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Predicting the pressure drop of a biofilter and the specific surface area of the packing material

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ABSTRACT

An analytical pore-scale model is proposed for predicting the pressure drop of a biofilter by taking the effect of biofilm development into account. Besides the average particle radius and fluid parameters, the pressure drop is expressed in terms of the initial bed porosity, the biofilm affected porosity, particle sphericity, surface roughness coefficient, coordination number and biofilm thickness. The coordination number represents the number of particles in contact with a single one in the bed. The biofilm affected porosity is based on the assumption of biofilm overlap and particle contact. The sphericity for a cluster of particles in contact and biofilm overlap is quantified in terms of the biofilm thickness and coordination number and its effect on the pressure drop investigated. The model predictions are verified against experimental pressure drop data obtained from a biofilter in operation for 107 days. Expanded schist was used as packing material. The proposed model is also compared to a modified Ergun equation from the literature of which the empirical coefficients and porosity exponents were adjusted to be applicable to a biofilter. The model proposed in this study contains no empirical coefficients. An equation is also presented for predicting the biofilm affected specific surface area which requires the measured pressure drop and superficial velocity values as input parameters. The effect of the biofilm affected porosity on the pressure drop is also investigated in the case of no biofilm overlap and no particle contact. Lastly a sensitivity analysis is performed on the initial bed porosity and coordination number.

1. Introduction

Several pilot scale experimental studies have contributed to the design and optimal operating conditions of large-scale biofilters (e.g. Yang and Allen [1]). The major challenge remains in achieving the balance between the control of excess biomass generation and the optimal gas pollutant removal efficiency (Delhoménie et al. [2]).

Although it is possible to measure the biofilm thickness (by e.g. optical procedures (Cunningham et al. [3]) it remains a challenging task and one often has to revert back to mathematical models that can retrieve such information. Many authors have performed numerical simulations to model the hydrodynamic flow, mass transport and biochemical reaction processes involved in biofilter operation. The steady state and transient numerical models mostly deal with solving the continuum equations for mass transport and biochemical reaction (a summary of these models is provided by Delhoménie and Heitz [4]). More recently Jani and Dadvar [5], for instance, developed a numerical pore-network model based on 3D Monte Carlo simulations that can predict the pressure drop, biofilm thickness and clogging in a biofilter. Although the numerical studies add significant value to the field of biofiltration, the source codes are usually not available to the reader, which hampers direct comparison of models describing similar biofilter operating conditions performed by different authors.

Empirical models, on the other hand, result from curve fitting of experimental data through the introduction of empirical coefficients. An example of such a model, which is frequently used for steady-state momentum transport in granular porous media, is the Ergun equation (Ergun [6]) relating the pressure drop Δp over a packed bed of length L to the magnitude of the superficial velocity q, i.e.

$$\frac{\Delta p}{L} = \frac{150\,(1-\epsilon)^2}{\epsilon^3 D_p^2}\,\mu q + \frac{1.75\,(1-\epsilon)}{\epsilon^3 D_p}\,\rho q^2 \quad , \tag{1}$$

where ϵ is the porosity, D_p is the average particle diameter and μ and ρ are the fluid viscosity and density, respectively. Cunningham et al. [3], for instance, used a friction factor based on the Ergun equation to quantify the frictional resistance in their laboratory scale biofilter. Morgan-Sagastume et al. [7] changed the empirical coefficients of the Ergun

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equation of $A = 150$ and $B = 1.75$ to $A = 180$ and $B = 4$ as well as the porosity exponent from 3 to 3.6, thus yielding

$$\frac{\Delta p}{L} = \frac{180(1-\epsilon)^2}{\epsilon^{3.6} D_p^2}\mu q + \frac{4(1-\epsilon)}{\epsilon^{3.6} D_p}\rho q^2 \quad . \tag{2}$$

According to Macdonald et al. [8] the coefficient B depends on surface roughness which ranges from a value of 1.8 for smooth particles to 4 for particles with high surface roughness. Sagastume et al. [7] chose to work with the maximum roughness value of $B = 4$ for their biofilter filled with rough Nova inert packing material.

Delhoménie et al. [2] found that the Ergun equation significantly under-predicted their experimental pressure drop data obtained for a biofilter filled with compost. Following a similar curve fitting procedure as Morgan-Sagastume et al. [7], they adapted the porosity exponents from 3 to 6 to incorporate the experimental uncertainties in the biofilm affected porosity and introduced another empirical coefficient of $C = 0.9$ as a correction factor, i.e.

$$\frac{\Delta p}{L} = 0.9\left(\frac{150(1-\epsilon)^2}{\epsilon^6 D_p^2}\mu q + \frac{1.75(1-\epsilon)}{\epsilon^6 D_p}\rho q^2\right) \quad . \tag{3}$$

Iliuta and Larachi [9] used the Ergun equation in which wall effects are accounted for to describe the fluid-solid interaction in a biofilter, i.e.

$$\frac{\Delta p}{L} = \frac{150 C_w^2 a_s^2 (1-\epsilon)^2}{36\epsilon^3}\mu q + \frac{1.75 C_{wi} a_s (1-\epsilon)}{6\epsilon^3}\rho q^2 \quad . \tag{4}$$

Eq. (4) is expressed in terms of the specific surface area a_s (defined per solid volume) due to the significant role that it has in the biofiltration process. C_w and C_{wi} are the wall correction functions of the viscous and inertial terms, respectively (Liu et al. [10]).

The empirical coefficients introduced strictly apply to the specific experimental conditions under which they were determined. Should they correspond well to other data sets that were obtained under different operating conditions and packing material it is often difficult to explain the reason for this from a physical point of view. Although analytical models are in the minority and therefore less frequently used, they avoid the introduction of empirical coefficients. They can therefore be adapted from a physical point of view (i.e. based on physical reasoning by relaxing an assumption). One such model is the granular rectangular Representative Unit Cell (RUC) model of Du Plessis and Woudberg [11], given by

$$\frac{\Delta p}{L} = \frac{25.4(1-\epsilon)^{4/3}\mu q}{d_s^2\left(1-(1-\epsilon)^{1/3}\right)\left(1-(1-\epsilon)^{2/3}\right)^2} + \frac{(1-\epsilon)c_d\rho q^2}{2\epsilon d_s\left(1-(1-\epsilon)^{2/3}\right)^2} \quad , \tag{5}$$

where $d_s = D_p$ is the width of the solid cube in the RUC model and $c_d = 1.9$ is the form drag coefficient. Eq. (5) has been proven by Du Plessis and Woudberg [11] to be a theoretical derivation of the empirical Ergun equation (i.e. Eq. (1)). They have, in addition, expressed the empirical coefficients A and B as a function of porosity in order to give it physical meaning.

The aim of this study is to model the physical flow processes in a biofilter by adapting the analytical RUC model, given by Eq. (5). The pressure drop over a biofilter will be predicted by incorporating the sphericity, surface roughness and biofilm thickness in order to contribute to the understanding of the effect of biofilm development on the pressure drop over a biofilter. Special attention will be given to the effect of the particle sphericity on the pressure drop prediction as well as the assumption of biofilm overlap and particle contact versus no biofilm overlap and no particle contact. The equations to be proposed are suitable for use by other authors to validate their own model(s) and/or data.

2. Calculating biofilm affected porosity and biofilm thickness

Eqs. (2) and (3) are considered applicable to biofilters, as opposed to conventional packed beds, by the adjustment of the empirical coefficients and porosity exponents of the Ergun equation. The porosity at different stages of biofilter operation should be known to predict the pressure drop over time. In this study an alternative approach will be followed: In order to describe the physical flow phenomena in a biofilter by taking the effect of biofilm development into account, the porosity ϵ in Eq. (5) will be replaced with the biofilm affected porosity ϵ_f, taking the biofilm thickness into account. Since the experimental measurement of biofilm thickness is a challenging task (e.g. Hu et al. [12]), one often has to rely on predictive equations for the dependence of the porosity on the biofilm thickness for the determination thereof. Authors in the literature have followed different approaches in this regard. The differences between the modelling procedures lie in whether the packing material (regarded as spheres) are considered to be in contact or not and whether the biofilm surrounding neighbouring spherical particles is considered to overlap or not.

Based on a cubic packing of uniform spherical particles of diameter D_p, Cunningham et al. [3] calculated the biofilm affected porosity by making use of a proportionality relationship between the measured and theoretical porosity values. The theoretical biofilm affected porosity ϵ_{ft} (without taking any overlap of biofilm between neighbouring spheres into account) is given by:

$$\epsilon_{ft} = \frac{V_p}{V_t} = 1 - \frac{(\pi/6)(D_p + 2L_f)^3}{D_p^3} \quad , \tag{6}$$

where V_t is the total cubic cell volume with a linear dimension of $2D_p$ and V_p is the total solid volume equal to four spheres of diameter $D_p + 2L_f$, where L_f represents the biofilm thickness. The biofilm thickness was incorporated into the calculation of V_p but not in the cell size when calculating V_t. For a biofilter with no biofilm (i.e. $L_f = 0$) a theoretical porosity value of $\epsilon_{ot} = 0.476$ is obtained. It is noted that the latter value is a purely theoretical value and not practically observed in biofilters. The biofilm thickness then results from

$$L_f = \frac{V_f}{S_p} \quad , \tag{7}$$

where V_f is the volume of the biofilm (obtained from V_p by measuring the porosity before and after biofilm accumulation) and S_p is the total particle surface area inside the biofilter. The biofilm affected porosity is then calculated from the proportionality relationship given by

$$\frac{\epsilon_{fe}}{\epsilon_{oe}} = \frac{\epsilon_{ft}}{\epsilon_{ot}} \quad , \tag{8}$$

with ϵ_{oe} the measured initial bed porosity of the biofilter (i.e. the porosity of the packed bed containing no biofilm on the first day of biofilter operation) and ϵ_{fe} the measured biofilm affected porosity. Finally the biofilm affected porosity is given by

$$\epsilon_f = \epsilon_o\left(2.1 - \frac{(\pi/6)(D_p + 2L_f)^3}{0.476 D_p^3}\right), \tag{9}$$

by setting $\epsilon_f = \epsilon_{fe}$ and $\epsilon_o = \epsilon_{oe}$.

Morgan-Sagastume et al. [7] determined the biofilm thickness L_f with the formula

$$L_f = \frac{X}{\rho_f} \quad , \tag{10}$$

by using the superficial biofilm concentration values (denoted by X and measured in g biomass/m^2 surface area) and the biofilm density