Air Flow Characteristics in Granular Biofilter Media

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Abstract: Pressure drop (ΔP) as a function of air velocity (V) is a key parameter controlling air cleaning biofilter cost efficiency. At present the V–ΔP relationship in biofilter materials must generally be determined experimentally, as no universal link between the V–ΔP relationship and material physical properties have been established. The objective of this study was, therefore, to investigate the link between the V–ΔP relationship, material particle size distribution, and wetting conditions for a common biofilter medium, Leca. Measurements of V–ΔP was carried out for 36 different Leca particle size fractions with different mean particle diameter (D_m) and particle size range (R) under both dry and wet conditions. Measurements showed that increasing D_m and decreasing R together with wetted conditions in the filter generally resulted in decreasing ΔP for the same V. A set of expressions allowing for accurate estimation of the V–ΔP relationship based on D_m, R, and wetting conditions were established, enabling reliable estimation of filter pressure drop (and operation costs) in Leca and similar granular materials. **DOI: 10.1061/(ASCE)EE.1943-7870.0000640.** *© 2013 American Society of Civil Engineers.*

CE Database subject headings: Air flow; Granular media; Permeability; Particle size distribution; Moisture; Filtration.

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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 (Best 2010). Also, pig farms have increased in size, producing increased airborne emissions of odorous compounds and nutrients (especially nitrogen). Odors from pig farms are a source of nuisance to people living in the vicinity, and the pressure for finding technical solutions to reduce odor emissions has been increasing (Schiffman et al. 1995). Odor emissions from livestock production are primarily associated with the large quantities of exhausted ventilation air from the production facilities (O'Neill et al. 1992). At present, biofiltration seems to be the most cost-effective technology for removing nutrients and odorous compounds from the exhaust air (O'Neill et al. 1992; Chen and Hoff 2009). The cost of treatment by biofiltration is primarily associated with (1) filter construction and (2) filter operation and maintenance (Chen and Hoff 2009). A nonnegligible part of the operation cost is the energy consumption to overcome air flow resistance in the filter. This energy consumption and, thus, the cost is directly proportional to the air flow rate and the pressure drop across the filter (Leson and Winer 1991; Scotford et al. 1996). Therefore, to reduce energy consumption-associated air-flow resistance for a given flow rate, the pressure loss should be reduced, for instance, through the choice of a proper biofilter material. According to the Danish Agriculture and Food Council, this energy consumption is a major concern when applying biofiltration because of 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 hour per pig depending on season and the size of the pigs. For systems with sows and piglets, ventilation rates up to 400 m^3 air per sow and hour are used (Pedersen 2005). Hence, filter pressure drop (ΔP) as related to air flow (V) is a key relationship in cost-effective biofilter design. The V–ΔP relationship for a given biofilter depends on filter geometry, filter material properties (such as particle size distribution and air-filled porosity), and accumulation of biomass in the filter. While filter geometry can be controlled directly, the link between the V–ΔP elationship and filter material properties is given once the choice of material has been made. Numerous studies have investigated the dependency of ΔP on V in granular media, and several expressions for estimating this relationship have been proposed (Darcy 1856; Forcheimer 1901; Ergun 1952; Macdonald et al. 1979). Several investigators have proposed expressions for directly relating the V–ΔP relationship to filter material properties across materials with different particle size distributions. Some well-known and widely used examples are Kozeny (1927), Carman (1937), Ergun (1952), and Bird (1960), of which Ergun (1952) is probably the most widely used. These equations generally predicts ΔP as a function of V on the basis of filter material air-filled porosity (ε) and a media specific characteristic length (D_{eq}) (in general, related to particle diameter) in combination with a number of empirical constants that are specific to each equation and whose values are supposed to be universal across different types of filter materials. Macdonald et al. (1979), however, documented that the values of the empirical constants were in fact dependent on the material being considered (likely because materials with different particle size distributions and particle shape can easily have identical ε). Macdonald et al. (1979) also pointed out that present expressions for predicting D_{eq} are not fully capable of producing proper D_{eq} values for materials consisting of differently sized particles.

To allow for reliable predictions of the V–ΔP relationship and estimates of energy consumption in such materials, further investigations are, therefore, required to establish improved expressions for predicting D_{eq} from filter material particle size distribution.

This study investigates the impact of particle size distribution on the V–ΔP relationship for granular filter materials suitable for use

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at high flow rates. The aim is to develop an improved expression for estimating ΔP as a function of V for coarse granular materials relevant for biofiltration focusing on the effects of filter material properties. Such an expression will be a valuable tool when choosing the optimal packing material for constructing a biofilter under specific conditions. A commercially available medium, Light Expanded Clay Aggregates (Leca), consisting of porous rounded aggregates available in sizes from 2–18 mm with similar shape was selected in this study. The advantage of this material is that it is available in well-defined particle size fractions, and it is not subject to degradation over time. The material has successfully been applied in industrial air cleaning biofilters at a Danish facility for destruction of dead animals and is currently being applied for air cleaning at pig production facilities (Nielsen and Nørgaard 2010; Saint-Gobain 2011). As the focus in the present work is on the effects of filter material physical properties on the V–ΔP relationship, investigations will be carried under conditions where no biomass is present. This is done to fully understand the link between the V–ΔP relationship and the physical properties of the Leca medium, and, investigations are therefore performed using clean Leca. The additional impact of biomass and dust accumulation in biofilters over time is addressed in Andreasen et al. (2012).

Theory

Flow of air in porous media is traditionally described using Darcy's law, which, for one-dimensional air flow through a section of porous medium with thickness L (m), is given as

$$\frac{\Delta P}{L} = \frac{\mu}{k_a} V \tag{1}$$

where ΔP = pressure drop (Pa) across the medium; μ = air viscosity (Pa · s); k_a = porous medium air permeability (m^2); and V = superficial air velocity ($m \cdot s^{-1}$), also known as the Darcy velocity given as

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

where Q = volumetric air flow ($m^3 \cdot s^{-1}$); and A_c (m^2) = cross-sectional area of the filter perpendicular to the flow direction, i.e., the area occupied by both particles and voids. The Darcy equation [Eq. (1)] is valid for Reynolds numbers (R) below approximately 1, where the inertial forces are insignificant (Trussell and Chang 1999).

Although Eq. (1) is valid for $R < 1$, the flow becomes significant affected by inertial forces at $R > 1$, and Eq. (1) no longer applies. Several relationships describing this so-called non-Darcy flow regime have been proposed (Forcheimer 1901; Antohe et al. 1997; Lage et al. 1997; Trussell and Chang 1999). One of the most widely used is the Forcheimer equation (Forcheimer 1901), which add a quadratic velocity term to the Darcy equation to correct for inertial forces (Trussell and Chang 1999):

$$\frac{\Delta P}{L} = \frac{\mu}{k_a} V + C_f \rho V^2 \tag{3}$$

where C_f = so-called form coefficient (m^{-1}) that depends on the characteristics of the porous medium; and ρ = air density ($kg \cdot m^{-3}$). The Forcheimer equation (Forcheimer 1901) is in theory valid within the Forcheimer regime ($1 < R < 100$) where the flow is dominated by inertial forces (Trussell and Chang 1999). However, it has been observed that at $R > 100$, the V–ΔP relationship follows an expression that is equivalent to Eq. (3), thus, Eq. (3) may be used to approximate the V–ΔP relationship also in this regime (Trussell and Chang 1999).

Thus, if flow regime corresponding k_a, and C_f are known for the biofilter medium in question, ΔP as a function of V across filters of any geometry using that medium can be calculated using Eq. (3).

Several semiempirical equations to predict k_a and C_f from porous media properties have been proposed. The most well-known and applied is likely the Ergun equation (Ergun 1952), which predicts the pressure gradient as

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

Combining Eqs. (2) and (3) yields

$$k_a = \frac{1}{A} \frac{\varepsilon_{ex}^p}{(1-\varepsilon_{ex})^2} D_{eq}^2 \tag{5}$$

$$C_f = B \frac{(1-\epsilon_{ex})}{\epsilon_{ex}^p} D_{eq}^{-1} \tag{6}$$

where ε_{ex} = external (inter particle) porosity ($m^3 \cdot m^{-3}$); D_{eq} = equivalent particle diameter (defined as 6 times the surface area to volume ratio of the particles); and A, B, and p = empirical constants equal to 150, 1.75, and 3, respectively. From a large experimental data set, Macdonald et al. (1979) found that the constants A and B were not universal but in fact depended on material properties and ranged over several orders of magnitude, depending on material. Macdonald et al. (1979) therefore proposed that A and B should be determined independently for each material considered but suggested that for practical engineering purposes A, B, and p could be chosen equal to 180, 1.8, and 3.6, respectively, for smooth particles. Macdonald et al. (1979) further pointed out the problems with estimating a proper value of D_{eq} in media where the particles are not of uniform size and proposed D_{eq} to be estimated as

$$D_{eq} = \frac{1}{\Sigma_i Y_i (6 \frac{V_{p,i}}{A_{p,i}})^{-1}} \tag{7}$$

where Y_i, $V_{p,i}$, and $A_{p,i}$ = volumetric fraction, particle volume, and particle surface area of the ith particle. Though Eq. (7) enabled D_{eq} estimation for media where the particles are not of uniform size, Macdonald et al. (1979) pointed out that in media with wide particle size distributions, Eq. (7) becomes inadequate.

Subsequently, an alternative expression for estimating D_{eq} was proposed by Macdonald et al. (1991), who estimated D_{eq} as the ratio between the first- and the second-order moment of the particle size distribution:

$$D_{eq} = \left(\frac{M_2}{M_1}\right)^2, \qquad M_i = \int_0^\infty D_p^i n_p^i(D_p) dD_p \tag{8}$$

where M_i = ith moment; D_p^i = particle diameter, and $n_p^i(D_p)\, dD_p$ represent the number of particles with diameters between D_p^i and $D_p^i + dD_p$. This expression generally yields D_{eq} predictions that are similar to those of Eq. (7).

The main challenges of using Eq. (4) with Eq. (7) or (8) for prediction of biofilter pressure drop is that the values of the "constants" A and B in Eq. (4) are material-dependent, meaning that new measurements are required each time a new material, for which A and B and are not known, is considered. The ranges for A and B given by Macdonald et al. (1979) were 124 to 841 and −1.5 to 583, respectively. Thus, when using the general values of $A = 180$ and $B = 1.8$, material dependency is not fully accounted for and substantial uncertainty is introduced into the predictions. Thus, to be practically applicable, Eq. (4) must be modified such that material-independent A and B values [as proposed by

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Macdonald et al. (1979) for engineering purposes] can be used while fully taking into account effects of material properties.

Materials and Methods

Pressure drop in biofilter material was investigated using a commercially available material, Leca (Light Expanded Clay Aggregates), which is used for multiple purposes, including insulation and biofiltration. Leca consists of rounded aggregates and has a very high porosity (0.87–0.92 $m^3 \cdot m^{-3}$). However, Leca is a dual-porosity medium with 55–70% of the pore space consisting of small internal (intraparticle) pores, which are either not connected with the external pores and/or very small and therefore do not conduct air. This material was chosen because it represents a wide range of both artificial and natural (stones, pebbles) granular biofilter materials. Saint-Gobain Weber A/S Randers, Denmark, provided the Leca used in this study in eight presorted size fractions with uniform particle size distributions. These fractions had a particle size range (R) of 2 mm, and particle diameters (D) of $2 \leq D < 4$ mm, $4 \leq D < 6$ mm, $6 \leq D < 8$ mm, $8 \leq D < 10$ mm, $10 \leq D < 12$ mm, $12 \leq D < 14$ mm, $14 \leq D < 16$, and $16 \leq D < 18$ mm corresponding to mean particle diameter (D_m) values of 3, 5, 7, 9, 11, 13, 15, and 17 mm, respectively. Additional fractions with $R = 4$ mm ($D_m = 4, 6, 8, 10, 12, 14, 16$ mm), $R = 6$ mm ($D_m = 5, 7, 9, 11, 13, 15$ mm), $R = 8$ mm ($D_m = 6, 8, 10, 12, 14$ mm), $R = 10$ mm ($D_m = 7, 9, 11, 13$ mm), $R = 12$ mm ($D_m = 8, 10, 12$ mm), $R = 14$ mm ($D_m = 9, 11$ mm), and $R = 16$ mm ($D_m = 10$ mm) and uniform particle size distribution were produced by combining appropriate quantities of the original $R = 2$ mm size fractions. Uniform particle size distributions were chosen for two reasons: (1) biofilter materials are usually available in presorted fractions, and (2) it was desirable to have well-defined and identical particle size distribution shapes for all fractions. Each fraction was prepared using both air dry Leca and Leca wetted to its maximum drained water content through immersion in water for a period of at least 3 days (no significant weight gain was observed for periods exceeding 3 days) followed by drainage for 2 h. This was done to saturate the small intraparticle pores in the Leca particles to mimic practical filtration conditions. These small pores are normally saturated during biofilter operation. A total of 72 Leca fractions (36 air dry and 36 wet) were produced. Gravimetric water content (ω, $g \cdot g\,Leca^{-1}$) in air dry Leca was determined by drying at 105°C until constant weight, and in wet Leca from the weight gain of air dry Leca after wetting and drainage. Mean dry bulk density (ρ_b, $g \cdot cm^{-3}$) for each fraction was determined in triplicate by filing a 20-L bucket to the edge with Leca, dropping it 3 times from a height of 3 to 5 cm to achieve a stable packing, and subsequently adding additional material to fill the empty volume created during packing. The packed Leca was then weighed. As Leca is nonexpanding when wetted, ρ_b is constant regardless of ω.

For each of the fractions with $R = 2$ mm, 10 particles were randomly selected and weighed. In addition, 3 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, $g \cdot cm^{-3}$). External volumetric air content (ε_{ex}) for these fractions were then determined as

$$\varepsilon_{ex} = 1 - (\rho_b \cdot \rho_p^{-1}) \tag{9}$$

For fractions with R larger than 2 mm, ρ_p was calculated as a weighted mean of the particle densities for all 2-mm fractions used in the preparation of these fractions. An overview of the physical characteristics of the Leca materials in terms of ρ_b, ρ_p, ω, total porosity (ϕ), and ε_{ex}, is given in Table 1. Each individual fraction was packed into a vertical 100-cm-long, 25-cm inner diameter steel ventilation tube connected to a CUBUFAN 160 EC ventilation pump (Jenk, Brøndby, Denmark). The height (L) of the Leca material inside the tube was approximately 30 cm, but for Leca fractions with high ΔP (fractions containing small particles) it was reduced to 15 cm to achieve a measurable V. After filter packing, the exact value of L was calculated from the mass of Leca added, ρ_b, and the tube cross-sectional area.

Table 1. Physical Characteristics of 36 Leca Fractions with Uniform Particle Size Distribution, in Terms of Particle Size, Dry Bulk Density (ρ_b), Particle Density (ρ_p), Water Content (Only for Wet Measurements) (ω), Total Porosity (ϕ), and External Volumetric Air Content (ε_{ex})

Fraction (mm)	ρ_b ($g \cdot m^{-3}$)	ρ_p ($g \cdot cm^{-3}$)	ω ($g \cdot g$ Leca^{-1})	ϕ ($m^3 \cdot m^{-3}$)	ε_{ex} ($m^3 \cdot m^{-3}$)
2–4	0.33	0.46	0.65	0.87	0.28
4–6	0.29	0.47	0.47	0.89	0.39
6–8	0.25	0.40	0.42	0.91	0.37
8–10	0.25	0.39	0.40	0.91	0.37
10–12	0.24	0.37	0.39	0.91	0.36
12–14	0.23	0.35	0.37	0.91	0.33
14–16	0.22	0.32	0.37	0.92	0.32
16–18	0.23	0.34	0.35	0.91	0.33
2–6	0.31	0.47	0.58	0.88	0.33
4–8	0.27	0.43	0.56	0.90	0.37
6–10	0.25	0.39	0.58	0.91	0.37
8–12	0.24	0.38	0.62	0.91	0.37
10–14	0.24	0.36	0.54	0.91	0.35
12–16	0.24	0.33	0.52	0.91	0.28
14–18	0.22	0.33	0.49	0.92	0.32
2–8	0.29	0.44	0.73	0.89	0.34
4–10	0.26	0.42	0.55	0.90	0.37
6–12	0.24	0.39	0.57	0.91	0.37
8–14	0.24	0.37	0.55	0.91	0.34
10–16	0.23	0.34	0.50	0.91	0.34
12–18	0.23	0.33	0.56	0.91	0.31
2–10	0.27	0.43	0.67	0.90	0.36
4–12	0.26	0.40	0.68	0.90	0.37
6–14	0.24	0.38	0.56	0.91	0.35
8–16	0.23	0.35	0.55	0.91	0.35
10–18	0.23	0.34	0.52	0.91	0.34
2–12	0.27	0.41	0.73	0.90	0.35
4–14	0.25	0.39	0.56	0.91	0.36
6–16	0.24	0.36	0.55	0.91	0.35
8–18	0.22	0.35	0.54	0.92	0.36
2–14	0.26	0.40	0.63	0.90	0.35
4–16	0.25	0.38	0.53	0.91	0.35
6–18	0.23	0.36	0.53	0.91	0.35
2–16	0.26	0.39	0.65	0.90	0.34
4–18	0.24	0.37	0.53	0.91	0.34
2–18	0.25	0.38	0.63	0.91	0.34

Air flow through the Leca was measured continuously in the inlet to the pump using a VA400 thermal mass flow sensor, (CS Instruments, Tannheim, Germany), while pressure drop across the Leca was measured at selected times using an ALNOR AXD 560 manometer (Alnor, Ontario, Canada), both calibrated by the manufacturers. All measurements were carried out at room temperature. No water irrigation of the wetted filters took place during the measurement, as the measurement duration was short enough to prevent significant loss of water (this was verified by control weighing of the wetted filter columns). A schematic of the experimental setup is given in Fig. 1.

Measured air flows were not corrected for variations in pressure, temperature, or water vapor concentration, as calculations showed that the combined effect of these parameters on the flow rate was

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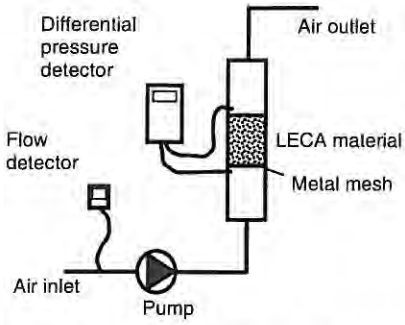

Fig. 1. Experimental setup for measuring V–ΔP relationships for air flow through biofilter media

less than 0.5%. Reported flow values in this study are given at actual conditions (room temperature and and atmospheric pressure).

Biofilter pressure drop (ΔP) and superficial velocity (V) were measured at 6 pumping levels (17, 33, 50, 67, 83, and 100% of the maximum pumping rate for each particle fraction). The corresponding ranges of V, Q, and empty bed residence time for filters with 25-cm inner diameter and $L = 30$ is 0.10–1.17 $\mathrm{m \cdot s^{-1}}$, 0.05–0.58 $\mathrm{m^3 \cdot s^{-1}}$, and 0.26–2.95 s, respectively. The ranges of these parameters were chosen on the basis of the conditions used in commercial biofilters for air cleaning at animal production facilities (Ottosen et al. 2011).

For each level, steady-state values of ΔP and V were determined over the same 30-s time period as the mean of three ΔP measurements and 30 V measurements, respectively. To prevent fluidization of media containing small particles, measurements were conducted with a small metal wire mesh at the outlet. Observed ΔP was corrected for empty column pressure drop at the same V. In case of wet Leca fractions, V–ΔP measurements were carried out using the same procedure following the 2-h drainage period. During the V–ΔP measurements in wet Leca, ω decreased slightly near the filter inlet because of evaporation. Comparison of ΔP values in wet and dry Leca, however, showed that this evaporation had insignificant impact on ΔP. For all particle size fractions, filter columns were prepared in triplicate, and for each filter column, V–ΔP measurements were carried out in triplicate for each pumping level. As the resulting V at a given pumping level was not constant but depended on the Leca fraction analyzed and the filter length used, the six resulting V values used for each Leca fraction were therefore not the same across the experiments.

Results and Discussion

In general, both ρ_b and ρ_p decrease with increasing D_m across all Leca fractions (Table 1). The reason is that small Leca particles have a denser internal structure with fewer and smaller internal pores compared with the larger particles that have more and larger internal pores. Also, the drained ω decreased with increasing D_m, likely because water retention is partly controlled by particle-specific surface area. Both ρ_b and drained ω were independent of R, and ε_{ex} did not show a clear relationship with either D_m or R (Table 1).

For all Leca fractions, ΔP increased with V following a second-order expression in V [Fig. 2(a)], thus, being consistent with Eq. (4). Values of R for the experiments calculated according to Ergun (1952) ranged between 18 and 1,455 and V–ΔP relationships were observed to follow a second-order relationship, thus equations equivalent to Eq. (4) can be used to describe the observed V-DP relationships.

Eqs. (4) and (7) with $A = 180$, $B = 1.8$, and $p = 3.6$ as suggested by Macdonald et al. (1979) were tested against the measured V–ΔP data for dry Leca. The results of this test (Case 1) are shown in Fig. 2(b), where measured values of ΔP are plotted against predicted ΔP [by Eqs. (4) and (7)]. Prediction accuracy was quantified using both the root mean square error (RMSE), defined as

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\Delta P_{\mathrm{measured}} - \Delta P_{\mathrm{fitted}})^2} \tag{10}$$

and the relative error (RE), defined as

$$\mathrm{RE} = \frac{Abs(\Delta P_{\mathrm{measured}} - \Delta P_{\mathrm{fitted}})}{\Delta P_{\mathrm{measured}}} \tag{11}$$

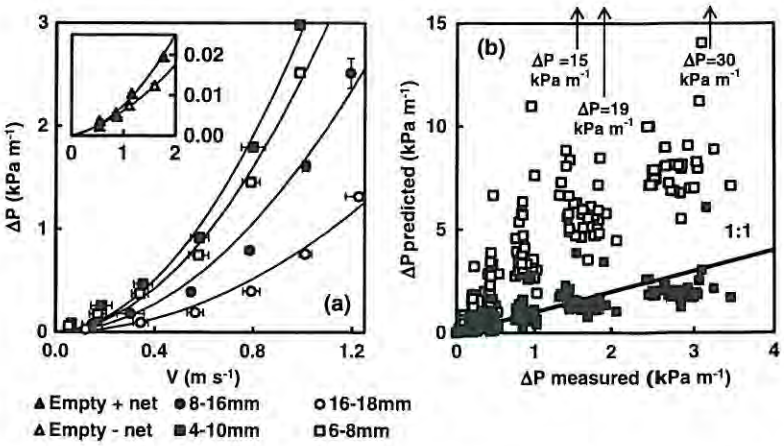

Fig. 2. (a) Measured V–ΔP relationships for selected Leca fractions; symbols indicate measured values (average of three measurements), error bars represent one standard deviation, and curves represent fitted V–ΔP relationships; empty column pressure drops both with and without media retaining net is shown in inserted plot; lines indicate best fits based on Eq. (4) $A = 180$, $B = 1.8$, and $p = 3.6$ and D_{eq} fitted; (b) measured versus predicted values of ΔP for all 36 Leca fractions using Eq. (4) with $A = 180$, $B = 1.8$, and $p = 3.6$ (empty symbols) and with $A = 10^{-4}$ (fitted), $B = 0.49$ (fitted), and $p = 3.6$ (closed symbols); corresponding V and ΔP mean standard error was 5% and 4%, respectively

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The RMSE and RE for Case 1 are shown in Table 2. In general, ΔP predictions are rather poor (RE = 277%), mainly attributable to overprediction. A similar test was carried out using Eq. (8) instead of Eq. (7) with similar results (data not shown).

From the suggestion by Macdonald et al. (1979) that A and B are material dependent, Eqs. (4) and (7) were fitted to the measured V–ΔP data using A and B as fitting parameters, minimizing the RMSE of measured versus fitted values of ΔP, to arrive at a set of A, B values valid across all Leca fractions (Case 2). Optimal values were $A = 10^{-4}$ and $B = 0.52$. Measured and fitted ΔP values are shown in Fig. 2(b), and resulting RMSE and RE are given in Table 2. Model accuracy is greatly improved as the RMSE is reduced by 86% and the relative error is reduced to 47%. However, the use of $A = 10^{-4}$ results in k_a values of 10^{-3}–10^{-1} m^2, which basically removes any linear pressure drop (the first term in Eq. (4) and, thus, the two terms of Eq. (4) no longer carries any physical significance.

In the development of a more accurate model that still retains the physical significance of the k_a and C_f terms in Eq. (4), it was chosen to maintain $A = 180$ and $B = 1.8$ as suggested by Macdonald et al. (1979) and instead focus on modifying the D_{eq} terms in Eqs. (4) and (7) to include effects of particle size distribution not yet accounted for. To enable subsequent validation, Eq. (4) was therefore fitted to each individual V–ΔP relationship for part of the data (for 33 out of the 36 dry Leca fractions) using D_{eq} as fitting parameter (Case 3) while keeping $A = 180$, $B = 1.8$, and $p = 3.6$. Fractions not used in the fitting were 4–8 mm, 4–16 mm, and 12–16 mm. Values of RMSE and RE are given in Table 2. The relationships between the model parameters ($D_{eq,fitted}$, k_a, and C_f) with the media parameters D_m, R and $D_{min} = D_m$–$0.5R$ (equivalent to the diameter of the smallest particle present in each fraction) are illustrated in Fig. 3.

$D_{eq,fitted}$ generally increase with increasing D_m and D_{min} but decrease slightly with increasing R [Figs. 3(a and b)] for air dry Leca, and similar tendencies were also observed for wetted leca (data not shown). The values of $D_{eq,fitted}$ are up to 600% higher than the diameter of the largest particle in each Leca fraction on average. This means that, although $D_{eq,fitted}$ does account for effects of particle size distribution, it does not directly represent an equivalent particle diameter. In case of both air dry and wetted Leca, k_a increased strongly with increasing D_m for constant R, decreased with increasing R for constant D_m [Fig. 3(c)] and increased strongly with increasing D_{min} for constant D_m [Fig. 3(d)]. In contrast, k_a was generally independent of ε_{ex} (Table 1) [Figs. 3(c and d)].

Table 2. Performance in Terms of the Root Mean Square Error, RMSE [Eq. (10)], and the Relative Error, RE [Eq. (11)], of Different V–ΔP Models Applied to the Measured V–ΔP Data for Dry and Wet Leca

Case	Medium	Model	RMSE	RE
1	Dry Leca	Eqs. (4) and (7), $A = 180$, $B = 1.8$, $p = 3.6$	3,947	2.77
2	Dry Leca	Eqs. (4) and (7), $p = 3.6$, $A = 10^{-4}$ (fitted), $B = 0.49$ (fitted)	535	0.47
3	Dry Leca	Eq. (4), $A = 180$, $B = 1.8$, $p = 3.6$, D_{eq} (fitted)	120	0.26
4	Dry Leca	Eq. (12), $A = 180$, $B = 1.8$, $p = 3.6$, $f = 5.84$ (fitted)	506	0.33
5	Dry Leca	Eq. (12), $A = 180$, $B = 1.8$, $p = 3.6$, $\varepsilon_{ex} = 0.35$ m^3 m^{-3} $f = 4.98$ (fitted)	219	0.26
6	Wet Leca	Eq. (14), $A = 142$, $B = 10.82$, $C = 5.28$ mm^3 (fitted)	184	0.28
7	Dry/wet Leca	Eqs. (13a) and (14), $A = 142$, $B = 10.82$, $C = 5.28$ mm^3	129	0.27

Note: Case 1 was based on V–ΔP data from all 36 Leca fractions, Cases 2–6 were based on the same data except the 4–8, 4–16, and 12–16 mm fractions, and Case 7 was based on the 4–8, 4–16, and 12–16 mm fractions.

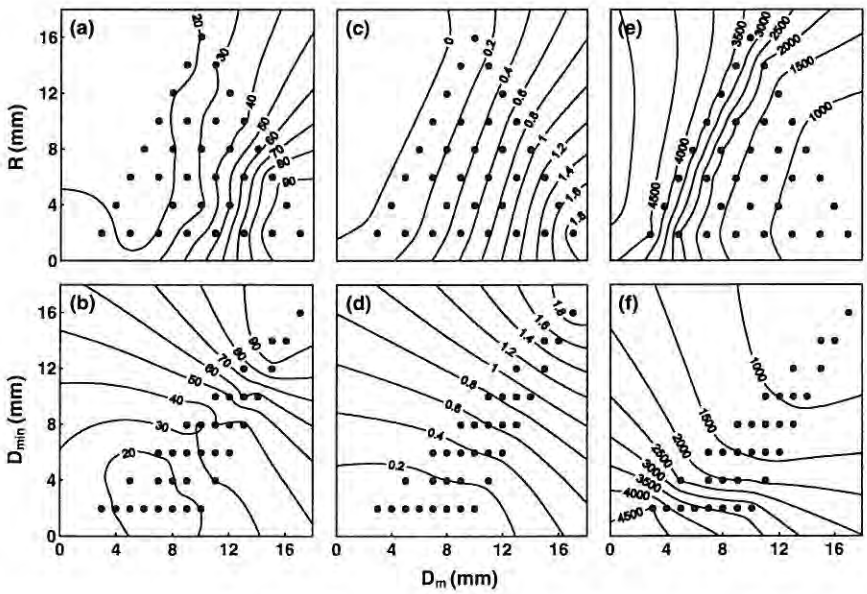

Fig. 3. Values of D_{eq} (mm) and corresponding k_a (mm^2) and C_f (m^{-1}), obtained by fitting Eq. (4) with $A = 180$, $B = 1.8$, and $p = 3.6$ using D_{eq} as a fitting parameter for each individual Leca fraction for 33 out of the 36 fractions: (a) D_{eq} as a function of D_m and R; (b) D_{eq} as a function of D_m and D_{min}; (c) k_a as a function of D_m and R; (d) k_a as a function of D_m and D_{min}; (e) C_f as a function of D_m and R; (f) C_f as a function of D_m and D_{min} (contours indicate kriged values and black dots indicate measured values)

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The reason is that k_a is proportional to the size of the air conducting pores that, in turn, are proportional to D_m (Hamamoto et al. 2009). As R for a given material increases (resulting in a larger difference between D_m and $D_{\min}$), more particles with small diameters will be present and these tend to fill the pores between the larger particles, reducing the size of the air conducting pores, thus, reducing k_a.

The reason why k_a is independent of ε_{ex} is that in coarse granular media k_a is mainly governed by pore diameter (and thus particle diameter) rather than air-filled porosity. Materials consisting of homogeneously packed uniform spheres for instance will have the same $\varepsilon_{ex}(0.33\ \mathrm{m^3\ m^{-3}})$ regardless of particle diameter, however their k_a will differ strongly depending on the diameter of the spheres. This is in contrast to soils where strong correlation between ε_{ex} and k_a often exists. Similar observation have been reported by Macdonald et al. (1979) who found that the porosity dependence in Eq. (4) was not valid over a wide range of porosities.

In both air dry and wetted Leca, C_f is also independent of ε_{ex} (Table 1) but decreases with increasing D_m for constant R, increase with R for constant D_m [Fig. 3(e)] and decreases with increasing $D_{\min}$ for constant D_m [Fig. 3(f)].

From Fig. 3 it can be concluded that k_a is roughly proportional to D_m^2, and C_f is inversely proportional to D_m. This indicates D_m to be a governing parameter for D_{eq}, as D_{eq} is linked to k_a and C_f through exponents of 2 and -1 [Eqs. (5) and (6)], which supports that improved ΔP predictions may be achieved by including D_m in a modified D_{eq} prediction [Eqs. (7) or (8)].

The observed relationships between $D_{\min}$ and k_a, C_f, and $D_{eq,fitted}$ indicate that when calculating D_{eq}, more weight should be put on $D_{\min}$ compared with what is done in Eqs. (7) and (8). It is therefore suggested that D_{eq} be calculated as a harmonic mean of D_m and $D_{\min}$. As $D_{eq,fitted}$ in general was observed to be up to 10 times larger than D_m, a correction factor, f, was used in the D_{eq} terms. With these modifications, Eq. (4) changes to

$$\frac{\Delta P}{L} = A\frac{(1-\varepsilon_{ex})^2}{\varepsilon_{ex}^p}\left(\frac{2f}{\frac{1}{D_m}+\frac{1}{D_m-\frac{R}{2}}}\right)^{-2}\mu V + B\frac{(1-\varepsilon_{ex})}{\varepsilon_{ex}^p}\left(\frac{2f}{\frac{1}{D_m}+\frac{1}{D_m-\frac{R}{2}}}\right)^{-1}\rho V^2 \tag{12}$$

Eq. (12) with $A = 180$, $B = 1.8$, and $p = 3.6$ was fitted to the measured V–ΔP data (Case 4) for the same 33 air dry Leca fractions as used in Case 3 yielding an optimal f-value of 5.84. Fitted versus measured ΔP values are shown in Fig. 4(a) and the corresponding RMSE and RE are given in Table 2.

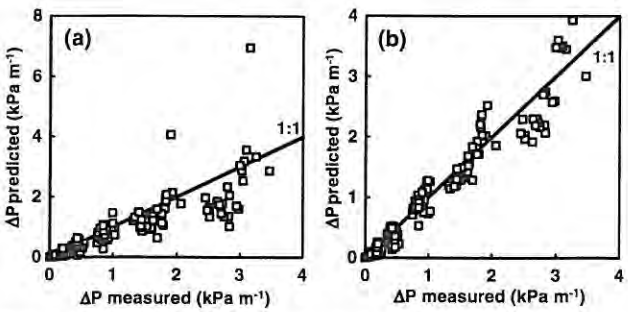

Fig. 4. Measured versus predicted values of ΔP for 33 Leca fractions using Eq. (12) with $A = 180$, $B = 1.8$, $p = 3.6$, together with: (a) individually measured values of ε_{ex}; (b) an average ε_{ex} across all 33 fractions of 0.35 $\mathrm{cm^3\ cm^{-3}}$; corresponding V and ΔP mean standard error was 5% and 4%, respectively

Predictions by Eq. (12) with $A = 180$, $B = 1.8$, $p = 3.6$, and $f = 5.84$ are of the same accuracy as Case 2. Fig. 4(a) shows that some values of ΔP are over predicted by up to 100% using Eq. (12). These are associated with the 2–4-mm Leca fraction, which has the lowest value of $\varepsilon_{ex}(0.28\ \mathrm{cm^3 \cdot cm^{-3}})$. Likewise was 4–6 mm, with the highest value of $\varepsilon_{ex}(0.39\ \mathrm{cm^3 \cdot cm^{-3}})$ observed to be underpredicted, with up to a 1.6-kPa underprediction for a 2.8-kPa measured value. The reason for the over/underprediction is that Eq. (12) assumes a strong relationship between k_a, C_f, and ε_{ex} but as discussed previously, k_a and C_f are relatively independent of ε_{ex}.

Eq. (12) was therefore refitted to the 33 Leca fractions using an average value of $\varepsilon_{ex} = 0.35$ (across all 33 fractions) and f as a fitting parameter (Case 5). The average ε_{ex} was used to maintain the physical meaning of both the k_a and C_f terms. The optimal value of f was and 4.98. Fitted versus measured values of ΔP are shown in Fig. 4(b), and corresponding RMSE and RE are given in Table 2. In Case 5, RE are reduced almost to the same level as in Case 3, and this clearly shows that the effect of variation in ε_{ex} on ΔP is overestimated in Eq. (4). This means that Eq. (12) reduces to

$$\frac{\Delta P}{L} = \frac{A}{(D_{eq})^2}\mu V + \frac{B}{D_{eq}}\rho V^2 \tag{13a}$$

where $A = 142$; $B = 10.82$ (f has been incorporated into A and B); and D_{eq} is given as

$$D_{eq} = \frac{2}{\frac{1}{D_m}+\frac{1}{D_m-\frac{R}{2}}} \tag{13b}$$

Wetting the Leca generally resulted in lower pressure drop across the filters compared with dry Leca, despite the fact that water occupied about 11% of the total porosity on average in all wetted Leca fractions. Selected V–ΔP relationship for wet and dry Leca are shown in Fig. 5(a).

This observation is in contrast to almost all studies of soils and other fine-grained materials where pressure drop normally increases with increasing ω (Ball et al. 1988; Gomez-Lahoz et al. 1991; Poulsen et al. 1998; Kawamoto et al. 2006), and further in contrast to studies by Dorado et al. (2010), who found ΔP to increase with increasing water content in biofilter media. There are two likely explanations for this behavior. First, under drained water content conditions, only pores with diameters less than 30 μm are water-filled (Sumner 2000; Poulsen et al. 2001). As the diameters of the air conducting interparticle pores in this study

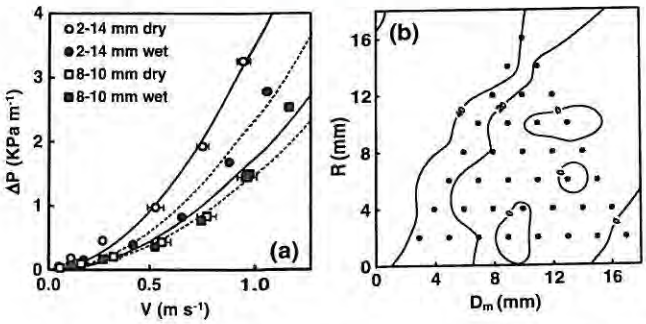

Fig. 5. (a) Dry and wet V–ΔP relationships; lines indicate best fit of Eq. (4) with $A = 180$, $B = 1.8$, $p = 3.6$, and D_{eq} fitted individual to each fraction; solid lines indicate dry media, dashed line wet media; (b) corresponding $(\Delta P_{dry} - \Delta P_{wet})/\Delta P_{dry}$ as a function of D_m versus R, where ΔP is interpolated between the measured V–ΔP points, using Eq. (4) with $A = 142$, $B = 10.82$, $p = 3.6$, and D_{eq} fitted

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are larger than about 600 μm (Glover and Walker 2009), the external porosity is not reduced by the presence of water under drained conditions. In contrast, the air conducting porosity of the media used in the previous studies [including the Dorado et al. (2010) study] was significantly reduced by the presence of water either because many of air conducting the pores were smaller than 30 μm (soil) and, thus, water-filled or because high irrigation rates were used (Dorado et al. 2010). Second, the thin water film present on the external particle surfaces may reduce surface roughness, thereby reducing air flow resistance. Water flow resistance in pipes have for centuries been known to depend partly on surface roughness (Hager 2010). It is therefore likely that the observed ΔP decrease for wet media is caused by a reduced surface roughness as water fills the small inconsistencies (cracks and craters) in the surface, without reducing the size of the air-conducting pores. It is likely that such surface smoothening effect could also be achieved through biofilm growth as long as the layer of biomass on the particle surfaces remain thin enough not to alter the external porosity. In practice, however, biomass growth is often significant enough to reduce external porosity and even cause clogging of the biofilter pores (Andreasen et al. 2012).

The effect of decreasing ΔP in response to wetting was largest for fractions with small $D_{\min}$ and decreased rapidly in a nonlinear fashion with increasing $D_{\min}$ such that there was almost no effect for fractions with $D_{\min} > 8$ mm. The average relative reduction in ΔP was calculated as an average of $(\Delta P_{\text{dry}} - \Delta P_{\text{wet}})/\Delta P_{\text{dry}}$ for each fraction based on Eq. (4) together with fitted D_{eq} values for wet and dry media. Results are shown in Fig. 5(b). The decrease in ΔP as a result of wetting across all fractions was found statistically significant with $p < 0.001$. The effect of wetting was roughly proportional to $D_{\min}^{-3}$. A possible explanation is that the effect of reducing surface roughness on ΔP is inversely proportional to the specific surface area of the medium and thus, proportional to particle diameter squared with small particles weighing heavier as they have a larger specific surface area. The effect of wetting will also be most prominent when air flow is most restricted, i.e., when pores are small, thus, the effect is strengthened in proportion to $D_{\min}^{-1}$ in addition to the effects of specific surface area. For wet particles, the V–ΔP relationship can therefore be described as

$$\frac{\Delta P}{L} = A\left\{D_{\text{eq}}\left[1 + \frac{C}{(D_m - \frac{R}{2})^3}\right]\right\}^{-2}\mu V + B\left\{D_{\text{eq}}\left[1 + \frac{C}{(D_m - \frac{R}{2})^3}\right]\right\}^{-1}\rho V^2 \tag{14}$$

where C = constant with the units of length cubed. Eq. (14) with $A = 142$ and $B = 10.82$, using C as a fitting parameter, was therefore fitted to the measured V–ΔP data for wetted Leca for the 33 fractions considered in Cases 3–5 (Case 6). The optimal value of C was 5.28 mm^3, measured and fitted values of ΔP are shown in Fig. 6, and RMSE and RE values are given in Table 2. Predictions by Eq. (14) with $A = 142$, $B = 10.82$, and $C = 5.28$ mm^3 are of the same accuracy as Case 5. As the only difference between Case 5 and Case 6 is the wetting of the media, this suggests that Eq. (14) is suitable for predicting effects of wetting.

To validate the proposed models [Eqs. (13a) and (14)], they were used to predict ΔP for the three Leca fractions not used in Cases 2–6 (4–6 mm, 14–16 mm, and 4–16 mm) under both wetted and air dry conditions (Case 7). Predictions were carried out using $A = 142$, $B = 10.82$, and $C = 5.28$ mm^3 (for wetted conditions). Measured and predicted ΔP values are shown in Fig. 7, and RMSE and RE values given in Table 2.

For both air dry and wetted Leca, predictions were almost as accurate as when fitting D_{eq} directly for each individual Leca fraction (Case 3, Table 2), indicating that the model [Eqs. (13a) and (14)] is valid for estimating ΔP as a function of V in coarse granular biofilter media where ΔP is independent of ε_{ex}. In comparison with Eqs. (4), (7) and (8), Eqs. (13a) and (14) offer significant improvements in prediction accuracy using only three empirical constants, as also used in Eq. (4) while maintaining the physical meaning of the parameters $k_a (= D_{\text{eq}}^2 \cdot A^{-1})$, $C_f (= B \cdot D_{\text{eq}}^{-1})$, and D_{eq}.

As the pneumatic power consumption of the air flow driving fan is the product of the flow multiplied by the pressure drop (Scotford et al. 1996), this means that the energy cost at a given time can be calculated based on Eq. (13) for dry media and Eq. (14) for wet media as

$$C_{\text{electricity}} = \frac{\Delta P}{L} L Q C_J \frac{1}{E} \tag{15}$$

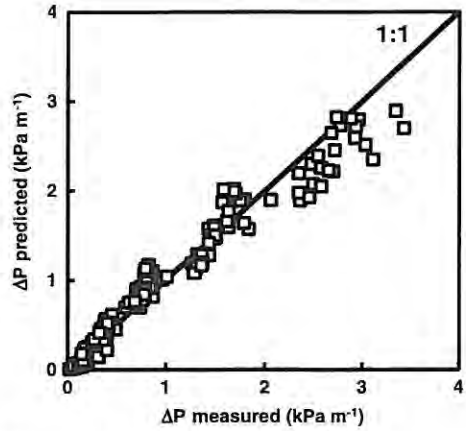

Fig. 6. Measured versus predicted ΔP for 33 Leca fractions using Eq. (14) with $A = 142$, $B = 10.82$, and $C = 5.28$ mm^3; corresponding V and ΔP mean standard error was 4% and 3%, respectively

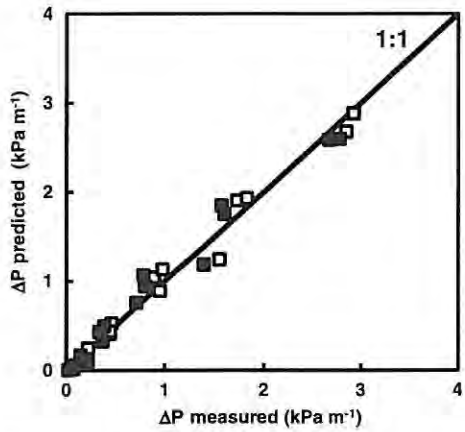

Fig. 7. Measured versus predicted ΔP for 3 Leca fractions not included in calibration of constants A, B, and C (4–6 mm, 14–16 mm, and 4–16 mm) for air dry (empty symbols) and wetted conditions (closed symbols); predictions of ΔP are based on Eq. (13a) for air dry media and Eq. (14) for wetted media, using values of $A = 142$, $B = 10.82$, and $C = 5.28$ mm^3; corresponding V and ΔP mean standard error was 5% and 4%, respectively, for dry measurements and 3% and 2%, respectively, for wet measurements

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where $C_{electricity}$ = electricity cost ($\$ \cdot s^{-1}$); C_J = price of energy ($\$ \cdot J^{-1}$); E = fan efficiency (output work/input energy) at the given ΔP (unique for each pump); and $\Delta P \cdot L^{-1}$ calculated based on Eq. (13) or Eq. (14) with V directly related to Q and filter dimensions as described by Eq. (2). As this is only correct for clean media, nonclean biofilters need an additional correction for the effect of accumulated biomass such as the one suggested in Andreasen et al. (2012).

The V–ΔP model presented in this work is only valid in coarse media where ΔP is independent of ε_{ex}, which excludes soils and similar fine-grained media. As the V–ΔP relationship depends not only on particle size but also on particle shape, it is expected that the values of A and B are particle shape-dependent. This means that the values suggested in this paper are likely not generally valid but should be used only for media with similar particle shape as the Leca media used. The parameter C depends not only on the wetting conditions but is likely also, like A and B, dependent on particle shape and perhaps also on particle surface roughness.

Conclusions

Pressure drop as a function of air velocity in granular air cleaning biofilter media with different particle size distributions was measured using Leca (a commercial insulation material also often used as carrier material in bio filters for air cleaning). A total of 36 different particle size fractions were considered under both air dry and wetted conditions. The V–ΔP relationships generally exhibited second-order relationships in agreement with earlier literature. A general existing model concept for predicting V–ΔP relationships in porous media was tested against the measured data but resulted in overprediction of ΔP at about 277% for dry media and even worse for wet media. The reason is because existing V–ΔP models generally are developed for fine-grained materials such as soils where conditions controlling the V–ΔP relationship are very different. The main findings of this study is that, unlike fine-grained materials, it was observed that the V–ΔP relationships in the Leca materials were independent of air-filled porosity but instead strongly related to the particle diameter, especially the diameter of the smallest particles present in each fraction, and this relationship could be explained by simple media characteristics.

It was further observed that wetting the Leca decreased ΔP for a given V. This effect was most pronounced for particle size fractions containing small particles and is in contradiction to almost all observations for soils and other fine-grained materials where ΔP increases with increasing water content. A possible reason is that the water covers the external surfaces of the Leca particles, making them smoother without reducing the size of the air-conducting pores, resulting in reduced resistance to air flow.

On the basis of these observations, a model for predicting ΔP as a function of V in coarse granular porous media under air dry and wetted conditions was proposed. This model predicts ΔP from V, mean particle diameter (D_m), and particle size range (R) using only three empirical fitting parameters. The values of the three fitting parameters were determined by fitting the model to V–ΔP data from 33 out of the 36 Leca fractions used in this study. The model was then tested against the three remaining Leca fractions and yielded predictions with an average error of 27% across all values of V under both air dry and wetted conditions (a total of 35 V–ΔP data points), equivalent to a 90% reduction in prediction error for both wet and dry compared with the existing model concept using the same number of fitting parameters.

These results indicate that to minimize ΔP and energy consumption for biofilter operation using coarse-grained materials (>2 mm), selection of biofilter media should be based on particle size distribution and particle diameter rather than on material air-filled porosity as is traditionally done. In fine-grained materials having a strong correlation between pore size and external porosity, external porosity is likely the optimal parameter to use. Particle diameter also controls material specific surface area, which in turn controls biofilter contaminant removal rate. Thus particle diameter appears to be a key parameter for biofilter material selection.

As the model presented in this paper has been developed from data for media with particle diameters of 2–18 mm and a rounded shape, the model is theoretically only valid for such media. However, as flow in porous media follows the same basic principles regardless of the medium properties, it is very likely that the concept is applicable to a much wider range of particle sizes and material types than considered here. As the V–ΔP relationship in coarse porous media depends not only on particle size but also on particle shape, the model fitting parameters are likely dependent on particle shape and to some degree also on particle surface roughness and wetting conditions. The materials used in this study all had uniform particle size distributions, where the definition of particle size range (R) is straightforward. For materials with other types of particle size distributions, it is very likely that R needs to be redefined, for instance, as the range of particle diameters covering a given percentage of all particles present. To address these issues, however, additional measurements using a range of different materials with different particle shapes and distributions are required. The investigations presented in this paper were based on materials where no microbial biomass was present. As the presence of biomass affects the air flow characteristics of biofilter media, this issue has been addressed in Andreasen et al. (2012).

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