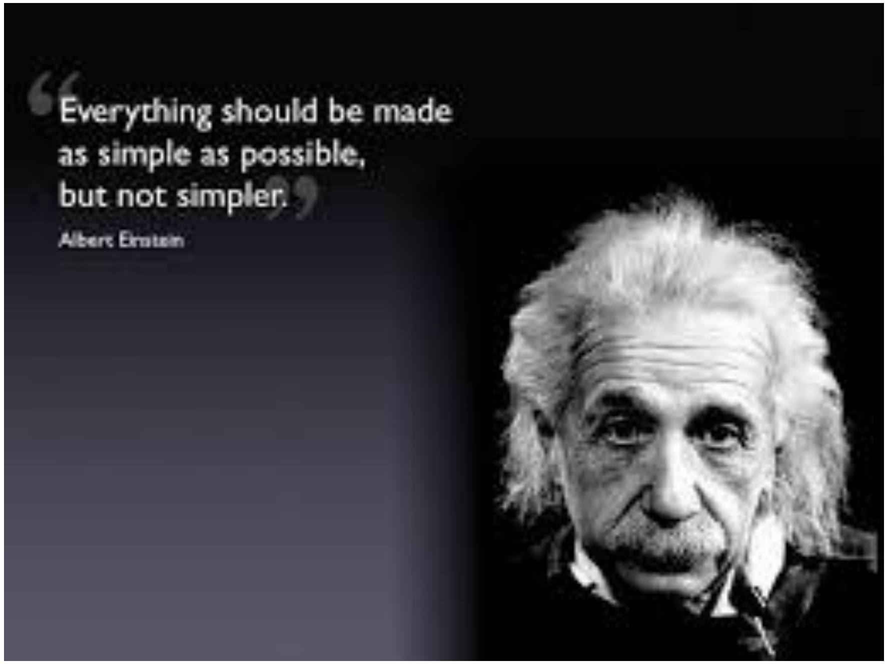
- Besides humidification, heating, or cooling, other pretreatment necessary may include removing particulates.
- Though the biofilter is capable of removing particulates, the solid matter can cause clogging of the biofilter and gas distribution system.

BIOFILTER COMPARED TO OTHER AVAILABLE CONTROL TECHNOLOGY

- Other control technology for the control of VOCs and air toxics include incineration, carbon adsorption, condensation, and wet scrubbing.
- The advantage that biofilters have over all of these technologies is their ability to treat **dilute gas** streams in a cost-effective manner.
- Other technologies often take the pollution from one form and place it in another, for example, removing contamination from an air stream and placing it in the wash water.
- Biofilters allow the **biotransforming** of the pollution to less-or nontoxic forms and reduced volumes.
- Incineration works as a control technology for highly concentrated waste streams. It is more expensive to install and operate than a biofilter system.
- Carbon adsorption is a very effective technology. However, it is very expensive to use, which is especially prohibitive to small operations. If the carbon is regenerated on site, the costs will be less than if it is not regenerated on site.
- Condensation is an effective technology for treating concentrated and pure off gases. As with incinerators, the treatment of dilute streams is too energy intensive to accomplish cost effectively.
- Wet scrubbing technology is also more expensive than biofilter systems.

CONCLUSIONS

BUT



"Everything should be made as simple as possible, but not simpler."

Albert Einstein

NEW REASEARCH FRONTIERS