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Emission of microorganisms from biofilters

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Abstract. Experiments are reported on the discharge of microbial germs by biofilter systems used for the treatment of waste gases containing volatile organic compounds. The systems investigated concern six full-scale filter installations located in the Netherlands in several branches of industry, as well as a laboratory-scale installation used for modelling the discharge process. It is concluded that the number of microbial germs (mainly bacteria and to a much smaller extent moulds) in the outlet gas of the different full scale biofilters varies between 10^3 and 10^4 m^{-3}, a number which is only slightly higher than the number encountered in open air and of the same order of magnitude encountered in indoor air. It is furthermore concluded that the concentration of microorganisms of a highly contaminated inlet gas is considerably reduced by the filtration process. On the basis of the experiments performed in the laboratory-scale filter bed, it is shown that the effect of the gas velocity on the discharge process results from two distinctive mechanisms: capture and emission. A theoretical model is presented describing the rate processes of both mechanisms. The model presented and the experimentally determined data agree rather well.

List of symbols

a_s	m^{-1}	specific area of the packing material
C	m^{-3}	microbial gas phase concentration
C_e, C_i	m^{-3}	microbial concentration in the exit and inlet gas resp.
CFU	–	colony-forming-units
d_c, d_m	m	diameter of collecting and captured particle resp.
D	m	diameter of the filter bed
E	–	single particle target efficiency
H	m	bed height
k_c	s^{-1}	first order capture rate constant per unit of bedvolume
k_e	m^{-3}	emission rate constant per unit of bedvolume
n	–	number of observations
r_c, r_e	m^{-3} s^{-1}	capture and emission rate per unit of bedvolume
$Re =$	–	$\dfrac{\varepsilon}{(1-\varepsilon)}\dfrac{\varrho\, u\, d_c}{\mu}$ Reynolds number
$S_t =$	–	$\dfrac{\varrho_m\, u\, dm^2}{9\,\mu\, d_c}$ Stokes number
u	m s^{-1}	superficial gas velocity
u_m	m s^{-1}	superficial gas velocity at which $C_e = C_i$

Greek symbols

ε	–	void fraction of the filter bed
ϱ	kg m^{-3}	density of the gas phase
ϱ_m	kg m^{-3}	density of captured particle
μ	Pa s	dynamic gas phase viscosity
$\eta =$	–	$1 - \dfrac{C_e}{C_i}$ filter bed efficiency

1 Introduction

Since the early sixties biological methods have been employed for the purification of waste gases containing volatile organic pollutants. At the outset, biofiltration as a technology for air pollution control, was mainly used for odour abatement in wastewater treatment plants, composting works, etc. Nowadays there is a clear trend to apply biofiltration on a much broader scale in different branches of the process industry and the application of and interest in biological gas treatment systems is rapidly increasing.

Microbial purification processes are based upon the ability of many microorganisms (generally bacteria, and to a small extent moulds and yeasts) to degrade a variety of organic compounds. Under aerobic conditions, these organisms are able to oxidize the compounds concerned into mineral endproducts (e.g. CO_2, H_2O etc.). Part of the organic compounds is transformed into new cell material.

In a biofilter the waste gas is forced to rise through a layer of biologically active packing material with a relatively high specific area (300–1000 m^{-1}). Different types of packing material are used in practice e.g. compost, peat and mixtures of these natural materials with chips of wood, heather branches, polystyrene particles, etc. The quality of the filling material is characterized by mechanical and physical properties, e.g. the structure, the void fraction, the specific area, the flow resistance, the water buffering capacity and biological properties, e.g. the availability and provision of inorganic nutrients for the microorganisms, the specific biological activity, etc.

Until now, little research has been carried out on the subject of contamination of biologically treated air by microorganisms. The intention of the European Economic Community is to establish guidelines for working with bio-

Table 1. Microbial concentration levels in different air compartments

Air compartment	Concentration (CFU/m^3)	Lit. ref.
Open air (coastal region)	$0.63 \cdot 10^2$	[2]
Operating room, hospital	$4.6 \cdot 10^2$	[3]
Open air (country side)	$10^2 - 10^3$	[2]
Open air (town)	$7.6 \cdot 10^2$	[4]
Canteen	$(4-9) \cdot 10^2$	own measurements
Cafeteria	$1.6 \cdot 10^3$	[3]
Office	$(1.4-2.3) \cdot 10^3$	[2, 10]
Biotechnological laboratory	$4 \cdot 10^3$	own measurements
Sewage treatment plants	$10^2 - 10^5$	[6-8]
Piggery, cow-house	$(7-13) \cdot 10^4$	[2, 5]
Poultry-house	$10^4 - 10^5$	[2, 9]
Compost factory	$10^3 - 10^5$	[6]

logically active materials, and requires data to evaluate the risks of working with these materials. Moreover, in some branches of industry, particularly the food-, pharmaceutical- and fermentation industry, some fear exists for an increased contamination of raw materials and products with undesirable microorganisms during handling processes, due to a putatively high microbial emission by an installed biofilter.

Data dealing with the concentration of microorganisms in gasflows emitted by biofilter systems are very limited. Recent investigations on several biofilter systems have been carried out by Bardtke's group [1] in Germany.

In order to evaluate experimental data concerning microbial concentrations present in air, Table 1 lists some concentration levels which are met in different air compartments.

The investigations presented in this paper deal with the emission of microorganisms from biofilters and the influence of the gas velocity on the rate of emission. Experiments were carried out on a number of full-scale- and pilot plants, as well as laboratory-scale biofilters. Besides, a theoretical model will be presented, which describes the rate of microbial emission from biofilters and the mechanisms affecting it.

Materials and methods

2.1 Determination of the CFU-number

To estimate the number of microorganisms in the influent- and effluent gas flows of a biofilter, samples were taken with a Millipore all-glass impinger [11]. According to this method a certain volume $(0.01-0.1 \text{ m}^3)$ of air is drawn by a vacuum-pump through a narrow capillary (internal diameter 1.2 mm) into the impinger fluid at an air flow rate of approx. $1.7 \cdot 10^{-4} \text{ m}^3/\text{s}$. Due to the high air velocity in the capillary (ca. 150 m/s) a continuous gaschannel is created in the vessel beyond the nozzle of the capillary, and due to inertial forces

microorganisms present in the air impinge on the humid glass bottom from which they are washed away by the surrounding impinger liquid.

The impinger vessel, containing 0.1 dm^3 of a physiological salt solution (8.5 g NaCl per dm^3 distilled water), is sterilized before use. The exact air volume, which has passed the apparatus during the sampling, is recorded by a gasflow-meter.

After the sampling the impinger liquid is diluted with 0.9 dm^3 of a sterile physiological salt solution and the standard membrane filter procedure is followed in order to determine the number of colony-forming-units (CFU). According to this method the microbial germs are separated by filtration on a membrane filter (porediameter 0.45 µm) which is put on a solid culture medium and incubated at room temperature during six days. The number of colonies are counted on the third and the sixth day and from this the CFU-number in the original air sample can directly be calculated. We used the ready-to-hand standard TTC "Nahr-kartonscheiben" of Sartorius, as this solid culture medium is appropriate to a broad range of microorganisms. It will be evident that the CFU-number indicates that a colony which appears at the solid culture medium after incubation originates from a germ consisting of one or more cells.

From visual observations it was determined whether a colony developed consisted of bacteria or moulds.

2.2 Processing of the experimental data

Because of the lack of reproducibility, several samples were taken at one sample site. The data obtained from that sampling site were assumed to be distributed lognormally. Especially in the field of air sampling good results have been obtained in the lognormal processing of the obtained data [13–18]. This procedure starts from the fact that the logarithmic transformations of the obtained data are normally distributed. The geometric mean and the geometric standard deviation, being the two parameters by which the lognormal distribution curve is completely determined, are the antilogs of the mean and the standard deviation, respectively, of the logarithmically transformed data points.

Hence, the value of the geometric mean of the obtained data is considered to be the representative CFU-number for the concentration of microorganisms in the air at the sampling site concerned. With the use of common statistical analysis procedures it is in this way possible to detect significant differences between the CFU-number of the inlet- and outlet gasflow of a biofilter, for example.

3 Experimental set-up

3.1 Full scale installations

Experiments were carried out at six full-scale biofilters to determine the rate of microbial emission under practical conditions. Three of the filters investigated belong to the

Table 2. Specifications of the full-scale plants

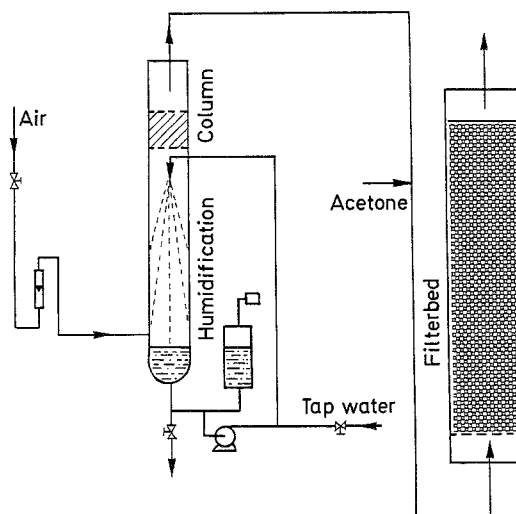| Code number	Type	Packing material	Waste gas source
I	Bioton	Compost-polystyrene	Oriental food processing
II	Conventional	Compost (coarsely structured)	Domestic sewage treatment plant
III	Bioton	Compost-polystyrene	Flavour and fragrance
IV	Conventional	Peat-heather branches	Destructor
V	Conventional	Peat-heather branches	Destructor
VI	Bioton	Compost-polystyrene	Industrial sewage treatment plant

Process specifications	Code number installation					
	I	II	III	IV	V	VI
Filter area, [m^2]	24	25	14	300	225	20
Packing height, [m]	1	0.75	1	1	1	1
Filter stages, [–]	2	1	2	1	1	1
Gasflow rate, [10^3 m^3/h]	9	0.75	3	60	30	8
Gas velocity, [m/h]	375	30	214	200	133	400
Water content of packing, [% w/w]	39	30	40	45	51	55
Inlet gas temperature, [°C]	30	18	45	20	27	15
Outlet gas temperature, [°C]	30	19	43	21	23	15
Outside temperature, [°C]	23	6	13	5	−2	3
Pressure drop, [kPa]	n.d.	0.7–1.2	0.45	0.18	0.36	n.d.

n.d.: not determined

Fig. 1. Schematic representation of the laboratory-scale biofilter

conventional open type filled with compost or a mixture of peat and heather branches, the other three belong to the closed type (trademark: Bioton) with a mixture of equal volumes of finely structured compost and polystyrene particles (d_c: 3–5 mm). All the installations are located in the Netherlands and treat different kinds of waste gases. Some further specifications of the installations and process conditions are listed in Table 2.

3.2 Laboratory-scale biofilter

A laboratory-scale biofilter was used to model the system and to investigate the influence of the gas velocity on the microbial emission rate. The filter, schematically shown in Fig. 1, consisted of a quickfit glass column with an inner diameter of 15 cm and a filter height of 1 m. At the bottom of the column a sieve plate was mounted to support the packing material consisting of a mixture of equal volumes finely structured compost and polystyrene particles (d_c: 3–5 mm). The package was inoculated with an activated sludge suspension from a municipal waste water treatment plant. To keep the humidity of the packing material at a desired

level of 40–60% (w/w), the influent air was humidified before entering the filterbed. A synthetic waste gas, with concentrations of up to 750 mg/m^3 of acetone, was created by the continuous injection of this compound in the air stream. The advantage of using acetone as a contaminant is the ready microbial degradability of the component. Furthermore, acetone can be used by a broad range of microorganisms as their sole carbon- and energy source.

When no experiments were carried out at the filter bed, the system was continuously operated at standard conditions, being a superficial gas velocity of 200 m/h, room temperature and a gas inlet concentration of 750 mg/m^3. At these conditions the stationary degree of conversion of the filter bed amounted to 80%.

4 Experimental results

4.1 The microbial emission by full-scale systems

The CFU-number of bacteria and moulds emitted by the different full-scale filter beds are listed in Table 3.

From the data presented in Table 3 it can be concluded that the number of microbial germs in the outlet gas of the different biofilters varies between 10^3–10^4 m^{-3}, a number which is only slightly higher than the number encountered in open air and of the same order of magnitude encountered in indoor air (see Table 1). The presented data are of the same order as those measured in the German investigation [1].

Furthermore, it can be concluded that the concentration of microorganisms of a highly contaminated inlet gas is considerably reduced by the filtration process (installations no. IV and V). On the other hand, there is an extra contamination due to the filtration process at low CFU-numbers of the inlet gas (inst. no. III and VI). From this it is obvious that a biofilter may serve as a system of capture as well as a source of emission.

Table 3. Microbial emission by full-scale filter beds

| Code number filter installation | Microbial concentration [CFU/m^3] | | | | | |
| | Inlet | | | Outlet | | |
	n	Bacteria	Moulds	n	Bacteria	Moulds
I		n.d.	n.d.	12	1750	1180
II		n.d.	n.d.	12	4780	600
III	6	933	302	12	1150	24
IV	6	>2·10^4	n.d.	12	9350	30
V	5	13900	5	10	6400	130
VI	9	580	3	9	1020	19

n: number of observations; n.d.: not determined

The data presented also show that the emitted concentrations are considerably affected by the structure of the packing material. Finely structured, homogeneous packing materials like the investigated compost-polystyrene mixtures (inst. no I, III and VI) emit lower CFU-numbers of bacteria than more inhomogeneous materials like coarsely structured compost and conventional mixtures of peat and heather branches (inst. no II, IV and V).

4.2 Influence of the gas flow rate on microbial emission

In a laboratory-scale filter bed, as outlined before, the influence of the gas flow rate on the rate of microbial emission was studied. During the sampling with the all-glass impinger the dosing of acetone into the inlet gas flow was interrupted.

In view of the rather constant inlet conditions of the synthetic waste gas and the laborious experimental manipulations, the determination of the CFU-numbers in the inlet gas was only performed in a restricted number of cases. The inlet CFU-number of bacteria of the synthetic waste gas usually varied between approx. 1500 and 2500 m^{-3}. The results concerning the emitted number of germs in dependence on the superficial gas velocity are given in Table 4.

As can be seen from Table 4, the results have been gathered during an operational period of the filter bed of over six months. This explains the scattering of the observed data in the course of time.

Nevertheless, some interesting conclusions can be drawn from the data presented:

a) the number of discharged moulds is generally low compared to the number of bacteria. The discharged total numbers of germs encountered in the laboratory-scale filter bed are in rather good agreement with the emission data of full-scale installations provided with the same packing material.

b) the number of bacteria discharged at low values of the gas velocity is generally above the range of the CFU-inlet number and there is a clear trend of a decrease of the outlet concentration at increased values of the velocity. As already stated before, a biofilter may serve as a system of capture as well as a source of emision. Since the emission rate may

Table 4. Influence of the gas velocity on the microbial emission

| Time after start-up [d] | Number of observations [-] | Superficial gas velocity [m/h] | Outlet gas concentration [CFU/m^3] | |
			Bacteria	Moulds
30	6	162	3940	10
30	6	314	2920	5
30	6	459	2070	3
37	6	238	3440	23
37	6	436	1880	12
37	6	634	1410	5
67	5	238	1130	12
67	5	436	930	18
67	6	634	400	7
107	6	158	6630	10
107	6	238	2910	5
129	6	79	3490	130
129	5	158	2810	600
129	6	238	1070	710
198	8	119	2950	250
198	8	555	1090	24

Table 5. Capture by a sterile filter bed

| Time after start-up [d] | Number of observations [-] | Superficial gas velocity [m/h] | Microbial concentration | | | |
| | | | Inlet | | Outlet | |
			Bacteria	Moulds	Bacteria	Moulds
0	9	446	1610	22	810	140
4	9	446	2390	190	1630	1

probably be expected to increase at higher gas velocities, it will be obvious that the capture mechanism produces a more pronounced and inversed effect on the number of germs discharged at increased gas flow rates.

In order to verify the capture by the filtersystem, experiments were performed in a filter bed ($D = 15$ cm) consisting of sterilized packing material with a bed height of 0.50 m. In this way the serving of the bed as a source of microorganisms can be eliminated. The packing material consisted of equal volumes of lava particles (d_c: 3–5 mm) and compost. Lava was chosen as an inert substitute for polystyrene, because the latter cannot be steam-sterilized without morphological changes. Sterilization of the packing material was carried out in an autoclave for 1 h at 120 °C.

The filter bed was packed immediately after the sterilization of the packing material, and air, containing airborne microorganisms was led through it, at a superficial gasvelocity of 446 m/h.

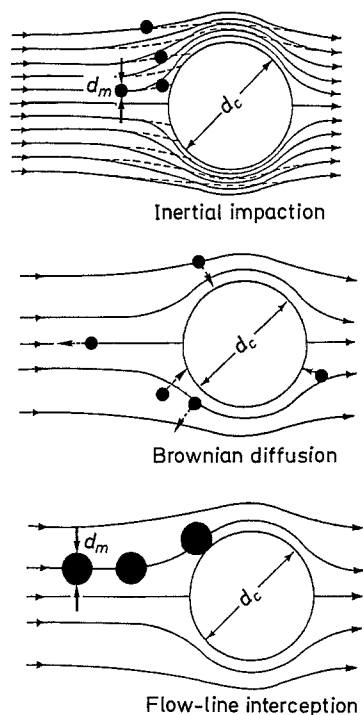The experimental results are listed in Table 5.

Fig. 2. Mechanisms of capture of dispersoid particles

Although the initially high amount of moulds in the outlet gas probably indicates insufficient sterilization conditions for spore killing, it can be concluded from the data presented in Table 5 that there is a considerable reduction of the number of bacteria due to capture by the filter bed.

5 Theoretical discharge model

The discharge of microorganisms by a biofilter bed is brought about by two simultaneous mechanisms: capture and emission.

5.1 Capture

Capture concerns with the removal or collection of solid dispersoids present in gases, due to impingement on the packed bed particles. When a dispersoid-laden gas impinges on a solid particle, the gas will be deflected around this particle, whereas the dispersoid particles by virtue of their greater inertia will tend to be collected on the surface of the body. Impingement is generally characterized in terms of the so-called target efficiency, which represents the fraction of dispersoids in a gas volume swept by a bed particle which will impinge on this particle. Capture of dispersoid particles in a granular packed bed is generally effected by three different mechanisms: 1. inertial deposition, 2. diffusional or Brownian deposition and 3. flow line interception. The mechanisms mentioned are visualized in Fig. 2.

A number of investigators have evaluated the relative contribution of each mechanism for dust particles and they agree that for dispersoid collection at sufficiently high veloc-

ities, the predominant mechanism is inertial impaction. Brownian diffusion is only effective for particles in the submicron range ($<0.1-1$ μm), where the velocity of the dispersoid particle relative to the collecting particle is very small [19, 20]. Interception can be significant when the particle path is obstructed by a great many collecting particles of a diameter similar to that of the dispersoid [2].

The average size of individual microorganisms (bacteria and moulds) which are responsible for biodegradation in biofilters, and (clusters of) microorganisms freely dispersed in the gas phase is generally in the μm range. As a consequence of the gas velocities normally applied in biofilters (0.01–0.15 m/s) and of the average size of the packing particles (3–10 mm), the combined effects of Brownian diffusion and interception are generally minor as compared to the inertial mechanism in the impingement of microorganisms in biofilter beds.

Several theoretical models for the removal of dispersoids in granular bed filters, consisting of equally sized spheres which are homogeneously distributed, have been suggested [e.g. 21, 22]. A combined overview can be found in a review of theoretical and experimental studies by Gutfinger et al. [23]. These models generally start from single particle target efficiency and the efficiency of the whole bed is found by integration over the entire granular bed. Moreover, single sphere target efficiency is generally assumed to be independent of the dispersoid concentration. This implies that collection is a first order process in dispersoid concentration [24] and may hence be regarded as a first order heterogeneous chemical reaction.

We accordingly propose for the capture rate in a biofilter that:

$$r_c = k_c\, C, \tag{1}$$

where:

r_c = capture rate (m^{-3} s^{-1});
k_c = first-order rate constant per unit of bed volume (s^{-1}); and
C = number of concentration of germs in the gas phase (m^{-3}).

For a homogeneous filter bed consisting of equally sized spheres the capture rate constant k_c is given by [24]:

$$k_c = \frac{3\,E\,u\,(1-\varepsilon)}{2\,d_c}, \tag{2}$$

where:

E = single particle target efficiency (–);
u = superficial gas velocity (m/s);
ε = void fraction of the packed bed (–); and
d_c = diameter of collecting particle (m)

If the target efficiency is only due to inertial impaction, the relation of Thambimuthu [25] may be used:

$$E = \left(1 + \frac{0.06\,\varepsilon}{S_t}\right)^{-3} \quad \text{(for } S_t < 0.02), \tag{3}$$

where:

$$S_t = \text{Stokes number} = \frac{\varrho_m \, u \, d_m^2}{9 \, \mu \, d_c};$$

d_m = diameter of captured particle (m);

ϱ_m = density of captured particle (kg/m^3); and

μ = dynamic gas phase viscosity (Pa · s).

From Eqs. (2) and (3) it follows that:

$$k_c = \frac{3(1-\varepsilon)}{2\,d_c} \frac{u}{\left(1 + \frac{0.06\,\varepsilon}{S_t}\right)^3} . \tag{4}$$

Since the structure of biofilter packing materials may deviate considerably from the idealized packed bed model, it is likely to combine physical constants of Eq. (4) into overall constants in order to describe the dependence of the capture rate constant on the gas velocity:

$$k_c = a \frac{u}{(1 + b/u)^3} . \tag{5}$$

The constants a and b in Eq. (5) depend on the nature and structure of the packing material. The values of these constants have to be determined experimentally, but may roughly be estimated from Eq. (4).

Example of application

According to Eq. (1) the capture efficiency for a filter bed amounts to:

$$\eta = 1 - \frac{C_e}{C_i} = 1 - \exp\left[-k_c \frac{H}{u}\right], \tag{6}$$

where:

C_e, C_i = the number concentration of germs in the exit and entrance gas, resp. (m^{-3}); and

H = the height of the filter bed (m).

From the experimental investigations on the sterile filter bed ($H = 0.5$ m; $u = 446$ m/h) and the data on the emitted number of bacteria presented in Table 5, an average value of k_c can be calculated according to Eq. (6) of approx. 0.1 s^{-1}.

With $\varepsilon = 0.3$ [26] and $d_c = 4 \cdot 10^{-3}$ m it follows from Eq. (2) for the value of the target efficiency for a single collector particle at $u = 446$ m/h that $E = 2 \cdot 10^{-3}$. On the basis of this value the average size d_m of bacterial germs in the gas phase can be estimated from Eq. (3). With $\varrho_m = 10^3$ kg m^{-3} and $\mu = 1.8 \cdot 10^{-5}$ Pa · s, it follows that $d_m = 4 \cdot 10^{-6}$ m, which seems a rather reliable estimation taking the possibility of cluster formation of microbial germs into acount. From Eq. (4) it can be concluded that the capture rate is highly affected by the gas velocity, which is visualized in Fig. 3.

5.2 Emission

The growing amount of experimental investigations in the field of biofiltration has among others led to the develop-
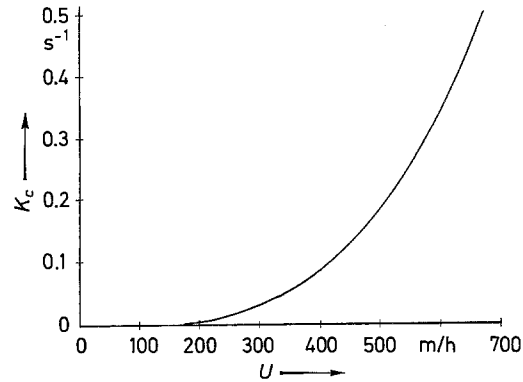

Fig. 3. The influence of the superficial gas velocity on the capture rate constant according to Eq. (4). ($\varepsilon = 0.3$; $\varrho_m = 10^3$ kg m^{-3}; $d_m = 4 \cdot 10^{-6}$ m; $d_c = 4 \cdot 10^{-3}$ m; $\mu = 1.8 \cdot 10^{-5}$ Pa s)

ment of theoretical and practical models describing the performance of biofilters very well [e.g. 26]. These models are generally based upon the concept of a wet biolayer, mainly containing bacteria, which surrounds the packed bed particles. As a result of the flow field of the gas phase the biolayer is continuously exposed to shear stresses. By virtue of the shear stress at the gas-biolayer interface microorganisms are evolved from the biofilter, and transported by the gas.

The granular bed particles may in this way serve as a continuous source of microbial emission. In describing the rate of the emission process we assume the microbial flux from the biolayer to the gas phase to be proportional to the interfacial shear stress.

In order to create a sufficiently long residence time in view of microbial degradation, gas velocities generally applied in biofilters are relatively low (0.01–0.10 m/s). Hence, Reynolds-numbers based upon the hydraulic diameter of the interstitial space in the bed $\left(Re = \dfrac{\varepsilon}{(1-\varepsilon)} \dfrac{\varrho\,u\,d_c}{\mu} \right)$ are low, typically in the range between 10 and 100. As a consequence, the flow regime of the gas phase can be regarded as laminar, which implies the interfacial shear stress is proportional to the superficial gas velocity.

If moreover the biolayer is considered as an inexhaustible source of emission and, consequently, a constant surfacial microorganism concentration is assumed, it follows on the basis of these considerations for the rate of emission per unit of bed volume:

$$r_E = k_e \, a_s \, u , \tag{7}$$

where:

k_e = emission rate constant per unit of bed volume (m^{-3}); and

a_s = specific area of the packing material (m^{-1}).

It is quite obvious that the emission rate constant k_e will largely depend on physical and biological properties of the packing material and biolayer, respectively. Slime producing bacteria and hyphae of sporing moulds can be expected to

show a completely different behaviour with respect to the emission process.

The further analysis will therefore be restricted to the emission of bacteria from the biolayer.

The rate expression according to Eq. (7) implies that in the absence of capture the increase of the concentration of (bacterial) germs in the gas passing the filter bed is equal to $\Delta C = C_e - C_i = k_e\, a_s\, H$ and is hence independent on the gas velocity.

It furthermore can be concluded that at low values of the gas velocity the rate of capture according to Eqs. (1) and (4) is proportional to u^4 and will, hence, be neglectable to the rate of emission. This phenomenon is probably responsible for the observed increase in bacterial concentration at low values of the gas velocity (see Table 4). To these aspects it will be returned further on.

5.3 Simultaneous capture and emission

Combining the mechanisms of capture and emission according to Eqs. (1) and (7), respectively, the axial bacterial concentration profile in a biofilter at steady state conditions is given by:

$$-u\frac{dC}{dh} + k_e\, a_s\, u - k_c\, C = 0 \qquad (8)$$

with the boundary condition:

$$h = 0, \qquad C = C_i. \qquad (9)$$

The outlet concentration C_e follows from the solution of Eqs. (8) and (9) and is given by:

$$C_e = \left(C_i - \frac{k_e\, a_s\, u}{k_c}\right)\exp\left(-\frac{k_c\, H}{u}\right) + \frac{k_e\, a_s\, u}{k_c}. \qquad (10)$$

From Eq. (10) it can be concluded that:

a) at a value of the gas velocity $u_m = \dfrac{k_c}{k_e\, a_s}\, C_i$, the outlet concentration just equals the inlet concentration. Consequently, two regions can be distinguished with respect to the gas velocity: a region of enrichment $(C_e > C_i)$ at $u < u_m$ and a region of impoverishment $(C_e < C_i)$ at $u > u_m$.

b) at low values of the gas velocity the increase in the concentration of the gas phase is mainly determined by the emission process. For a value of the gas velocity which approaches zero, it follows:

$$u \rightarrow 0; \qquad C_e - C_i = k_e\, a_s\, H$$

Figure 4 shows the theoretical paths of the outlet concentration as a function of the gas velocity according to Eq. (10) at process conditions for the laboratory-scale filter bed outlined in IV · 2 ($1500\ \mathrm{m}^{-3} < C_i < 2500\ \mathrm{m}^{-3}$; $H = 1$ m). In the computing of these curves, gas velocity dependent k_c-values have been used as given in Fig. 3; the value of $k_e\, a_s$ ($1500\ \mathrm{m}^{-4}$) has been obtained by curve-fitting of the experimental data presented in Table 4, which also have been plotted in Fig. 4.
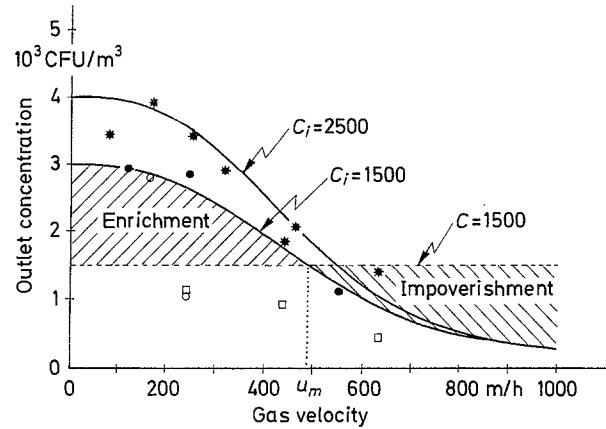

Fig. 4. The bacterial outlet concentration as a function of the superficial gas velocity at $C_i = 1500$ and $2500\ \mathrm{m}^{-3}$. (Drawn curves have been computed according to Eq. (10) with $k_e\, a_s = 1500\ \mathrm{m}^{-4}$ and k_c-values according to Fig. 3; data points according to Table 4)

From this it can be concluded that the theoretical model presented describes the experimental data rather well.

6 Conclusions

Microbial germs discharged by biofilters mainly consist of bacteria and to a minor extent of moulds. The concentration of microorganisms observed in the outlet gas of different full-scale filter installations is only slightly higher than the number encountered in open air and is of the same order of magnitude as in indoor air (10^3–$10^4\ \mathrm{m}^{-3}$). The concentration of an inlet gas, which is highly contaminated with microorganisms, is considerably reduced by the filtration process. From this it is concluded that a biofilter may serve as a system of capture. On the other hand, there is an extra contamination by the filtration process at low gas inlet concentration. From this it is concluded that a biofilter may also serve as a source of emission.

The rate of the capture process is of first order in the microorganism concentration with a rate constant that can be derived from expressions for single particle target efficiency for the deposition of dust particles in granular bed filters. The rate of the emission process is assumed to be proportional to the gas velocity. On the basis of both mechanisms an expression has been derived for the concentration of bacterial germs in the outlet gas as a function of the gas velocity, that is confirmed by observations in the laboratory-scale filter bed.

Acknowledgements

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