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Biological Odour Control Theory

Table of Contents:

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1 Introduction

This document was produced and published by Gary Slenders – Principal Process Engineer for AOMC Pty Ltd as part of the education series for Engineering Student in the field of Process, Chemical, and Environmental Engineers as a means of providing a better understanding of the fundamental processes involved in Odour Control. The information contained in this document is based on established material currently in the public domain. You are free to use this material, we ask only that you provide appropriate recognition to the author if you use a significant portion of this document for educational or commercial purposes.

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The key purpose of this document is to simplify the understanding of what Biological Odour Control is all about. As such the information presented is not as rigorous presentation as seen in the standard texts. For a more standardised assessment, we always recommend going back to the source documents.

This document is the fourth part of the series of documentation presented in relation to odour control. In systems, such as BioTrickling Filters and BioFilters the entire process of the removal of odour from the gas stream is based on advanced mass transfer concepts which is addressed in this paper as well as the biochemistry involved in system design.

This document extends previous concepts introduced in Mass Transfer Theory - Practical Design as applied to Wet Chemical Scrubbers. By reviewing the theory behind Biological Odour Control systems, it is assumed that the underlying principles are completely new, but nothing could be further from the truth. As it will be demonstrated the application of Biological Odour Control is the same basis as all mass transfer, except the boundary conditions are changed.

There are very few standard texts available that discuss Biological Odour Control. Having constructed the first BioFilter in 1996, nearly all the details documented have been developed based on experience and through construction experience, research and development.

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2 How bacteria are used to control odour

The primary driver for any bacteria to prosper is that they are able to replicate in numbers and that there is sufficient food source available for energy and a mechanism to prevent

There are autotrophic bacteria that will in circumstances directly convert hydrogen sulphide through enzymic reaction to sulphuric acid in acidic, and aerobic conditions.

$$H_2S + 2O_2 \xrightarrow{Enzymes} H_2SO_4 + energy$$

These bacteria are common in sewers and in wastewater treatment plants are able to grow in abundance if conditions are permitting.

Autotrophic bacteria utilise carbon dioxide from the atmosphere as well as inorganic sources of nitrogen, phosphorus, calcium, magnesium, iron and some sulphur for cell growth.

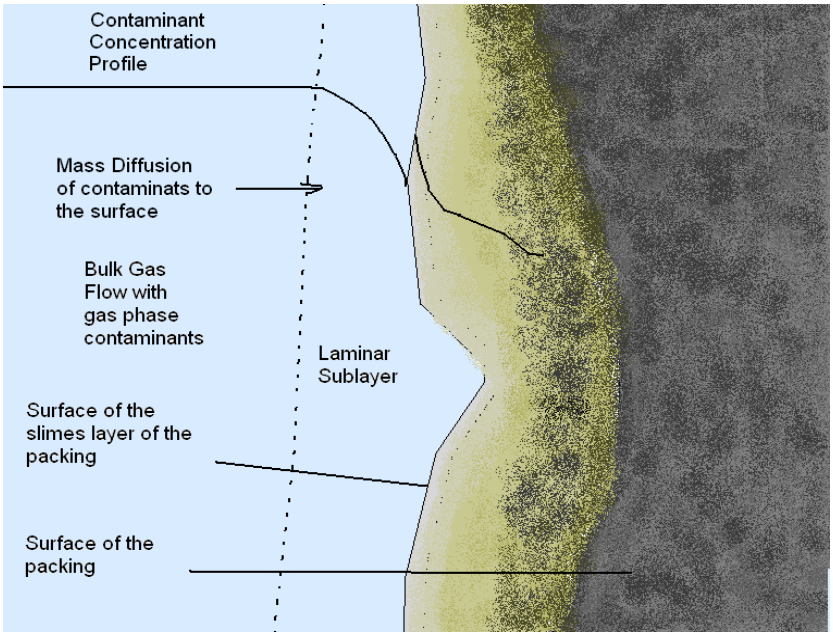
The aim of the scrubber system is to generate conditions by which bacteria are able to convert in sufficient numbers hydrogen sulphide to sulphuric acid.

- Provide a support platform for bacteria to adhere to and promote growth to high concentration
- Provide moisture for maintaining the bacteria metabolic function, and carry nutrients and discharge contaminants.

3 Mechanism for diffusion

The traditional concept of the diffusion of hydrogen sulphide is that of contact with a laminar sublayer of air adjacent to an aqueous layer, through this layer through the membrane wall of the bacteria to the enzymes within the bacterial cell.

The problem with this model is the very acidic conditions ensure that all sulphide in any aqueous phase is in the form of hydrogen sulphide which based on its Henry's Law value is only sparsely soluble in water. There would be insufficient driving force to promote mass transfer.



The likely mechanism is where moisture is only sparingly used and that there is direct contact between the gas phase and the surface membrane of the bacteria allowing adequate performance of the system.

4 Biological Reaction mechanism

The rate equation of biological systems is based on Michaelis–Menten reaction kinetics:

$$\frac{dC}{dt} = -\mu_{Max} X \frac{C}{K_C + C}$$

There are two limits in design. The first limit:

$$C \longrightarrow 0 \quad \frac{dC}{dt} = -\frac{\mu_{Max} X}{K_C} C = -k_{r1}\, C \quad Diffusion\ Limiting$$

The diffusion limiting process suggests that there is a gradient not only across the gas phase, but also across the internals of the bacteria that needs to be taken into account. The key to this second gradient is that it will allow contaminant to be converted to a water-soluble product.

The other limit:

$$C \gg K_C \quad \frac{dC}{dt} = -\mu_{Max} X = -k_{r0} \quad Reaction\ Limiting$$

The reaction limiting process suggests that within the surface of the bacteria to which the enzymic reactions take place that the concentration of contaminants is at a saturation level and that the process can only reduce the contaminant at a fixed rate. There is still diffusion limit process happening, but they exist in the gas phase.

5 Design based on Reaction Limiting Process

The basic driving force equation is able to be used, but there is now an additional factor. Rather than just the driving force being limited by the mass transfer gradient, the additional factor accounts for the biochemical conversion at the end of the mass transfer gradient. This concept existing in chemical scrubbers with reactions such as that of hydrogen sulphide, caustic and sodium hypochlorite, but it has been assumed that the rate of chemical reaction is so much faster than the diffusion reactions that the reactions occur instantaneously. This cannot be assumed in the case of biochemical systems.

Driving force reaction based on Fick's law:

$$\frac{dCg}{dt} = -D \frac{d^2 Cg}{dx^2} - k_{r0}$$

Multiplying both sides by ΔV

$$\frac{\Delta V dCg}{dt} = -D\Delta V\frac{d^2Cg}{dx^2} - k_{r0}\,\Delta V, \qquad QdCg = -\frac{D}{\Delta x}adV(Cg - Cg^*) - k_{r0}\Delta xadV$$

$$QdCg = -K_G a\left(Cg + \frac{k_{r0}\Delta x}{K_G} - Cg^*\right)dV, \qquad QdCg = -K_G a(Cg + \theta - Cg^*)dV$$

Again, the linearity formula can be applied.

$$\frac{Q}{-K_G a}\int_{Cg_1}^{Cg_2}\frac{dCg}{(Cg + \theta - Cg^*)} = \frac{Q}{-K_G a}\int_{Cg_1}^{Cg_2}\frac{dCg}{(\propto + \beta Cg)} = \int_0^V dV$$

$$V = \frac{Q}{-K_G a\beta}ln\left[\frac{\propto + \beta Cg_2}{\propto + \beta Cg_1}\right] = \frac{Q}{K_G a\beta}ln\left[\frac{(Cg_1 + \theta - Cg^*_1)}{(Cg_2 + \theta - Cg^*_2)}\right]$$

$$(Cg_1 + \theta - Cg^*_1) - (Cg_2 + \theta - Cg^*_2) = \beta(Cg_1 - Cg_2)$$

$$\frac{1}{\beta} = \frac{(Cg_1 - Cg_2)}{(Cg_1 - Cg^*_1) - (Cg_2 - Cg^*_2)}$$

$$V = \frac{Q(Cg_1 - Cg_2)}{K_G a}\frac{ln\left[\frac{(Cg_1 + \theta - Cg^*_1)}{(Cg_2 + \theta - Cg^*_2)}\right]}{(Cg_1 - Cg^*_1) - (Cg_2 - Cg^*_2)} \; with\; \theta = \left(\frac{k_{r0}\Delta x}{K_G}\right)$$

Although this formula is developed for the case where the system is reaction limiting, all practical applications for odour control are diffusion limiting.

6 Design based on Diffusion Limiting Process

Similar to the design equation based on reaction limiting process, diffusion limiting rate equation can be applied using Fick's Law.

Driving force equation is:

$$\frac{dCg}{dt} = -D\frac{d^2Cg}{dx^2} - k_{r1}\,C$$

Multiplying both sides by ΔV

$$\frac{\Delta V dCg}{dt} = -D\Delta V\frac{d^2Cg}{dx^2} - k_{r1}\,C\Delta V \;\; QdCg = -\frac{D}{\Delta x}adV(\mathrm{Cg} - Cg^*) - \frac{k_{r1}}{H}\,Cg^*\Delta xadV$$

Taking into the account the effects of turbulence:

$$QdCg = -k_{Cg}adV(\mathrm{Cg} - \psi Cg^*)\; where\; \psi = \left(1 - \frac{\Delta x k_{r1}}{HK_{Cg}}\right)$$

Again, the linearity formula can be applied.

$$\frac{Q}{-K_G a}\int_{Cg_1}^{Cg_2}\frac{dCg}{(Cg - \psi Cg^*)} = \frac{Q}{-K_G a}\int_{Cg_1}^{Cg_2}\frac{dCg}{(\propto + \beta Cg)} = \int_0^V dV$$

$$V = \frac{Q}{-K_G a\beta}ln\left[\frac{\propto + \beta Cg_2}{\propto + \beta Cg_1}\right] = \frac{Q}{K_G a\beta}ln\left[\frac{(Cg_1 - \psi Cg^*{}_1)}{(Cg_2 - \psi Cg^*{}_2)}\right]$$

$$(Cg_1 - \psi Cg^*{}_1) - (Cg_2 - \psi Cg^*{}_2) = \beta(Cg_1 - Cg_2)$$

$$\frac{1}{\beta} = \frac{(Cg_1 - Cg_2)}{(Cg_1 - \psi Cg^*{}_1) - (Cg_2 - \psi Cg^*{}_2)}$$

$$V = \frac{Q(Cg_1 - Cg_2)}{K_G a} \frac{ln\left|\frac{(Cg_1 - \psi Cg^*_1)}{(Cg_2 - \psi Cg^*_2)}\right|}{(Cg_1 - \psi Cg^*_1) - (Cg_2 - \psi Cg^*_2)}$$

$$with\ \psi = \left(1 - \frac{\Delta x k_{r1}}{H K_{Cg}}\right)$$

This is the standard process equation with a subtle change that has a dramatic effect. If the first order reaction rate is sufficiently high enough and the gas phase mass transfer is low enough, then ψ approaches zero then we have

$$V = \frac{Q}{K_G a} ln\left|\frac{Cg_1}{Cg_2}\right|$$

Which is the optimum design equation for a pack column gas scrubbing system.

This is the basis of applying biological odour control in place of wet chemical scrubbing systems

7 Mass Transfer Coefficients for Biological Systems

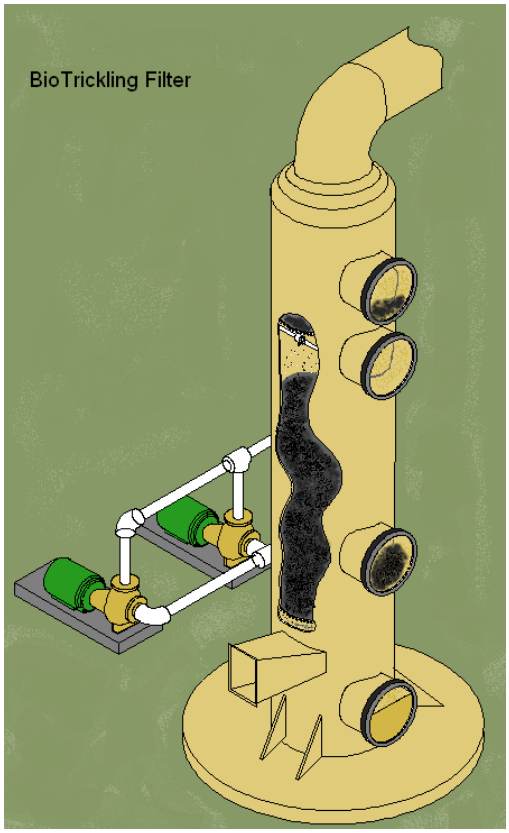
The corrected mass transfer coefficient values have been determined for a number of different chemical species. This information is available from proprietary process designers based on extensive research undertaken by the process designers. The relationship exists that correlates Mass Transfer with transport conditions within the biological odour control systems

$$K_G = \frac{\mu_{Max} X}{k_c}\left(\frac{\rho_{Air} v_{Air}}{a \mu_{Air}}\right)^{0.285}\left(\frac{\mu_{Air}}{\rho_{Air} D_{Cont}}\right)^{0.51} a D_{Cont} \alpha \theta^{(T-20)}$$

The value of the mass transfer coefficient is characterised by:

- The properties of the specific chemical species being removed
- The properties of the bacteria involved
- The degree of turbulence (as measured by the superficial velocity) through the bed
- Size of the packing and specific area of the packing used.
- Temperature has a significant impact on the bed performance up to 34 C through Arrhenius theory
- Chemical and biological data at standard conditions for which coefficient data available for at least 30 compounds

8 Practical Layout of BioTrickling Filters



The basic flow arrangement for a BioTrickling Filter is for air to pass through a bed consisting of an inorganic packing of materials including polyurethane foam, pumas, and speciality injected plastic packing all of which have the characteristic of an extended surface area

The media is wetted with recirculating water sufficient to maintain the delivery of nutrients and to remove accumulation of contaminants.

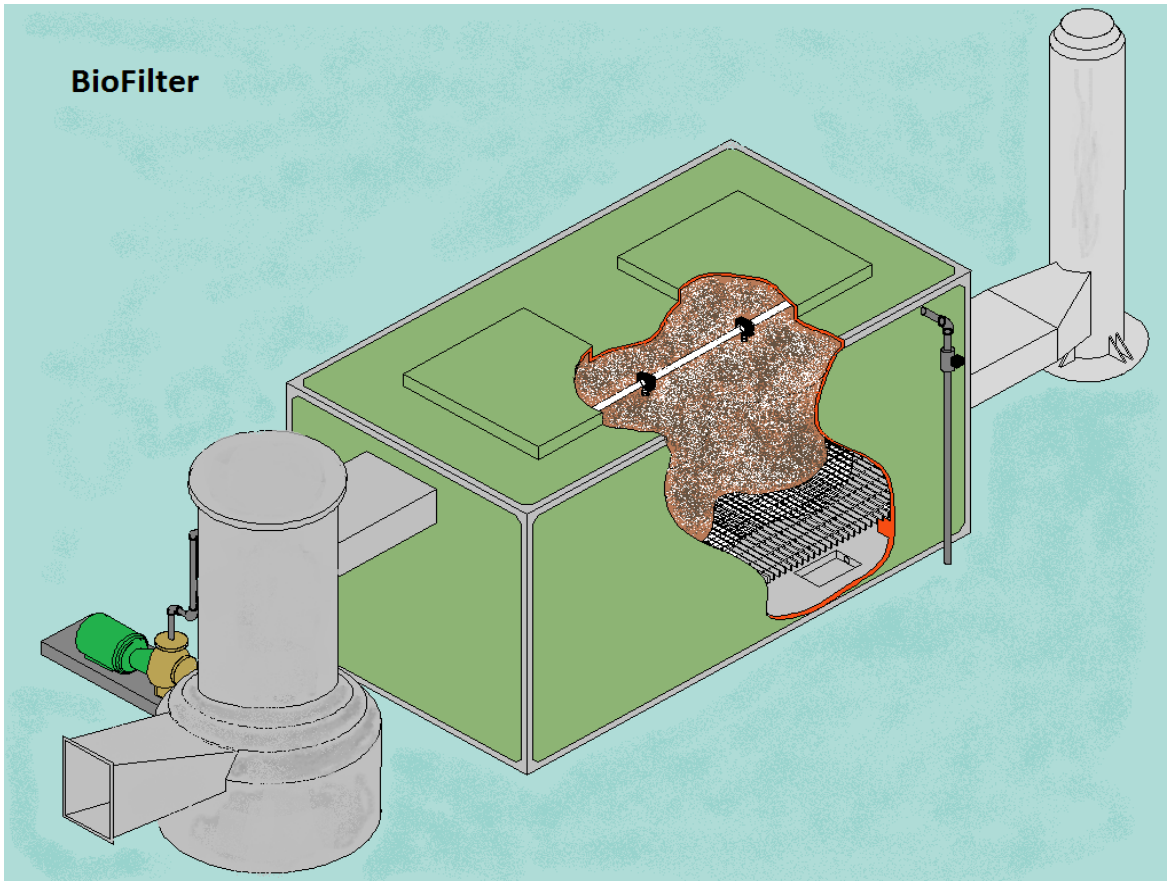
The bacteria adhering to the surface of the packing is at concentrations much greater than what could be achieved otherwise and provides the performance of the system.

The air stream provides a source of oxygen, and carbon (from carbon dioxide and from volatile carbon). Nutrients are required to be added into the recirculation water supply in order to maintain the operations of the system.

There are some traces of nutrients naturally available in water supplies, but normally a nutrient solution is injected into the sump of the system to maintain trace levels.

As the media used is normally inorganic by nature, they are very stable and are chemical resistant. Most BioTrickling Filter media are designed to last for up to 10 years. The levels of contaminants that they can tolerate is extremely high. Systems have been developed that can operate with hydrogen sulphide levels exceeding 2500 ppm.

9 Practical Layout of BioFilters



The Biofilter consists of a contained housing of Fiberglass, Plastic, or Concrete.

It has top entry flow across a plenum area above the bed and then flowing evenly through a bed of organic media. The air flow then discharges through a lower plenum and out to a discharge stack.

Media in a bed manufactured of a recipe of materials consisting of a mixture of organic and inorganic compounds. Materials such as wood chips, pine bark, rice hulls, perlite, and limestone are used to make up various forms of media.

Moisture is added to the system by way of atomiser sprays across the surface of the media. Air flow into the system is also pre-humidified in order to ensure even distribution of moisture.

The contaminants are converted to water soluble by-products, but unlike BioTrickling Filters, the contaminants are locked into the bed requiring addition of alkalinity to maintain the stability of the bed.

Once the alkalinity is exhausted, the organic media starts digesting, resulting in breakdown of the media into fine silt and mud. This increases the pressure drop over time through the bed, and ultimately the bed must be replaced. The beds in Biofilters generally are only designed to last 2 – 3 years.

There is a limited stable concentration of alkalinity that can be incorporated into media. For this reason, a limit of 50 ppm hydrogen sulphide is applied to the maximum inlet concentration of a BioFilter.

10 BioFilter or BioTrickling Filters?

At its core, there is no difference between BioFilters or BioTrickling Filters. The differences are predominantly the quality of the materials, the use of organic mixes of media as compared to inorganic media.

The essential considerations that need to be taken into account when considering whether to use BioFilters or BioTrickling Filters are:

- Of primary consideration is the inlet concentration of the contaminants. BioFilters do not tolerate very high concentrations, so if the inlet concentration are high then BioTrickling Filters should be specified.
- As the organic media in BioFilters tends to have much lower specific surface area, the required volume of media is much greater than that of BioTrickling Filters. The offset is that the media can be much cheaper per unit volume. It becomes a balance between area requirements and cost differential between BioTrickling Filter media and BioFilter media.
- Organic media has preloaded into it bacteria and nutrients thereby providing upfront performance whereas BioTrickling Filters require time for the bacteria to migrate across to the packing surface.
- BioTrickling Filters can tolerate poorer water quality than that of BioFilters that use atomiser sprays.
- Both systems are relatively simple to operate, require the minimum amount of instrumentation, and are both very much reliable.

11 Multicomponent Systems

The descriptions of the process of biological odour control to this point only described single component systems. Sewer gas is very much made up of more than just hydrogen sulphide. There are around 800 known compounds found in sewer gas as various traces.

The most common compounds found in sewer gases that are predominantly domestic by nature include:

Hydrogen Sulphide

Ammonia

Methyl Mercaptan

Ethyl Mercaptan

Dimethyl Sulphide

Dimethyl Disulphide

Toluene, Xylene, Styrene, Benzene

Trichloro Ethylene

Volatile Fatty Acids, Tallow

Methanol, Ethanol, Butanol

Ethyl amine

Methyl Ethyl Ketone, Acetone,

For a biological system to work to reduce this cocktail of different compounds, it requires a sequence of separate biological units in series treating each individual compound by a bed of specifically cultured bacteria.

In practice, there is only a single bed used, but there are zones generated within the bed. The offset to this is that there is a limitation in performance as bacteria compete against each other for sections of the bed.

There is considerable complexity in creating a function bed able to deal with a multitude of components.

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12 Variables and Units

Variable	Units	Description
a	m^2/m^3	Specific Surface Areas
D	m/s^2	Diffusion coefficient
f	-	Fanning's friction factor
H	mol/mol	Henry's Law Coefficient
k_{r0}	kg/m^3-s	Zero order rate equation coefficient
k_{r1}	1/s	First order rate equation coefficient
K_C	mg/L	Specific Concentration. Concentration in the liquid phase were the rate of conversion is half the maximum
Q	m^3/s	Volumetric Flow
v	m/s	Bulk flow velocity
V	m^3	Volume
T	C	Temperature
ρ	kg/m^3	Bulk Fluid Density
X	kg/m^3	Concentration of bacteria per unit volume of packing
pH	-	Log Scale Hydrogen Ion concentration
μ_{MAX}	kg/kg-s	Specific rate of contaminant conversion

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