Research Article

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Pressure drop in biofilters as related to dust and biomass accumulation

Rune R. Andreasen,[a]* Richard E. Nicolai[b] and Tjalfe G. Poulsen[a]

Abstract

BACKGROUND: Pressure drop is a key parameter controlling cost efficiency of air cleaning biofilters. Pressure drop tends to increase with time due to accumulation of dust and biomass (DBM) within the filter medium. Although this is well known no easily applied expression for accurately estimating pressure drop under such conditions is available. Thus, evaluation of filter operating costs is at present uncertain.

RESULTS: In this study the relationship between filter pressure drop and accumulation of DBM in the filter was examined using a commercial available material: light expanded clay aggregates (Leca®) consisting of porous rounded aggregates with similar shape. Pressure drop as a function of operating time (for a 60 day period), filter depth and DBM accumulation was measured on a set of pilot scale biofilter units filtering exhaust air from a full scale pig stable (as opposed to using artificially contaminated air). Pressure drop was observed to increase with time at all filter depths in response to DBM accumulation. Both DBM accumulation and pressure drop increase was most pronounced near the filter inlet.

CONCLUSION: Pressure drop and DBM accumulation were closely related and both linked to the fraction of air-filled flow conducting voids. Based on the data a simple expression for predicting pressure drop in porous biofilter media as a function of DBM accumulation was developed. This expression can serve as an easily applied tool in assessment of biofilter cost efficiency.
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Keywords: pressure drop; biofilter media; air flow; biomass and dust accumulation; biofiltration

NOTATION

A	empirically medium describing constant (–)
a	linear pressure drop coefficient (Pa s m^{-2})
A_c	filter cross-sectional area (m^2)
B	empirically medium describing constant (–)
b	quadratic drag coefficient (Pa s^2 m^{-3})
C_f	form coefficient (m^{-1})
D_{eq}	media specific characteristic length (m)
D_m	mean particle diameter (mm)
F_{cor}	correction factor (–)
k_0	DBM accumulation constant (cm^3 DBM cm^{-3} filter)
k_1	DBM accumulation constant (cm^{-1})
k_a	air permeability (m^2)
L	length of porous medium in the flow direction (m)
L_f	thickness of the biofilm growing on the spheres (m)
n	number of predictions (–)
P	porosity exponent (–)
Q	filter flow (m^3 s^{-1})
r	radius of a sphere equivalent to the packing medium (m)
R	width of the particle size distribution (mm)
S_{con}	number of neighboring spheres in contact with a single sphere (–)
V	superficial air velocity (m s^{-1})
z	filter depth (cm)

Greek symbols

ΔP	pressure drop (Pa)
ΔP_0	pressure drop in clean media (Pa)
ΔP_m	measured pressure drop (Pa)
ΔP_p	predicted pressure drop (Pa)
μ	air viscosity (Pa s)
ρ	air density (g cm^{-3})
ρ_b	dry bulk density (kg m^{-3})
ρ_p	particle density (g cm^{-3})
ρ_s	solid density (g cm^{-3})
ε_0	clean bed air filled flow conducting porosity (m^3 m^{-3})
ε_{ex}	air filled flow conducting porosity (m^3 m^{-3})
ε_f	air-filled porosity as a function of biofilm thickness (m^3 m^{-3})
$\phi_{C,DBM}$	observed ϕ_{DBM} level at complete air blockage (cm^3 DBM cm^{-3} filter)
ϕ_{DBM}	volumetric DBM accumulation (cm^3 DBM cm^{-3} filter)
$\phi_{DBM,average}$	ϕ_{DBM} averaged across a given depth (cm^3 DBM cm^{-3} filter)
ϕ_R	relative quantity of remaining flow conducting air-filled pores $\left(\frac{\phi_{C,DBM}}{\phi_{C,DBM} - \phi_{DBM}}\right)$

* *Correspondence to: Rune R. Andreasen, Department of Chemistry and Biotechnology, Aalborg University, Sohngaardsholmsvej 57, DK-9000, Denmark. E-mail: rra@bio.aau.dk*

a *Department of Chemistry and Biotechnology, Aalborg University, Sohngaardsholmsvej 57, DK-9000, Denmark*

b *Agricultural and Biosystems Engineering, South Dakota State University, Ag Engineering Building, 1400 North Campus Drive, Brookings, SD 57007-1496, USA*

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INTRODUCTION

During recent decades global pork production has increased rapidly. In 2005 the annual production exceeded 100 million tons, an increase of about 50% over the previous 15 years.[1] Also pig farms have increased in size producing increased airborne emissions of odorous compounds and nutrients (especially nitrogen). Odor from pig farms is a source of nuisance to people living in the vicinity, and the pressure for finding technical solutions to reduce odor emissions has been increasing.[2] Odor emissions from livestock production is primarily associated with the large quantities of exhausted ventilation air from the production facilities.[3] At present biofiltration seems to be the most cost effective technology for removing nutrients and odorous compounds from the exhaust air.[3,4] The cost of treatment by biofiltration is primarily associated with (1) filter construction and (2) filter operation and maintenance.[4] A non-negligible part of the operating cost is the energy consumption to overcome air flow resistance in the filter. This cost is proportional to the air flow rate and the pressure drop across the filter.[5,6] According to the Danish Agriculture and Food Council this energy consumption is a major concern when applying biofiltration due to the often very large air volumes vented from pig stables. Typical ventilation rates for systems with finishing pigs, range between 10 and 100 m^3 air per pig per hour, depending on season and the size of the pigs. For systems with sows and piglets ventilation rates can reach up to 400 m^3 air per sow per hour.[7] Hence filter pressure drop is a key parameter in cost effective biofilter design. Pressure drop across a given biofilter depends on filter geometry, air flow rate, and filter material air flow resistance. While geometry and flow can be controlled directly, material flow resistance is fixed once the choice of material has been made. Observations indicate that pressure drop and air flow rate in coarse granular biofilter media are proportional[8–11] and that the proportionality depends on material particle size.[8,9] Materials with large particles exhibit low pressure drop and vice versa. During operation the pressure drop has been observed to increase as a result of dust and biomass (DBM) accumulation and filter medium compaction.[8,9,12–15]

Studies of DBM-induced media flow resistance have been performed in various media including wood chips (particle size 0.7–3.5 cm), porous inflated glass pellets (particle size 5–11 mm), a mixture of organic binder (average diameter 8 mm) and compost, porous ceramic (mean particle size 9 mm), Jeju scoria (lava, mean particle size 12 mm), a mixture of granular activated carbon (mean particle size 5.2 mm) and Jeju scoria and cubic polyethane foam with dimensions 1 × 1 × 1 cm.[12–14,16] All studies concluded that DBM accumulation increased the media flow resistance due to a reduction of the void space available for flow. Pressure drop in biofilters has generally been predicted based on the Ergun equation.[12,13,17,18] A comprehensive study of the Ergun equation,[18] has shown that in its original form it is not capable of predicting pressure drop in materials with wide particle size distributions or across media with different particle sizes. Previous work[12,13,18] has shown that to predict pressure drop accurately in biofilters with DBM accumulation, a modified version of the Ergun equation requiring 5–6 empirical medium-dependent constants must be used. These constants must in general be determined based on several measurements making the approach somewhat difficult to apply in practice. Using so many empirical constants when fitting reduces the original physical significance of the different terms in the Ergun equation. The objective of this study is, therefore, to examine the relationship between media-specific flow resistance and DBM accumulation in biofilters for cleaning exhaust air from animal production facilities, with the aim of establishing an easily applied predictive model that can be used to predict biofilter pressure drop as a function of DBM accumulation based on a very limited number of measurements on filters in which DBM accumulation is not necessarily evenly distributed.

This task will be carried out by measuring the level and distribution of both pressure drop and DBM accumulation within a biofilter cleaning exhaust air from a full scale pig production facility in order to describe the impact of DBM on biofilter pressure drop. Air pumped from a real pig facility (as opposed to artificially produced contaminated air) was used to better reflect filtration under practical conditions.

The measurements will be based on filters constructed using a commercially available biofilter medium: light expanded clay aggregates (Leca®) consisting of porous rounded aggregates. The advantage of this material is that it is available with a well-defined mean particle size, it is not subject to degradation over time and it has a relatively large specific surface area.

THEORY

In chemical engineering, soil science and other fields involving transport in porous media, flow of air through porous media is traditionally described using Darcy's Law, which for air flow through a section of porous medium with thickness L (m) is given as:

$$\frac{\Delta P}{L} = \mathrm{a} \cdot V \tag{1a}$$

where a is a linear pressure drop coefficient (Pa s m^{-2}) defined as:

$$\mathrm{a} = \frac{\mu}{k_a} \tag{1b}$$

ΔP is the pressure drop (Pa) across the medium, μ is air viscosity (Pa s), k_a is the porous medium air permeability (m^2) and V is the superficial air velocity (m s^{-1}) also known as the Darcy velocity given as:

$$V = \frac{Q}{A_c} \tag{2}$$

where Q is the flow (m^3 s^{-1}) and A_c (m^2) is the filter cross-sectional area, i.e. the area perpendicular to the flow direction.

The Darcy equation has been found valid at low air velocities while at higher velocities the flow becomes affected by inertial forces and Equation (1a) no longer applies. Several authors have proposed relationships to describe the non-Darcy flow regime.[19–21] One of the most widely used relationships is the Forcheimer equation,[19] which adds a quadratic velocity term to the Darcy equation in order to correct for inertial forces:[21]

$$\frac{\Delta P}{L} = \mathrm{a} \cdot V + \mathrm{b} \cdot V^2 \tag{3a}$$

where b is a quadratic drag coefficient defined as:

$$\mathrm{b} = C_f \rho \tag{3b}$$

Where C_f is a so-called form coefficient (m^{-1}) that depends on the characteristics of the porous medium, and ρ is the air density (kg m^{-3}).

Thus if a (or k_a) and b (or C_f) are known for the biofilter medium and fluid in question, the pressure drop across filters of any dimensions using that medium can be calculated using Equation

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(1a) or (3a) depending on fluid velocity. As a result Equations (1a) and (3a) have become very widely applied equations for describing fluid flow through porous media.[12,13,17,21–23]

Several semi-empirical equations to predict k_a[17,18,22–24] and C_f[17,18] from porous media properties have been proposed. The most well-known and widely applied (for biofilters) is the Ergun equation[17] which predict the pressure gradient as:

$$\frac{\Delta P}{L} = A\frac{(1-\varepsilon_{ex})^2}{\varepsilon_{ex}^p} D_{eq}{}^{-2}\mu V + B\frac{(1-\varepsilon_{ex})}{\varepsilon_{ex}^p} D_{eq}{}^{-1}\rho V^2 \quad (4a)$$

Corresponding to:

$$\mathrm{a} = A\cdot\mu\frac{(1-\varepsilon_{ex})^2}{\varepsilon_{ex}^p D_{eq}{}^{-2}}, \quad \mathrm{b} = B\cdot\rho\frac{(1-\varepsilon_{ex})}{\varepsilon_{ex}^p D_{eq}} \quad (4b)$$

where ε_{ex} ($m^3\ m^{-3}$) is the fraction of the total air filled porosity that conducts flow, D_{eq} is a media specific characteristic length (m) (6 times the volume to surface ratio of the particles in the case of a medium consisting of uniform particles), p is 3, and A and B are empirically determined medium independent constants with values of 150 and 1.75 (–), respectively. A and B values were determined empirically using data from nine different studies of flow in various types of porous media (glass beads, fibers, sand, gravel, ground blue metal, sandstone, ceramic samples and cylindrical packing). The results indicated that the values of A and B varied by several orders of magnitude across different types of media. Hence it was proposed[18] that A and B were unique for a given medium and should be determined empirically for each specific medium. However for engineering purposes it was proposed that A and B be set to 180 and 1.8 for smooth particles and 180 and 4 for rough particles, and further, that the value of P be set to 3.6 in order to give a better fit to the data obtained. Lastly, the parameter D_{eq} was found to be problematic for materials with non-uniform particle size distributions and inadequate for materials with wide particle size distributions as a relative small amount (by volume) of very small particles will cause D_{eq} to be very small while the large channels between large particles, governing the media flow resistance, would only be affected insignificantly.[18] Hence D_{eq}, does not reflect media flow resistance in such media. Similarly it was concluded[25] that the Ergun equation was inadequate for description of the flow resistance in mixtures of coal particles with wide particle size distributions.

Biofilter studies considering pressure drop have applied the Ergun[17] or the modified Ergun[18] equations with some additional modifications to describe the effects of DBM accumulation in biofilter materials on material flow resistance. Delhomenie *et al.*[13] used the Ergun equation with $p = 6$ (instead of 3 as proposed by Ergun[17]) and further multiplied the predicted pressure drop by a correction factor (F_{cor}) = 0.9 in order to fit the observed pressure drop in a biofilter as a function of DBM accumulation. Although this results in improved predictions of ΔP as a function of DBM accumulation, the physical significance of the original Ergun equation is strongly compromised as the adjustment of p in Equation (4a) from 3 to 6 is not physically based. Hence the value of $p = 6$ cannot be assumed valid for other filters as it is a pure fitting parameter controlled by the distribution of DBM within the filter medium, and thereby dependent on numerous parameters including filter dimensions, air flow rate, medium characteristics and the composition and particle size of the contaminants in the air. Morgan-Sagastume *et al.* (2001)[12] adjusted the modified Ergun equation (Equation (4a)) to account for bioaccumulation by exchanging the air filled porosity with a biofilm thickness dependent air filled porosity (ε_f) (Equation (5)), previously described by Alonso (1997).[26]

$$\varepsilon_f = 1-(1-\varepsilon_0)\left[\left(1+\frac{L_f}{r}\right) - \frac{S_{con}}{4}\left(\frac{L_f}{r}\right)^2\left(2\frac{L_f}{r}+3\right)\right] \quad (5)$$

where ε_f ($m^3\ m^{-3}$) is the air-filled porosity as a function of DBM quantity, ε_0 ($m^3\ m^{-3}$) is the clean bed porosity, r (m) is the radius of a sphere equivalent to the packing medium, S_{con} (–) is the number of neighboring spheres in contact with a single sphere (can vary from 6 to 12 depending on packing geometry) and L_f (m) is the thickness of the biofilm growing on the spheres, which can be estimated from the medium specific surface area, together with the volumetric mass and density of the biofilm.[26] In addition to the adjustment of ε_{ex} to ε_f Morgan-Sagastume *et al.* (2001)[12] changed the value of p from 3 to 3.6 (Equation (4a)) as suggested by Macdonald *et al.* (1979).[18]

At present these are the two models available for estimating pressure drop versus DBM accumulation. Because both models are based on the Ergun equation, the A and B constants (Equation (4a)) applied should be media and fluid specific as suggested by Macdonald *et al.* (1979)[18], and should be determined empirically for each individual media. Similarly, D_{eq} must be determined empirically for media with non-uniform particle size distributions or wide particle size distributions as the original D_{eq} definition was found inadequate for such distributions.[18]

Hence A, B, D_{eq}, p and F_{cor} must be known or empirically determined *a priori* when using the Delhomenie *et al.* model,[13] while prior knowledge or empirical determination of A, B, D_{eq}, r, S_{con} and L_f is required when using the Morgan-Sagastume *et al.* (2001)[12]

In media consisting of porous particles (such as Leca®) where only the inter-particle air-filled porosity (the porosity surrounding the particles) conducts air flow, the air conducting porosity (ε_{ex}) is determined as:

$$\varepsilon_{ex} = 1-(\rho_b\rho_p^{-1}) - \phi_{DBM} \quad (6)$$

where ρ_b ($g\ cm^{-3}$) is the dry bulk density of the medium, ρ_p ($g\ cm^{-3}$) is the porous particle density, and ϕ_{DBM} (cm^3 DBM cm^{-3} filter) is the volumetric content of dust and/or biomass accumulated in the filter medium, calculated as:

$$\phi_{DBM} = M_{DBM}\ \rho_{DBM}{}^{-1} \quad (7)$$

Where M_{DBM} ($g\ cm^{-3}$) is the volumetric mass gain of dust and/or biomass and ρ_{DBM} is the density of the accumulated dust and biomass ($g\ cm^{-3}$) in the filter (assumed equal to 1 $g\ cm^{-3}$).

In practice ϕ_{DBM} is not constant but will typically vary with filter depth. While the Morgan-Sagatume *et al.* (2001)[12] model assumes constant ϕ_{DBM}, the Delhomenie *et al.* (2003)[13] model can be applied to filters with variable ϕ_{DBM} by fitting the parameters F_{cor} and p to adequate data prior to using the model. However, none of the present models are capable of describing the change in ΔP, caused by a non-uniform DBM distribution, without the use of several media- and DBM distribution-specific empirical constants that must be fitted individually in each case. This means that in addition to losing the physical significance of the applied flow equation (Equation (4a)), the present models also have limited applicability across different filter media and DBM distributions.

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MATERIALS AND METHODS

Three identical biofilter columns were constructed using a commercially available material, light expanded clay aggregates (Leca®), as biofilter medium. Leca® is used for multiple purposes including building insulation and biofilter carrier material. It has been successfully used in industrial biofilters at a Danish facility for destruction of dead animals and is currently being applied for air cleaning at pig production facilities.[27,28]

Leca® consists of rounded aggregates that are resistant to chemical and biological degradation, have very high internal porosity and compressive strength and therefore provides a material well suited as biofilter carrier material. Leca® is available in several particle sizes (particle diameters (D) 0–20 mm) with unique biofilter properties (small D for high surface area and high ΔP, large D for low surface area and low ΔP). The Leca® used in this study was supplied by Saint-Gobain Weber A/S Randers, Denmark, and provided in three pre-sorted particle size fractions with uniform particle size distributions. The width (R) of the particle size distribution for all three fractions was 2 mm, corresponding to D of 8–10 mm, 10–12 mm and 12–14 mm. Appropriate quantities of these three fractions were combined to form an additional fraction of 8–14 mm (with R equal to 6 mm, and mean diameter (D_m) equal to 11 mm) with a uniform particle size distribution. This new fraction was selected as a tradeoff between high surface area and low ΔP and was used as carrier material in the biofilter columns.

Dry bulk density ρ_b (kg m^{-3}) for the carrier material was determined in triplicate by filling a 20 L bucket to the top with the material, dropping it three times from a height of 3 to 5 cm to achieve stable packing, and subsequently adding additional material to fill the empty volume created during packing. The material was then weighed. As Leca® is non-expanding when wetted ρ_b is constant regardless of water content.

For each of the original Leca® fractions (with $R = 2$ mm), 10 particles were randomly chosen and weighed. In addition three perpendicular diameters of each particle were measured starting with the widest part of the particle. These data were then used to calculate the mean particle density, ρ_p (kg m^{-3}), for each of the three fractions.

The mean particle density for the 8–14 mm fraction was calculated as a weighted mean of the ρ_p values for the original 3 Leca® fractions. An overview of the physical characteristics of the media is given in Table 1.

12 kg of biofilter carrier material (8–14 mm) was wetted to its maximum water holding capacity by immersion in water for more than 3 days (no significant additional weight gain was observed for periods exceeding 3 days) followed by drainage for 2 h, before the total wet mass was measured using a Doron 8000 balance, in order to calculate the media water holding capacity and wet bulk density.

To avoid effects of scale and to make sure that the measured data would be applicable also to full-scale filters, a filter diameter of 25 cm was used. Effects of scale are typically caused by increased flow near the filter column walls due to increased porosity here. This can be avoided when the diameter of the filter bed is at least 15 times higher than D_m of the filter media.[29] In our case the ratio was approximately 23.

Eighteen filter units (Ø 25 cm, height 19 cm) were constructed. Each unit was filled with wetted and drained Leca® (8–14 mm fraction) to a height of 5 cm (≈600 g dry weight). Each filter unit had a metal mesh mounted at a depth of 8.5 cm to support the Leca®. From these filter units three filter columns were assembled. Each column consisted of six filter units stacked on top of one another and sealed by hose clamps with rubber packing. A schematic of the experimental filter column set-up is given in Fig. 1(a).

Table 1. Physical characteristics of the Leca® media in terms of dry bulk density, particle density, solid density, water content at filter initiation, total porosity, and external volumetric air content

	Media properties	
ρ_b	0.24	(g cm^{-3})
ρ_p	0.37	(g cm^{-3})
ρ_s	2.65	(g cm^{-3})
ω	0.83	(g g^{-1}Leca®)
ϕ	0.91	(cm^3 cm^{-3}filter)
ε_{ex}	0.34	(cm^3 cm^{-3}filter)

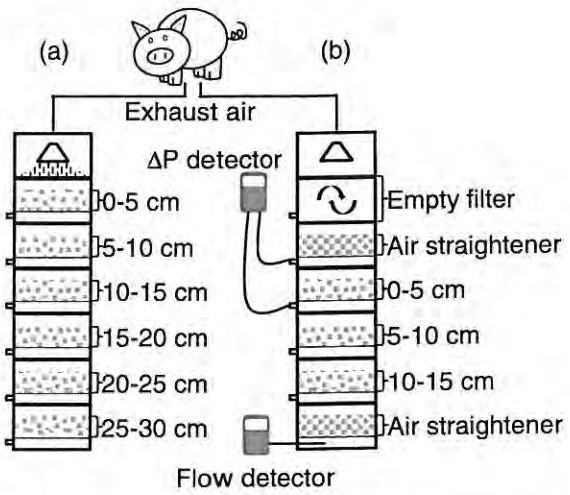

Figure 1. Experimental biofilter setup for: (a) filtration of pigs table exhaust air, filter velocity (V) is constant 0.3 m s^{-1}, irrigation rate is 8 cm h^{-1}. (b) Measurement of $V - \Delta P$ relationships. Note that only three units are characterized at the same time and air straighteners are inserted before and after the filter units in order to avoid effects of turbulence on the ΔP measurements.

A tube (length 37 cm, diameter 25 cm) containing an irrigation system was placed at the inlet of the column. This system irrigated the filters at a rate of 4 L h^{-1} (corresponding to superficial velocity of 8 cm h^{-1}) and excess water was drained from the bottom of the column. Closable 6.35 mm outlets were mounted 2 cm below the metal mesh of each of the six filter units. The inlet to each of the three filter columns was connected to a supply of pig stable exhaust air sucked through the floor of an unused pen in a pig barn with finisher pigs. All three filters were operated over a period of 60 days at a flow of 53 m^3 h^{-1} corresponding to a superficial velocity of 0.3 m s^{-1}. After 60 days of operation the inlet filters began to clog and the experiment was therefore terminated. The pig population in the barn was 56 (113–122 kg) from day 0–6, 0 from day 6–8, 94 (27–45 kg) from day 8–22 and 82 (27–45 kg) from day 22–60.

Measurements of the $V - \Delta P$ relationship were performed before filtration initiation and after 3, 29, 43 and 60 days of filtration. After each $V - \Delta P$ measurement event the filter velocity was readjusted to 0.3 m s^{-1}.

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Prior to $V-\Delta P$ measurements the filter units were rearranged as turbulence was observed to affect ΔP measurements at both inlet and outlet. During the rearrangement the filter units were divided into two groups: 0–15 cm. and 15–30 cm. An air straightener was then connected to the inlet and outlet of each group by rubber sealed hose clamps in order to reduce turbulence at these locations. A schematic drawing of the setup for measuring the $V-\Delta P$ relationship at filter depths of 0–15 cm is given in Fig. 1(b).

The applied air straighteners consisted of a filter unit with a >5 cm Leca® layer (16–18 mm pellets). The Leca® in the top air straightener was moistened in order to prevent consecutive filters from drying during measurements.

Air flow was measured in the filter outlet using an Omega HHF710 anemometer with a HHF7-P1 propeller or a TSI VELOCICALC 8345 hotwire anemometer. When the hotwire anemometer was used its output was calibrated to represent the propeller anemometer. Pressure drop across each filter unit was measured using a TSI Alnor AXD620 digital manometer connected to the closable outlets below the metal net (supporting 5 cm of Leca®) in each of the six individual filter units in each filter column. Pressure drop across each filter unit was measured at five values of V between 0.2 and 0.6 m s^{-1} or the maximum possible value of V whichever was lower. For each filter unit both ΔP and V were determined over a 45 s. time period as the mean of three individual measurements. Observed values of ΔP were not corrected for empty column pressure drop as this was observed to be insignificant ($\leq$ 0.2 Pa).

For each of the observed $V-\Delta P$ data sets corresponding values of a and b in Equation (3a) were obtained by fitting Equation 3(a) to the measured data. The fitted a and b values were later used to interpolate ΔP for selected values of V in order to compare ΔP across all individual filter units for identical values of V.

The total mass of each individual filter unit were measured at each $V-\Delta P$ measurement using a Voyager pro VP4102CN balance.

During filtration air dust concentrations were measured in the pig stable, the filter column inlet and between individual filter units (at column depths of 5, 10 and 15 cm) using a MiniVol Portable Air Sampler model 4.2 without any separator jets in order to get total air dust concentration. No significant dust concentrations were observed in the air at filter column depths below 15 cm.

After 60 days of filtration experiments were terminated and the water and organic contents (g g^{-1}Leca®) in each of the 18 individual filter units were determined by drying at 105 °C until constant weight, igniting at 550 °C until constant weight and cooling in an exicator until room temperature. All masses were measured using a Voyager pro VP4102CN balance.

Finally values of ε_{ex} corresponding to each individual filter unit and measurement event were determined. Instead of using air pychnometry that yields total air-filled porosity rather than ε_{ex}, ε_{ex} was calculated from ρ_b, ρ_p and M_{DBM} together with Equations (6) and (7). Also air pychnometry is rather difficult to use on filter materials containing DBM as samples of the filter material cannot be removed for pychnometry as this will ruin subsequent $V-\Delta P$ measurements.

RESULTS AND DISCUSSION

Air dust concentration, was highest in the pig barn, reduced in the filter column inlets and decreased almost exponentially down through the filter columns (Fig. (2)).

The exponential decline indicates that dust settlement in the biofilter follows a first-order relationship where the dust removal rate is directly proportional to the dust concentration in the air. Dust removal between the barn and the filter column inlet is due to dust settlement in the piping leading from the barn to the filter column inlets and probably involves the larger dust particles.

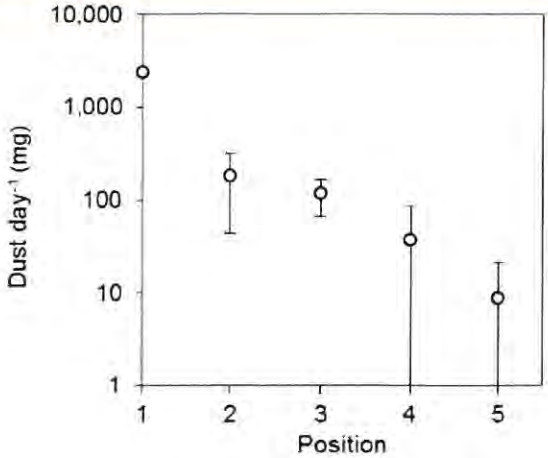

Figure 2. Observed dust loads in different positions: 1 barn; 2 filter column inlet; 3 filter media depth = 5 cm; 4 filter media depth = 10 cm; and 5 = filter media depth = 15 cm. Position 2–5 values are averages of three measurements, error bars represent one standard deviation.

All filter units showed increasing ΔP for increasing V and the $V-\Delta P$ relationships were observed to be well described by Equation (3a) in all cases ($R^2 \geq 0.975$). At filtration initiation the average pressure drop was 290 Pa m^{-1} which is within the range of reported pressure drops for airflow through woodchips (a widely applied bio filter media) where values of 580[30] and 220[30] Pa m^{-1} have been reported at $V = 0.3$ m s^{-1} and $D_m = 10$ and 20 mm, respectively.

Pressure drop at a specific location in the filter columns at a specific value of V was observed to increase with time (Fig. 3(a)) probably due to accumulation of DBM in the biofilters. Similar observations have been made in earlier studies.[12,13,16]

Correspondingly k_a decreased and C_f increased with time (Fig. 3(b)) in response to DBM accumulation. Hence DBM accumulation increases both the linear and the quadratic pressure drop. As the linear pressure drop constitutes only about 18% of the total pressure drop on average, estimated k_a values are very uncertain, as also indicated by the relatively large standard deviations in Fig. 3(b). Hence for the remainder of this study focus will be on $\Delta P/L$ rather than on k_a and C_f.

Pressure drop, at a given filter velocity, increased with time across all individual filter units although increases were most prominent for units placed near the filter column inlet (Fig. 4(a)).

This observation indicates that the increase in ΔP is caused by DBM accumulation as this is known to be most pronounced near the filter column inlet.[12] The contribution by each of the six individual filter units to total pressure drop across the filter column is shown in Fig. 4(b). The pressure drop across the filter unit nearest the inlet (0–5 cm) increases its relative contribution (Fig. 4(b)) to total biofilter column pressure drop, at $V = 0.3$ m s^{-1}, from 16.3% ($\approx$ 1/6) on day 0 to $\approx$ 80% on day 60 (similar contributions were also observed at filter velocities of 0.2, 0.4 and 0.5 m s^{-1}). Equivalent observations were also made by Morgan-Sagastume *et al.* (2001)[12] who found that the top 10 cm of a 1 m thick biofilter column contributed 50–70% to the total pressure drop across the column after 83 days of filtration.

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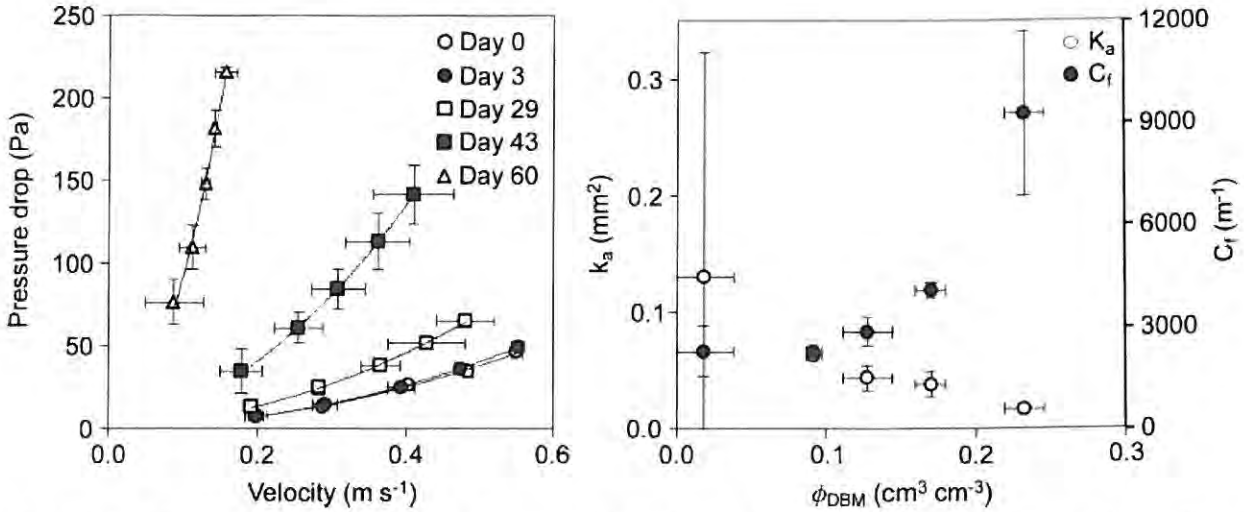

Figure 3. (a) $V-\Delta P$ relationships observed across the filter column depth of 0–5 cm after 0, 3, 29, 43 and 60 days of filtration. Values are averages of three measurements. Curves represent Equation (3a). (b) Corresponding k_a (Equation (1b)) and C_f (Equation (3b)) calculated from fitted a and b values (Equation (3a)). Error bars represent one standard deviation.

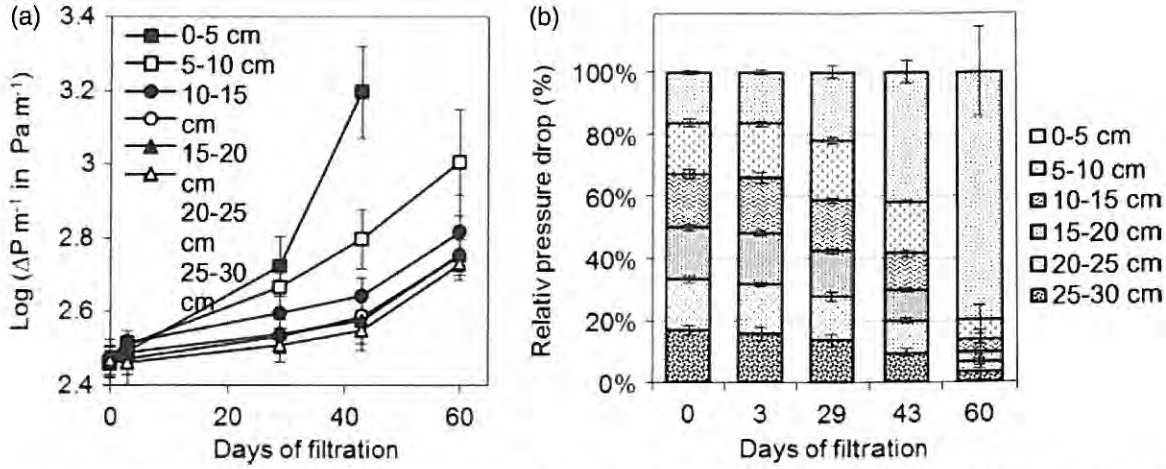

Figure 4. (a) Observed log (ΔP) (across biofilter depths) as a function of time at $V = 0.3$ m s^{-1}. (b) Relative contribution to ΔP across the filter column by each of the six individual filter depths at $V = 0.3$ m s^{-1}. The value corresponding to the column depth of 0–5 cm at day 60 is extrapolated as a value of $V = 0.3$ m s^{-1} could not be achieved. Each point/level in both figures is a mean of three measurements, error bars represent one standard deviation.

The ΔP–time relationship across a given unit exhibited a similar shape for all V, indicating that the ratio between ΔP at a given point in time and the pressure drop in clean Leca® (ΔP_0), was independent of V. Figure 5 shows the $\Delta P(V)\Delta P_0(V)^{-1}$ ratio for each individual filter unit at different points in time for $V = 0.2$, 0.3 and 0.4 m s^{-1}, as a function of the mean $\Delta P(V)\Delta P_0(V)^{-1}$ for all three velocities across the same filter unit.

Figure 5 clearly shows that the relative increase in pressure drop is independent of air velocity. This means that the ratio between a and b in Equation (3a) must remain constant regardless of the quantity of DBM present in the filter units.

Prior to filtration, biofilter media were observed to retain 0.87 g water g^{-1} dry Leca®. This mass is assumed to be retained in internal pores in the Leca® particles. All individual filter units were further observed to gain mass during the 60 days of filtration, with an initially rapid increase in mass from day 0 to day 3 followed by a more moderate and approximately linear increase in mass with time (Fig. 6(a)). The initial rapid increase is mainly caused by the development of a moving water film on the surface of the filter material, and filling of any dead-end pores facing upwards in the media, both established when irrigation is initiated.

The gain in mass was most pronounced in the top filters, decreasing with increasing filter depth (Fig. 6(a)). This observation is in agreement with observations by Morgan-Sagastume *et al.*[12] who reported biomass accumulation to be most pronounced near the filter inlet. The results in Figs 2, 4, and 6 indicate that increases in pressure drop with time are primarily caused by DBM accumulation in the filter material. Similar observations have previously been made in studies of biomass accumulation and pressure drop in biofilter materials.[12,13]

Less than 1% of the observed mass gain consisted of organic matter (Fig. 6(b)) and gain of inorganic mass could not be detected. Despite the very low mass gain of organic solid matter, accumulation of DBM is probably the underlying cause of media weight gain, as the total mass gain (water and organic matter) is proportional to the organic mass gain. This means that the

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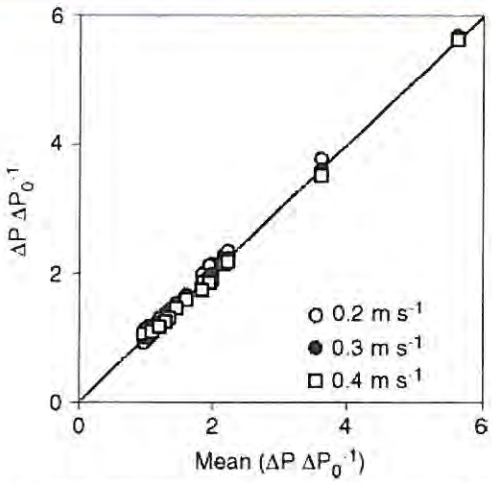

Figure 5. $\Delta P(V)\Delta P_0(V)^{-1}$ ratio for each individual filter unit at 0, 3, 29, 43 and 60 days of filtration for $V = 0.2$, 0.3 and 0.4 m s^{-1}, as a function of the mean $\Delta P(V)\Delta P_0(V)^{-1}$ ratio for all three velocities across the same filter unit. Data for filter unit 0–5 cm after 60 days of filtration is not included as the maximum observed velocity was <0.2 m s^{-1}.

DBM consists mainly of water held together with a skeleton of organic matter, which may be dust particles, microbial cells or material such as exopolymers excreted by the bacteria. Increasing ϕ_{DBM} results in increasing ΔP for constant V (Fig. 7(a)) because the fraction of air filled porosity available for air flow (ε_{ex}) decreases. For constant ΔP, V decreases with increasing ϕ_{DBM} (Fig. 7(b)) for the same reason.

As ϕ_{DBM} increases, ΔP for constant V approaches infinity while V for constant ΔP approaches zero. A critical value of ϕ_{DBM} where V reaches zero ($\phi_{C,DBM}$) can be defined. This value corresponds to the situation when air flow through the filter no longer is possible due to pore clogging by DBM. It is noteworthy that this critical porosity seems to be slightly lower than the total external porosity of 0.34 (m^3 m^{-3}). As DBM accumulation is largest in a thin layer near the inlet of the filter clogging will normally occur here. This means that in a clogged biofilter unit there may still be air-filled pores especially at larger filter depths, but all significant pathways for air flow through the filter will be blocked at some location rendering the filter impassable for air. This means that in a filter unit of given dimensions $\phi_{C,DBM}$ represents the average volumetric DBM content at which the air flow through the filter is blocked and this parameter therefore depends on both filter dimensions and the distribution of DBM in the filter as a function of depth. As $\phi_{C,DBM}$ and ε_{ex} in this study seems close this means that the heterogeneity of the biomass distribution across the depth of 5 cm is only significant at higher ϕ_{DBM} levels. This significance, however, will increase with increasing filter thickness over which ϕ_{DBM} is averaged. Using $\phi_{C,DBM}$ together with the data in Fig. 7, the relationship between ΔP at any specific ϕ_{DBM} and ΔP_0 can be expressed as:

$$\frac{\Delta P(\phi_{DBM}, V_a)}{\Delta P_0(V_a)} \frac{\phi_{C,DBM}}{\phi_{C,DBM} - \phi_{DBM}} = \frac{1}{\phi_R} \quad \text{for } \phi_{DBM} < \phi_{C,DBM} \tag{8}$$

where $\Delta P(\phi_{DBM}, V_a)$ is the pressure drop at any given value of ϕ_{DBM} at $V = V_a$, and ϕ_R is the relative quantity of remaining flow conducting air-filled pores (assuming both air flow and DBM accumulation to occur only in the external pores between the particles).

Values of $\phi_{C,DBM}$ for the data in Fig. 7(a) were determined by fitting Equation (8) to the data yielding $\phi_{C,DBM} = 0.300$, 0.303 and 0.304 for $V = 0.2$, 0.3 and 0.4 m s^{-1}, respectively. Optimal fits are shown as curves in Fig. 7(a). As relative pressure drops ($\Delta P \Delta P_0^{-1}$) were similar for all velocities (Fig. 5) $\phi_{C,DBM}$ should be independent of V which seems to be the case judging from the fitted values above. A general value of $\phi_{C,DBM}$ based on ΔP–V measurements at $V = 0.2$, 0.3 and 0.4 m s^{-1} was found equal to 0.301 and described the observed data with an R^2 equal to 0.97. Combining Equations (3a) and (8) yields:

$$V(\phi_{DBM}, \Delta P_a) = \frac{-a}{2b} + \sqrt{\left(\frac{a}{2b}\right)^2 + \frac{\phi_R \cdot \Delta P_a}{b}} \tag{9}$$

where $V(\phi_{DBM}, \Delta P_a)$ is the velocity at any given value of ϕ_{DBM} at $\Delta P = \Delta P_a$.

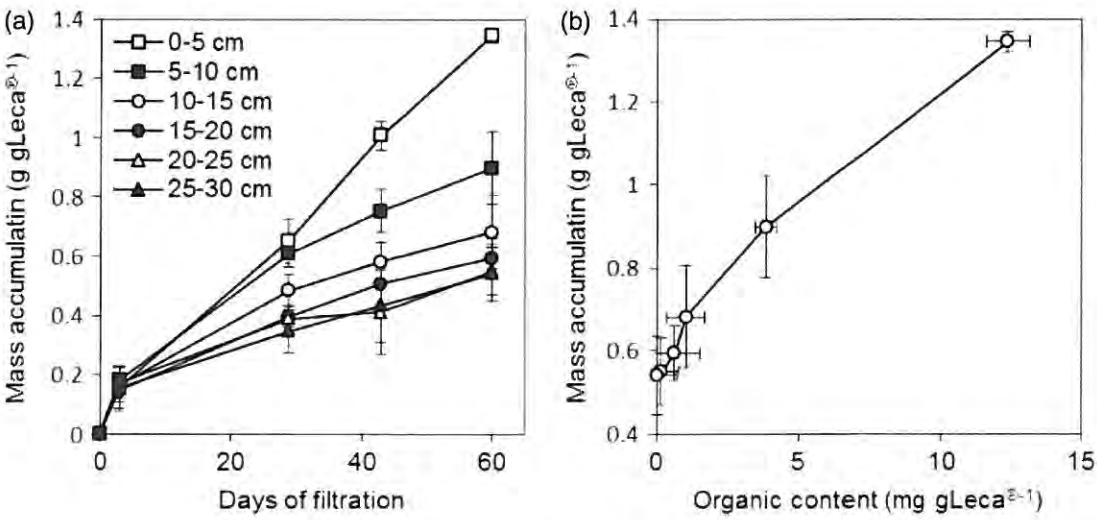

Figure 6. (a) Mass accumulation for the six filter depths during 60 days of filtration. (b) Relationship between mass accumulation and organic matter content after 60 days of filtration. Each point in both figures is a mean of three measurements, error bars represent one standard deviation.

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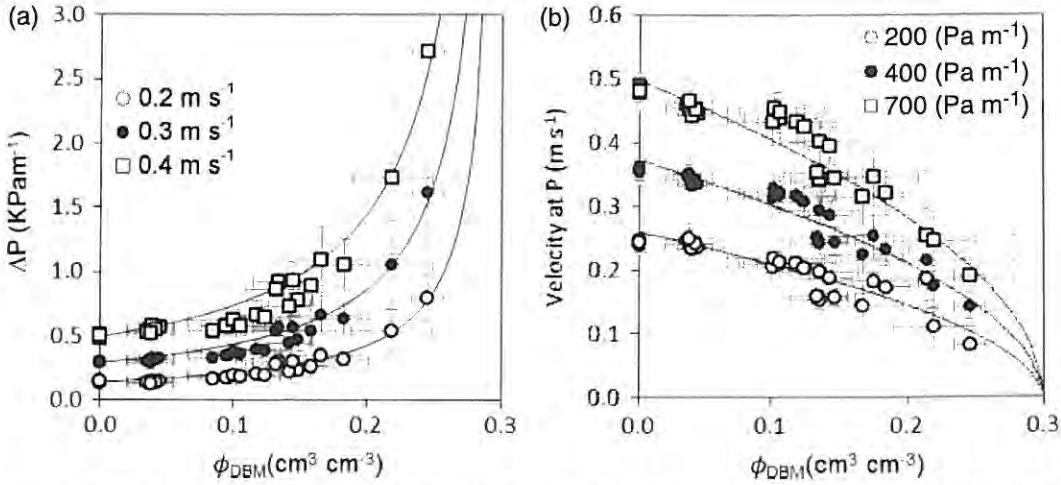

Figure 7. (a) Pressure drop (ΔP) versus porosity displaced by dust and biomass (ϕ_{DBM}) at three velocities. Curves represent Equation (8) for the three velocities. (b): Velocity vs. ϕ_{DBM} at three biofilter ΔP levels. Curves represent Equation (9). Each point in both figures is a mean of three measurements, error bars represent one standard deviation.

Predictions by Equation (9) for different values of V are shown in Fig. 7(b) (values of a and b are fitted by Equation (9) with ϕ_R calculated using Equation (8) together with $\phi_{C,DBM} = 0.301$).

Approaches similar to Equation (8) have been used to describe several types of soil transport parameters such as solute diffusivity, gas diffusivity, air permeability and water permeability[31] where the media resistance to transport is assumed inversely proportional to the fluid phase content in a given power. The main difference between Equation (8) proposed here and these approaches is the introduction of $\phi_{C,DBM}$ which accounts for the fact that the accumulation of DBM is not evenly distributed across the filter depth of interest.

During biofilter measurements the observed ϕ_{DBM} will be a mean across a given length of filter rather than an exact value observed at a specific filter depth. This means that the average accumulation level of DBM at complete clogging in practice will be highly dependent on the choice of filter length as DBM is usually not evenly distributed. The value of $\phi_{C,DBM}$ therefore represents the average value of ϕ_{DBM} in the filter when clogging occurs. If specific values of ϕ_{DBM} at the time clogging are known as a function of filter depth (such as those given in Fig. (6a) $\phi_{C,DBM}$ averaged ($\phi_{DBM,average}$) across a given filter depth can be calculated. In this study $\phi_{DBM,average}$ versus filter depth (z) (cm) was found to follow a first-order distribution as:

$$\phi_{DBM,average} = k_0 \cdot \exp(-k_1 \cdot z)) \tag{10}$$

where k_0 (cm^3 DBM cm^{-3} filter) and k_1 (cm^{-1}) are empirical time-dependent DBM accumulation, and first-order distribution constants, respectively. Values of k_0 and k_1 at day 60 (when filter clogging occurred) were 0.36 and 0.024, respectively. When filter clogging occurs the k_0 value theoretically corresponds to the $\phi_{C,DBM}$ level at $z = 0$. The k_0 value of 0.36 therefore corresponds closely with the external porosity of 0.34 (cm^3 cm^{-3}) as filter clogging is probably located at the filter inlet ($z = 0$) where DBM accumulation are most pronounced.[12] Equation (10) described the observed ϕ_{DBM} levels with an $R^2 > 0.98$. As k_0 was found to increase with time (data not shown) and k_1 was found positive at all times (data not shown) the model predicts that the biomass in the filter increases with time and decreases with increasing depth, in accordance with observations made in this and other studies.[12,13]

As $\phi_{C,DBM} = (\phi_{DBM,average})$ when filter clogging occur, Equation (10) can be used to calculate $\phi_{C,DBM}$ as a function of filter thickness provided values of k_0 and k_1 are known. It is noted that at z close to 0, both $\phi_{DBM,average}$ and $\phi_{C,DBM}$ are very sensitive to z and, thus, Equation (10) should only be used within the range of z for which values of k_0 and k_1 were fitted (5–30 cm in this study). It should further be noted that strictly spoken the ϕ_{DBM} used in this study is an average across 5 cm filter thickness and the $\phi_{C,DBM}$ determined in this study therefore corresponds to $\phi_{DBM,average}$ at $z = 5$ cm.

Three different approaches for predicting ΔP as a function of DBM accumulation based on a limited set of measured data taken from the data set measured during this study were tested. This data consisted of ΔP and ϕ_{DBM} observed at $V = 0.2$, 0.3 and 0.4 m s^{-1} during all measurements. All three approaches were based on calibration of Equation (8) but differed with respect to the number of measured data used in the calibration. Remaining data not used in the calibration were used for validation of the approaches.

In approach 1 (A1), $\Delta P(\phi_{DBM})$ is predicted for a given air velocity (V_a) using only two ΔP–ϕ_{DBM} measurements. These were pressure drop in clean medium ($\Delta P = \Delta P_{0,a}, \phi_{DBM} = 0$) and pressure drop in medium with significant DBM accumulation ($\Delta P = \Delta P_{1,a}, \phi_{DBM} = \phi_{DBM,1}$ in this case taken at day 43). Both were measured across the 5–10 cm filter unit (as this had the highest DBM accumulation of the filters with measureable flow in the entire period) at $V_a = 0.3$ m s^{-1}. An estimate of $\phi_{C,DBM}$ was then found by inserting these two measurements in Equation (8) and rearranging as:

$$\frac{\Delta P_{0,a}}{\Delta P_{1,a}} = \frac{\phi_{R1}}{\phi_{R0}} = \frac{(\phi_{C,DBM} - \phi_{DBM_1})}{(\phi_{C,DBM})} \Rightarrow \phi_{C,DBM} = \frac{\Delta P_{1,a}\,\phi_{DBM_1}}{\Delta P_{1,a} - \Delta P_{0,a}} \tag{11}$$

The calibrated Equation (8) was then used to predict $\Delta P(\phi_{DBM})$ at $V = V_a$. The procedure was applied for $V_a = 0.2$, 0.3 m, and

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Table 2. Performance of three approaches for prediction of the $V-\Delta P-\phi_{DBM}$ relationship in granular biofilter medium based on a limited set of measurements. Subscript 0 indicates clean medium and a indicates a fixed value of V

Approach	Data used in calibration	No. of data used in calibration	No of data predicted	MRPE %	Bias %
1	3 × 2 points: (1) ΔP at $V = V_a$ and $\phi_{DBM} = 0$, (2) ΔP at $V = V_a$ and $\phi_{DBM} > 0$	6	81	14	−2
2	1 curve: $V-\Delta P$ for $\phi_{DBM} = 0$ and 1 point: ΔP at $V = V_a$ and $\phi_{DBM} > 0$	4	83	11	−3
3	2 curves: (1) $V-\Delta P$ for $\phi_{DBM} = 0$, (2) $\phi_{DBM}-\Delta P$ for $V = V_a$	7	80	11	−3

0.4 m s^{-1} for all six filter depths at 0, 3, 29, 43, and 60 days of filtration (a total of 84 points).

In approach 2 (A2), $\Delta P(\phi_{DBM}, V)$ is predicted across different air velocities using one $\Delta P - \phi_{DBM}$ measurement in medium with significant DBM accumulation (in this case taken at day 43 for $V_a = 0.3$ m s^{-1}), together with measurements of the ΔP–V relationship in clean medium ($\Delta P_0(V)$ for this approach equal to three measurements). All measurements used for calibration were taken across the 5–10 cm filter unit. Initially $\phi_{C,DBM}$ was estimated the same way as in approach 1 using Equation (11) while a and b were estimated by to fitting Equation (3a) to the measured $\Delta P_0(V)$ data. Predictions of $\Delta P(\phi_{DBM}, V)$ were calculated using the estimates of a, b, and $\phi_{C,DBM}$ together with Equation (9) for all six filter depths at $V = 0.2$, 0.3, and 0.4 m s^{-1}.

In approach 3 (A3), predictions of $\Delta P(\phi_{DBM}, V)$ is based on measurements of ($\Delta P - V$) relationship in clean medium together with the $\Delta P - \phi_{DBM}$ relationship at a given $V = V_a$. Parameters a and b are estimated using the measured ΔP_0–V data together with Equation (3a) while $\phi_{C,DBM}$ is estimated using the ΔP–ϕ_{DBM} data together with the estimated a and b and Equation (9). Both curves were measured across the 5–10 cm filter unit. Predictions of $\Delta P(\phi_{DBM}, V)$ were calculated using the estimates of a, b, and $\phi_{C,DBM}$ together with Equation (9) for all six filter depths at $V = 0.2$, 0.3, and 0.4 m s^{-1}.

For each of the three approaches the mean relative prediction error (MRPE) and the bias in the predictions were calculated as:

$$MRPE = \frac{1}{n}\sum_{0}^{n}\left|\left(1 - \frac{\Delta P_p}{\Delta P_m}\right)\right| \quad (12)$$

$$Bias = \frac{1}{n}\sum_{0}^{n}\left(1 - \frac{\Delta P_p}{\Delta P_m}\right) \quad (13)$$

where n is the number of predictions and ΔP_p and ΔP_m is the predicted and the measured pressure drop, respectively.

A summary of the performance of the three approaches is given in Table 2.

With a MRPE between 11 and 14% and a bias between −2 and −3% all approaches yield fairly accurate predictions with similar accuracy. The main difference is the number of data points included in the calibration. In this study we predicted and calibrated at three different velocities and five levels of DBM accumulation, causing the need of 6, 4 and 7 data points for calibration of A1, A2 and A3, respectively. However as the need for calibration points in A1 is two per predicted velocity, the data points for predicting ΔP at only one velocity will be reduced to two causing A1 to be the approach with the least amount of experimental work for such prediction. Though for predicting ΔP at more than one velocity, A2 will be favorable as it is slightly more accurate and the need of data points for calibration lower or equal than for A1.

In this study A2 and A3 gave similar accuracy likely due to a well-chosen level of DBM accumulation for calibration of $\phi_{C,DBM}$. We suggest calibration of $\phi_{C,DBM}$ in A1 and A2 to be performed at ϕ_{DBM} levels between 50 and 75% of $\phi_{C,DBM}$ equivalent to a ΔP2–4 times higher than ΔP_0 (in this study the ΔP, used for calibration of $\phi_{C,DBM}$, in 5–10 cm after 43 days of filtration, were roughly 2.5 times higher than ΔP_0).

DBM accumulation depends on filter medium properties (such as particle and pore size distribution, particle shape, water content, and air pore velocity), filter depth, irrigation, and composition of exhaust air being filtered. When using either of the three prediction approaches discussed above for instance in connection with filter design, measurements needed as input must be carried out on a filter using the same medium, having the same thickness and filtering the same air as the filter being designed. It is, however, not necessary that the experimental filter has the same cross sectional area as that being designed. If the design filter thickness is not known, $\phi_{C,DBM}$ can be estimated later using Equation (10) provided sufficient knowledge of the DBM distribution at filter clogging is available as discussed earlier.

The three approaches (A1, 2 and 3) presented in this study differ from other models by their simplicity in predicting ΔP as a function of DBM accumulation. Other models require knowledge of several parameters most likely to be empirically determined such as A, B and D_{eq} in Equation (4) and S_{con} and L_f in Equation (5)[12] or p and D_{eq} in Equation (4) together with F_{cor}.[13] In contrast, the model presented in this study can be calibrated using only one empirical parameter determined from as little as two data points in combination with Equation (11).

This two data points approach (Equal to A1) only enables ΔP prediction at $V = V_a$, if prediction at different velocities is needed a clean $V - \Delta P$ curve must be measured in order to estimate a and b in Equation (3a). Calibration of a and b in Equation (3a) corresponds to calibrating D_{eq} in the Ergun equation or D_{eq}, A and B and in the modified Ergun equation (Equation, (4a)), which as previously mentioned has been used as foundation for previous models.[12,13]

In this study we have presented a new concept, Equation (8), for modeling pressure drop induced by DBM accumulation in biofilters, and expanded it using respected and validated equations describing flow in porous media (Equations (3a) and (9)).

The presented concept is likely to be valid for other types of incompressible nondegradable granular biofilter media as air flow in granular media follows the same basic rules regardless of medium properties. Biofilter media which are compressible are known to have lower porosity in the compressed (lower) layers and hence $\phi_{C,DBM}$ for the upper part of the filter will be higher than for the lower (compressed part). Determination of an overall $\phi_{C,DBM}$ for the entire filter will, however, be possible as $\phi_{C,DBM}$ simply correlate the measured change in ΔP with the change in biomass. For degradable media the model concept is likely to be valid if ϕ_{DBM} is replaced with the total displaced porosity (porosity displaced by

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DBM accumulation and by compaction). However this hypothesis still needs validation through measurements of $V-\Delta P$ and DBM accumulation data in other types of porous granular media, as well as exhaust air with other characteristics (chemical compound, dust concentrations filter velocity, humidity, etc.) as a change in these parameters will likely affect media flow resistance and/or the distribution of accumulated DBM.

CONCLUSIONS

In this study we measured the relationship between air flow and pressure drop (ΔP) in biofilters cleaning real exhaust air from a full scale pig production facility. These biofilters were based on a commercially available biofilter medium: light expanded clay aggregates (Leca®) consisting of porous rounded aggregates. All measurements showed a second order relationship between ΔP and superficial air velocity (V) in the filters. The ΔP at a given V was further observed to increase over time in response to accumulation of dust and biomass (DBM) in the filter medium pores. This increase was observed to be proportional to the fraction of pore space occupied by accumulated DBM. In this study we proposed a simple model based on a limited set of measurements that enables prediction of ΔP versus V and DBM accumulation. The applied model is based on the semi-empirical parameter: critical dust and biomass displaced porosity $\phi_{C,DBM}$. This approach differs from previous studies predicting ΔP as a function of DBM accumulation in its simplicity and limited number of data point needed for calibration. Three calibration approaches were tested and were found to predict the measured V, ΔP and DBM accumulation data with a mean relative error of 11–14%, based on 2–7 calibration points.

As air flow in granular media follows the same basic rules regardless of medium properties it is very likely that the model concept presented in this study will also be valid for other types of granular biofilter media. However this hypothesis still needs validation through measurements of $V-\Delta P$ and DBM accumulation data in other types of porous granular media, as well as exhaust air with other characteristics (chemical compound and dust concentrations).

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ABOUT THE AUTHORS

Rune R. Andreasen is a Ph.D. student and Tjalfe G. Poulsen is an associate professor in the Department of Chemistry and Biotechnology at Aalborg University, Aalborg, Denmark. Richard E. Nicolai is associate professor at the Agricultural and Biosystems Engineering section at South Dakota State University. Please address correspondence to: Rune R. Andresen, Department of Chemistry and Biotechnology, Aalborg University, Sohngaardsholmsvej 57, DK-9000 Aalborg, Denmark. Phone: +45-9940-8493; e-mail: rra@bio.aau.dk.

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