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Analytical Determination of the Effect of Biofilm Growth on the Pressure Drop over a Biofilter

Sonia Woudberg[1], Jacoline van Jaarsveld[1], Eric Dumont[2]
[1]Stellenbosch University
Private Bag X1, Matieland, 7602, Stellenbosch, South Africa
woudberg@sun.ac.za; 16106741@sun.ac.za
[2]UMR CNRS 6144 GEPEA, L'UNAM, École des Mines de Nantes, La Chantrerie
4 rue Alfred Kastler, B.P. 20722, 44307 Nantes Cedex 3, France
Eric.dumont@mines-nantes.fr

Abstract - An existing analytical pore-scale model is adapted in order to predict the pressure drop over a biofilter. The difference compared to a conventional packed bed is the effect of biofilm growth that has to be incorporated. Being able to predict the pressure drop and also the specific surface area of the packing material over several days of biofilter operation, aids in the optimization of the biofiltration process. The proposed model is validated against available experimental data of a biofilter with schist as packing material. The data includes measured pressure drop values, flow rates and porosity for 7 different days over a 106 day period. Two methods are proposed to predict the biofilm affected specific surface area. The first method is based on a relationship available in the literature in which the biofilm thickness and biofilm affected porosity are incorporated into the biofilm affected specific surface area. A second method is proposed in which the specific surface area can be determined if measured pressure drop and superficial velocity values are provided. The analytical pressure drop prediction is compared to an empirically adapted model proposed in the literature, with satisfactory results. The advantage of the analytical model is that it can provide physical meaning to the adaptations made.

***Keywords*:** packed bed, permeability, pressure drop, specific surface area, biofilm, biofilter

1. Introduction

Biofiltration is an environmentally friendly process by which pollution can be controlled. A biofilter consists of a packed bed containing packing material and a thin layer of moisture. The packing material acts like a filter when a polluted air stream passes through the packed bed. The thin layer of moisture, known as biofilm, consists of living organisms that develop under optimized conditions. When contaminated gas is slowly being pumped through the biofilter it will come into contact with the moist biofilm layer. During this process the biofilm is responsible for consuming the biodegradable pollutants and biologically cleaning the polluted gas [1,2].

Morgan-Sagastume et al. [3] suggest the use of the following modified Macdonald equation in order to determine the pressure gradient $\Delta p/H$ over a biofilter, with H being the bed height:

$$\frac{\Delta p}{H} = A\frac{(1-\epsilon)^2}{\epsilon^{3.6}}\frac{\mu q}{D_p^2} + B\frac{(1-\epsilon)}{\epsilon^{3.6}}\frac{\rho q^2}{D_p} \tag{1}$$

Where $A = 180$, ϵ is the porosity, μ [Pa s] and ρ [kg m^{-3}] are the gas viscosity and density, respectively, D_p [m] is the particle diameter and q [m s^{-1}] the superficial velocity. The empirical coefficient $B = 4$ depends on surface roughness.

Dumont et al. [4] performed experiments involving the removal of hydrogen sulphide (H_2S) from the air stream within a biofilter, using schist as packing material. H_2S is a colourless highly toxic gas and therefore a risk to the health of humans. It is also highly flammable and can be explosive when mixed with the wrong type of gas. The treatment of a synthetic gas polluted with H_2S was carried out in a laboratory-scale biofilter (10 cm in diameter) filled with 3.97 kg of schist (0.87 m in height). Various concentrations of H_2S (up to 200 mg m^{-3}) were used to determine the biofilter performances. The packing material, i.e. expanded schist, was produced in Mayenne, France. It is a granular inorganic material obtained by the thermal expansion of schist. This expansion provides a large surface area which is used by

microorganisms to develop widely. Expanded schist was chosen due to its shape, its size distribution and its mechanical resistance. No attrition and no bed compaction were observed over 1 year in operating conditions [5,6] even under extreme acidic conditions [7]. As a result, it can be assumed that the change in porosity of the bed material over time is only due to the development of biofilm. The schist pieces are roughly round with an average diameter of 10 mm. The bulk density, the apparent density and the water retention capacity were 633 kg m^{-3}, 1120 kg m^{-3} and 6% respectively. The biofilter was inoculated with 3.76 g of sieved and washed activated sludge from the waste water treatment plant of Nantes, France. Apart from the polluted air (dynamic viscosity 1.8 10^{-5} Pa s; density 1.21 kg m^{-3}), no nutritive solution for feeding micro-organisms was introduced into the biofilter. H_2S treatment was operated continuously for 106 days and biofilter performances were quantified in terms of elimination capacity and removal efficiency. It appeared that expanded schist inoculated with activated sludge was a good material for H_2S biofiltration in terms of mechanical stability, removal efficiency and effective treatment of high H_2S loading rates at short empty bed residence time [4]. During biofilter operation, the pressure drop was measured on seven different days (i.e. 0, 19, 39, 57, 71, 92, 106) by five different sampling ports, vertically separated by a distance of 20 cm. The packed bed porosity ranged from 0.423 to 0.398 and the particle sphericity is $\varphi = 0.806$.

The aim of this study is to adapt an existing analytical pore-scale model [8] in order to incorporate the effect of biofilm growth on the pressure drop.

2. Predicting the Pressure Drop over a Biofilter

In this section, the existing analytical model is introduced. The adaptation of the existing model is discussed in order to predict the pressure drop as well as the specific surface area in which the biofilm thickness and biofilm affected porosity are incorporated. An alternative method is also discussed for predicting the biofilm affected specific surface area values.

2.1. Existing analytical model

Du Plessis and Woudberg [8] proposed an analytical geometric pore-scale model for granular porous media, referred to as the RUC (Representative Unit Cell) model, that serves as a theoretical derivation of the empirical Ergun equation. The model is based on rectangular geometry containing a single solid cube inside a cubic unit cell. The unit cell is representative of the average pore-scale geometry. The pressure gradient prediction as a function of the specific surface area a_0 is given by:

$$\frac{\Delta p}{Hq} = \frac{25.4\,\mu\,a_0^2}{36(1-\epsilon)^{2/3}(1-(1-\epsilon)^{1/3})(1-(1-\epsilon)^{2/3})^2} + \frac{1.9\rho\,q\,a_0}{12\,\epsilon\,(1-(1-\epsilon)^{2/3})^2} \tag{2}$$

Where the specific surface area is given by $a_0 = 6(1-\epsilon)/(\varphi\,D_p)$ with φ being the sphericity and D_p being the width of the solid cube. The model is applicable over a wide range of porosities and the entire steady laminar flow regime.

2.2. Adapted analytical model

Morgan-Sagastume et al. [3] proposed the following relationship between the biofilm affected porosity ϵ_f, and the biofilm thickness L_f, based on a single sphere in contact with neighbouring spheres, all covered with biofilm:

$$\epsilon_f = 1-(1-\epsilon_0)\left[\left(1+\frac{L_f}{\varphi\,R}\right)^3 - \frac{n}{4}\left(\frac{L_f}{\varphi\,R}\right)^2\left(2\frac{L_f}{\varphi\,R}+3\right)\right] \tag{3}$$

Where ϵ_0 is the initial bed porosity without biofilm, R is the radius of a sphere and n is the coordination number, representing the number of contact points between a sphere and its adjacent neighbouring spheres. Before obtaining the biofilm thickness from equation (3), the value of the coordination number n needs to be obtained by solving the roots of [9]:

$$\epsilon_0 = 1.072 - 0.1193n + 0.004312n^2 \tag{4}$$

The initial porosity for the biofilter used in this study is ϵ_0 = 0.4230 for which equation (4) yields a value of 7. By setting $x = L_f/\varphi R$, and then solving equation (3), after being rearranged as a third degree polynomial in x, the biofilm thickness can be obtained.

The biofilm affected specific surface area a_f can be calculated from [3]:

$$a_f = \frac{3(1-\epsilon_0)}{2\,\varphi\,R}\left[\left(1+\frac{L_f}{\varphi\,R}\right)\left((2-n)\frac{L_f}{\varphi\,R}+2\right)\right] \tag{5}$$

Rewriting equation (5) in terms of a_0 and introducing it into equation (2) leads to

$$\frac{\Delta p}{Hq} = \frac{25.4(1-\epsilon)^{\frac{4}{3}}\,\mu\,a_f^2}{9(1-\epsilon_0)^2\left(1-(1-\epsilon)^{\frac{1}{3}}\right)\left(1-(1-\epsilon)^{\frac{2}{3}}\right)^2}\left[\left(1+\frac{L_f}{\varphi\,R}\right)\left((2-n)\frac{L_f}{\varphi\,R}+2\right)\right]^{-2} + \frac{1.9\,\alpha\,(1-\epsilon)\,\rho\,q\,a_f}{6\,\epsilon\,(1-\epsilon_0)\left(1-(1-\epsilon)^{\frac{2}{3}}\right)^2}\times\left[\left(1+\frac{L_f}{\varphi\,R}\right)\left((2-n)\frac{L_f}{\varphi\,R}+2\right)\right]^{-1} \tag{6}$$

Equation (6) serves as the prediction of the pressure gradient divided by the magnitude of the superficial velocity provided by the adapted granular RUC model. It requires $\epsilon, \epsilon_0, \mu, \rho, R, \varphi, n, L_f, a_f, q$ and α as input parameters. The parameter α is introduced in order to account for surface roughness, similar to the coefficient B in equation (1). For this study $\alpha = 2$ is used since Morgan Sagastume et al. [3] also increased their roughness factor with about 2 (i.e. from 1.8 to 4).

2.3. Alternative approach for predicting the biofilm affected specific surface area

The specific surface area values can alternatively be obtained directly from the measured pressure drop and superficial velocity values. This is done by solving the second degree polynomial in a_f, obtained by rearranging the terms of equation (6) and retaining only the positive roots for each of the measured pressure drop and superficial velocity values. Determining the average value will then be the representative specific surface area value for that specific day of biofilter operation. This method may be used as alternative to obtaining the specific surface area values, should the pressure drop and superficial velocity values be known.

3. Results

Day 0 is used for "calibration" of the coefficient values (i.e. φ and α) in the RUC model, since the RUC model has proven to successfully predict pressure drops over isotropic granular porous media [8]. As a result, φ = 0.7 and α = 2 are used in the model predictions. Table 2 gives the values for the biofilm thickness L_f (obtained from equation (3)) and the specific surface area a_f obtained by the two methods proposed (i.e. from equation (5) in the second last column of Table 1 and from equation (6) in the last column of Table 1).

The values obtained for the biofilm thickness do not continuously decrease over time. This is due to the fluctuating measured porosity values which is expected to continuously decrease over time as the biofilm grows. The values for a_f are of the same order of magnitude as those given by Dumont et al. [4] in their Table 2, and are observed to differ less over the period of biofilter operation. The specific surface area values obtained by the two methods also show satisfactory correspondence.

Table 1: Biofilm thickness and specific surface area values for each day for φ =0.7.

Day	Porosity	L_f (m) (from eq. (3))	a_f (m^{-1}) (from eq. (5))	a_f (m^{-1}) (from eq. (6))
0	0.4230	-	495	495
19	0.3880	1.47×10^{-4}	472	458
39	0.4050	7.49×10^{-5}	483	561
57	0.4090	5.81×10^{-5}	486	588
71	0.4110	4.98×10^{-5}	487	550
92	0.3920	1.30×10^{-4}	474	476
106	0.3980	1.04×10^{-4}	479	573

The value of the coordination number n calculated in this study is 7, in other words, there are 7 spheres in contact with a single sphere. The sphericity of such a structure can be calculated as $\varphi = 0.5$. For this calculation R = 0.01/2 was used together with the average computed value of 93.9 μm for L_f (obtained from Table 1).

Figure 1 shows the pressure drop prediction for Day 39 (left figure) and Day 92 (right figure) for sphericity values of 0.8 (experimentally measured value) and 0.5 (calculated for the cluster of spheres). The enclosure of the empirical model and experimental data by the model predictions in each subfigure is satisfactory.

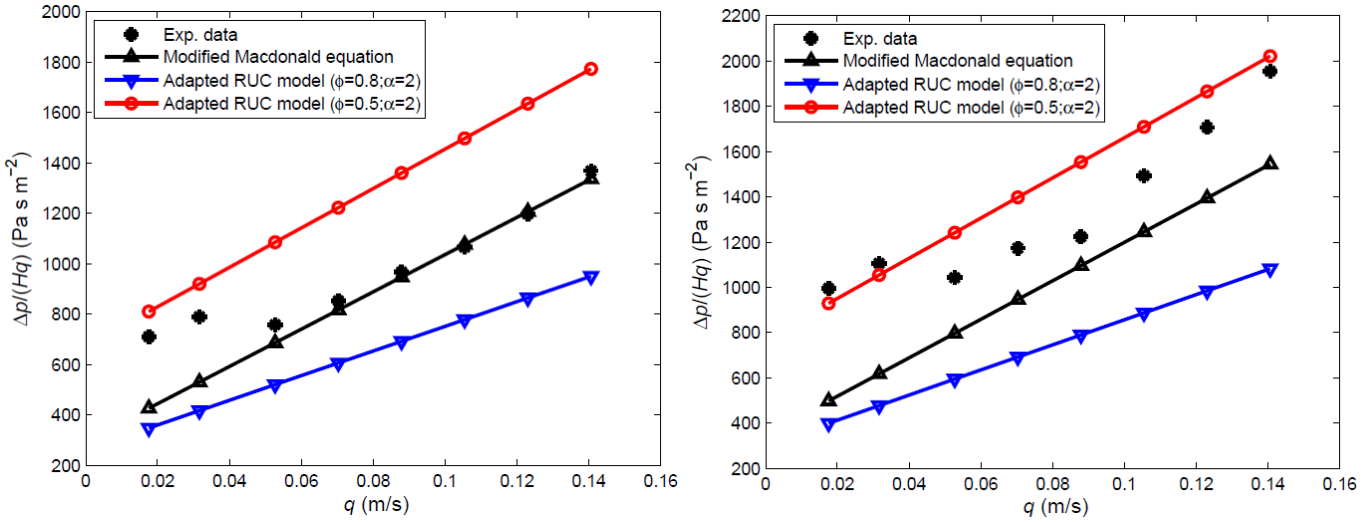

Fig. 1: Pressure drop prediction for Day 39 (left) and Day 92 (right).

The biofilm thickness L_f (though equation (3)), the coordination number n (through equation (4)) and the specific surface area (given by equation (5)) all depend on the value of the initial bed porosity ϵ_0. According to Dumont et al. [4], an experimental error range of 1% is associated with the measured porosity values. It is therefore worthwhile to perform a sensitivity analysis to determine the effect of a 1% error in ϵ_0 on the values obtained for L_f and a_f. Figure 2 shows the effect of a 1% error range in ϵ_0 on the values obtained for a_f (left) and L_f (right). The effect of a 1% difference in ϵ_0 on a_f decreases with an increase in porosity, i.e. a 1% difference in ϵ_0 on a_f at $\epsilon = 0.3880$ leads to $a_f = 471 \pm 7$ m^{-1} whereas a 1% difference in ϵ_0 on a_f at $\epsilon = 0.4230$ leads to $a_f = 495 \pm 4$ m^{-1}. A 1% difference in ϵ_0 on the values obtained for L_f leads to a difference of approximately 0.2×10^{-4} in the value of L_f. The effect of a 1% error in the value of the particle radius R on both a_f and L_f was also investigated but was found to be negligible in comparison to the effect of a 1% error in ϵ_0. The latter value therefore has to be measured with precision in order to obtain reliable model predictions for the biofilm thickness and specific surface area.

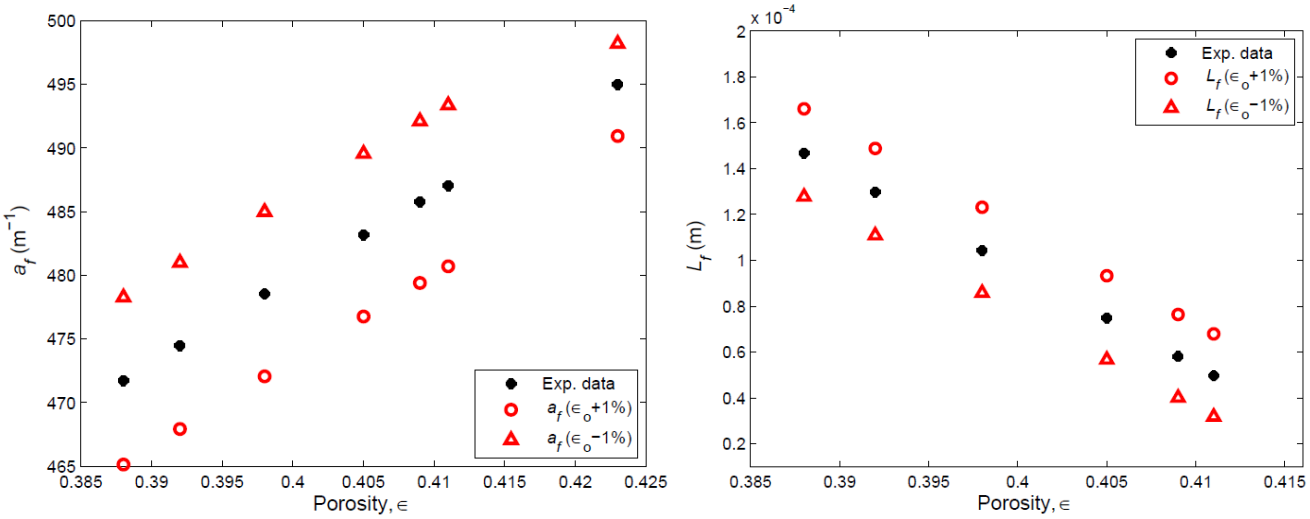

Fig. 2: Effect of a 1% error range in ϵ_0 on a_f (left) and L_f (right).

4. Conclusions

The existing granular RUC model is adaptable to predict the pressure drop over a biofilter by incorporating the biofilter thickness as well as the biofilm affected porosity into the equation for the specific surface area for the packing material. The sphericity is included as well as a coefficient that accounts for particle roughness. Alternatively the specific surface area for each day of biofilter operation can be predicted if the experimental pressure drop and superficial velocity data is available. The biofilm affected specific surface area values obtained by the two methods show satisfactory correspondence. The pressure drop predictions for different sphericity values also satisfactory enclose the experimental data and empirical model prediction. The model predictions prove to be sensitive to the value of the porosity of the bed without biofilm. The advantage of the proposed analytical model above that of the empirically modified model of Macdonald is that the proposed model can provide physical meaning to the adaptations made.

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