Influence of air flow rate and backwashing on the hydraulic behaviour of a submerged filter
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ABSTRACT

The aim of this study was to evaluate backwashing effects on the apparent porosity of the filter media and on the hydraulic behaviour of a pilot scale submerged filter, prior to biofilm colonization, under different hydraulic retention times, and different air flow rates. Tracer curves were analysed with two mathematical models for ideal and non-ideal flow (axial dispersion and Wolf and Resnick models). The filter media was lava stones sieved to 4.5 mm. Backwashing causes attrition of media particles, decreasing the void volume of the filter media and, consequently, the tracer flow is more uniform. The eroded media presented lower dead volumes (79% for the filter with aeration and 8% for the filter without aeration) compared with the new media (83% for the filter with aeration and 22% for the filter without aeration). The flow patterns of eroded and new media were different because the more regular shape of the particles decreases the void volume of the filter media. The dead volume is attributed, in the case of the filter with aeration, to the turbulence caused by the air bubbles that generate preferential channeling of the bulk liquid along the filter media, creating large zones of stagnant liquid and, for the filter without aeration, to the channels formed due to the irregular shaped media.

Key words | hydraulic behaviour, lava stones, mathematical models, submerged biological filter, tracer studies

INTRODUCTION

Uniformity and effective contact between substrate and biomass in a biological filter play an important role in its performance and behaviour. These parameters are conditioned by liquid mixing and have an effect in bioreactor performance. Factors such as water flow, air flow rate, packed media shape and morphological characteristics, and filter porosity also affect the flow pattern in the system (Smith et al. 1996; Nabizadeh et al. 2000; Escudié et al. 2005; Tembhurkar & Mhaisalkar 2006; Fatihah & Donelli 2008).

The hydraulic characteristics of bioreactors containing fixed biofilms are commonly analysed using tracers to determine the residence time distribution (RTD) of the liquid (Wolf & Resnick 1963; Smith et al. 1993, 1996; Morgan-Sagastume et al. 1997; de Nardi et al. 1999; Escudié et al. 2005). To describe the deviations from the ideal completely mixed reactor (CMFR) or ideal plug flow reactor (PFR), several reactor models have been developed. Deviation from ideal behaviour of PFR or CMFR can be caused by channeling of the fluid or presence of slow moving regions in the reactor due to recirculation or stagnant pockets of fluid (Levenspiel 2012; Fatihah & Donelli 2008). Hydraulic short circuits affect the hydrodynamic behaviour of reactors originating ‘dead volumes’ (Morgan-Sagastume et al. 1997; Fatihah & Donelli 2008) decreasing the reactor’s effective volume and, as a result, the real hydraulic retention time (HRT) and efficiency decrease proportionally (Morgan-Sagastume et al. 1997).

Different types of models may be used to describe non-ideal flow within reactors. The most widely used model for tubular reactors is the axial dispersion model (Smith 1981; Turan & Ozturk 1997; Levenspiel 2012). This model describes mass transport in the axial direction in terms of an effective longitudinal dispersion coefficient ($D_L$). By changing the magnitude of this single parameter, the performance of reactors ranging from an ideal PFR ($D_L = 0$) to ideal CMFR ($D_L = \infty$) can be described (Smith 1981; Smith et al. 1993; Morgan-Sagastume et al. 1997, 1999; Levenspiel 2012).
Although the role of media-related factors on filter performance has been widely investigated and there is abundance of literature on the topic of packed bed reactor hydraulics, limited studies have been conducted to examine the hydraulic behaviour of submerged biofilters in their startup phase or prior to biofilm colonization of the filter media. The aim of this study was to evaluate the backwashing effects on the apparent porosity of irregularly shaped media in a filter and the hydraulic behaviour prior to biofilm colonization under different hydraulic retention times and different air flow rates.

**MATERIALS AND METHODS**

**Pilot filter**

In order to visually document what happens inside the filter, a pilot filter was made from 15 cm square glass sheets and packed with lava stones. The effluent orifice was placed 15 cm above the upper stone layers (Figure 1) and a diffuser was placed under the lava stones at the bottom. Table 1 presents the filter’s main characteristics.

![Figure 1](image)

**Table 1 | Pilot submerged filter characteristics**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total height</td>
<td>1.90 m</td>
</tr>
<tr>
<td>Effective volume</td>
<td>15.6 L</td>
</tr>
<tr>
<td>Filter bed depth</td>
<td>1.0 m</td>
</tr>
<tr>
<td>Total volume</td>
<td>22.5 L</td>
</tr>
</tbody>
</table>

**Packing bed material**

In addition to its availability and price, their high porosity, roughness and specific area, make lava stones ideal as filter media. Lava stones sieved to 4.7 mm (between 4.0 and 4.75 mm) were used as filter media (Figure 2 and Table 2). This size was selected based on the work of Mendoza-Espinoza & Stephenson (1999) and Moore et al. (2001) who suggest that the media size has a strong influence on process performance and so recommend smaller particle sizes, presenting a greater exposed surface area for biofilm formation.

**Tracer tests**

Direct Blue 2, diazo dye (\(\lambda = 598\) nm), was used as tracer. During the 2 days before the beginning of the tracer studies, the filter material was exposed to the tracer to evaluate possible adsorption; no change in the colour of the filter media was observed and the azo dye concentration did not change during this test, leading to the conclusion that the...
Azo dye is not adsorbed by the lava stones. The excess dye was washed out with tap water until only tap water filled the void volume and, at the beginning of the tests (time = 0), the tracer solution was continuously pumped from the bottom of the filter. The dye concentration at the effluent was determined with a spectrophotometer.

Considering an effective volume (apparent porosity) of 15.6 L, influent flow rates were adjusted to achieve a theoretical hydraulic retention time (HRT) of 4.5 h (269 min), which is common for biological aerated filters (Mendoza-Espinoza & Stephenson 1999). The tracer tests were performed for two cases: (1) with new media (originally packed) without and with aeration ($Q_{air} = 10$ L/min); and (2) with eroded media using different air flows (0, 2, 4, 6, 10 L/min) after 60 backwashing procedures. Because the lava stones are too heavy to achieve a bed expansion with conventional procedures, backwashing was performed as described by Humby & Fitzpatrick (1996) using pulses. After 60 backwashing procedures, it could be observed that the particle edges were smoother, that the particles had less irregular shapes and presented a better distribution in the filter.

**Mathematical models**

The experimental curves were analysed considering two different mathematical models for non-ideal reactors and the Excel Solver was used to fit the experimental data.

**Axial dispersion model**

This model considers the deviation from plug flow ideal behaviour due to longitudinal dispersion that may occur along the filter bed. For an ideal plug flow reactor, the dispersion coefficient is zero (0) and for an ideal completely mixed flow reactor, it is infinite (∞) (Equation (1)) (Smith 1981; Levenspiel 2012).

\[
\left( \frac{C}{C_0} \right) = 1 - \text{erf}\left( \frac{1}{2} \sqrt{\frac{uL}{D_L}} \frac{1 - t/t_0}{\sqrt{t/t_0}} \right)
\]

(1)

where: $C_0 =$ Tracer maximal (influent) concentration, $C =$ Tracer in the effluent at any given time, $t_0 =$ Theoretical residence time, $t =$ Time, $D_L/uL =$ Dispersion coefficient.

Dispersion is the general concept used to describe the velocity differences (distribution) that can take place when a liquid flows through a reactor. The effects of dispersion are particularly important in packed bed reactors. Neglecting the fluid dispersion may result in inefficient transport of substrate through the reactor and an inaccurate estimation of effective volume of the system (Turan & Ozturk 1997).

**Wolf and Resnick model**

This model considers that a real system (non-ideal) may behave as a combination of plug flow and completely mixed flow containing a dead volume which, combined, affect the reactor's hydraulic behaviour. The fractions corresponding to these flow types and the dead volume can be estimated using this model (Equation (2)).

\[
\left( \frac{C}{C_0} \right) = 1 - \text{EXP}\left[ -\left( \frac{1}{(1-p)(1-m)} \right) \frac{t}{t_0} - p(1-m) \right]
\]

(2)

Here the term $(1-p)$ represents the fraction of non-plug flow and $m$ the dead volume. Modifying Equation (2) results in Equation (3):

\[
\log\left( \frac{1 - C}{C_0} \right) = \left( \frac{-\log e}{(1-p)(1-m)} \right) \frac{t}{t_0} - p(1-m)
\]

(3)

This equation can be represented graphically as a straight line where $(1 - C/C_0)$ represents the fraction of tracer that remains in the system as a function of the relative time $(t/t_0)$. The slope is $\log e/(1-p)(1-m)$ and, using this value and Equations (4) and (5), the plug flow ($P$), complete mixed flow ($M$) fractions and the dead volume ($m$) can be calculated.

\[
P = p(1-m)
\]

(4)

\[
M = (1-p)(1-m)
\]

(5)

**RESULTS AND DISCUSSION**

**Tracer tests**

Figure 3 shows the tracer curves for new and eroded media. For the test with new media (dotted lines) and aeration, the tracer appears in the effluent within a few minutes after the beginning of the test and it displaces the entire effective volume before reaching the theoretical HRT. This curve has a linear behaviour indicating that the tracer concentration in the effluent increases linearly with time. Without
aeration, the tracer has a radically different behaviour compared to the test with aeration.

The tracer curves, obtained under different air flow rates (2 to 10 L/min, Figure 3), present the same behaviour, indicating that the air flow rate is not a variable that is important to the hydraulic behaviour of the system and that air flow rate is not a possible cause for deviations from ideal flow.

The linear behaviour of the new media ‘curve’ indicates that the liquid replacement in the filter can be completely achieved in less time than expected when the reactor is considered completely mixed under a constant replacement rate.

In the filter without aeration, channelling of the tracer was visually observed. These channels allow that, in specific places, the tracer flows faster than in most of the packing bed, causing deviations from ideal plug flow reactor behaviour. In the filter with aeration, the turbulence provided by the air bubbles is the cause for the formation of stagnant zones of fluid and does not provide a homogeneous mixing along the filter media; the tracer leaves the filter in a shorter time than the theoretical HRT. Tracer curves for both cases indicate that there is a reduction of the effective volume of the filter as a result of channelling and the volume occupied by the air bubbles. To avoid the formation of the same channels between tests, backwashing of the filter was performed every day to redistribute the particles inside the filter bed.

Backwashing procedures expose the filter media particles to continuous hits against each other and against the filter walls, causing rounding of the edges and reducing surface irregularities (Figure 2); the particles resulting after many backwashing procedures are slightly smaller than the parent particles (Humby & Fitzpatrick 1996). Backwashing also causes the reduction of the apparent porosity of the eroded media (50%), compared with the new one (54%). Channelling of the fluid in the eroded media was less visible than in the new media. Comparing the tracer curves for the new filter media with the media after repeated backwashing (eroded media), it can be concluded that erosion of the filter particles caused by backwashing procedures influences particle geometry, filter media porosity and, as consequence, flow patterns. The tracer remains longer in the eroded filter media than in the newly packed bed for both conditions, without or with aeration.

**Axial dispersion model**

The experimental data used to construct Figures 4(a) and 4(b) was adjusted using the axial dispersion model to calculate the HRT, effective volume and dispersion coefficient. In Figures 4(a) and 4(b), \( C/C_0 \) is the tracer concentration (C) at any chosen time divided by the initial tracer concentration (\( C_0 \)). For the experimental data, \( t \) is the time at any chosen value and \( t_0 = V/Q \), where \( V \) is the void volume measured in the lab and \( Q \) is the liquid flow. For the modelled curves, \( t_0 \) is calculated solving the axial dispersion model for \( V \), which is, in this case, the effective volume. The ‘dead’ volume results from subtracting the effective volume from the experimentally measured void volume. The dotted line in Figures 4(a) and 4(b) represents the axial dispersion model for the filter with and without aeration for the calculated dispersion coefficients.

![Figure 3](https://iwaponline.com/wst/article-pdf/68/9/2000/472472/2000.pdf)  
**Figure 3** | Tracer curves for new and eroded media at different air flow rates.

![Figure 4](https://iwaponline.com/wst/article-pdf/68/9/2000/472472/2000.pdf)  
**Figure 4** | Experimental and modelled tracer curves, using the axial dispersion model, before and after backwashing. (a) Without aeration, (b) with aeration.
Figures 4(a) and 4(b) present the experimental and modelled tracer curves for HRT = 269 min. For the filter without aeration containing the new media, the tracer begins to appear at \( t/t_0 = 0.4 \); in contrast, with the eroded media, the tracer appears at \( t/t_0 = 0.6 \). Finally, the tracer reaches its maximum value in the new media earlier than in the eroded media. The model shows that the tracer should not appear in the effluent (for both filter media) until \( t/t_0 = 0.85 \) and reach its maximum until \( t/t_0 = 1.2 \). The differences between observed and theoretical concentrations indicate that the tracer begins to leave the system earlier than expected due to channelling in the media and that there is a reduction in the effective volume of the filter for both packed media (eroded and new).

Figure 4(b) shows that, for the filter with aeration, there is a significant difference between theoretical and experimental times \( (t/t_0) \). For both new and eroded media, the tracer exits the filter in much shorter time than calculated with the axial dispersion model. The experimental data show that the tracer begins to appear in the effluent a few minutes after starting the test (for both new and eroded media) while the model shows that, at \( t/t_0 = 1.0 \), approximately 50% of the tracer concentration should appear in the effluent.

In Figure 4(b), the modelled curve for the eroded media shows better correlation than the curve for the new media. The modelled curve for the new media shows good correlation until \( t/t_0 = 1.3 \) and, after this, the curve deviates from the predicted path and it does not follow the model due to the lower effective volume. Flow patterns of eroded and new media were different because backwashing (1) causes attrition of the particle surface, reducing the edges to a more regular shape, (2) decreases the void volume of the media, (3) improves the particle size distribution (Fitzpatrick 1998) and, consequently, a more homogeneous flow through the filter bed is obtained.

Table 3 shows the effective volumes calculated for the filter without and with aeration. For both new and eroded filter media, the calculated effective volumes are lower than the theoretical effective volume of the filter (void volume of filter media = 15.6 L). Despite the visual differences between the hydraulic behaviour of new and eroded media observed in Figure 3, it was possible to determine that, for both media, the dispersion coefficient was the same (Table 3).

The effective volume of eroded media in the filter without aeration (15 L) is larger than that of the new media (13 L), indicating that the eroded media presents less dead volume (4%) than the filter with the new media (22%). The dead volume fractions, for new and eroded media, in the filter without aeration were estimated using the same dispersion coefficient of 0.003. Similarly, for the filter with aeration, the effective volume for eroded media is larger (4.0 L) than for new media (2.6 L) estimated using the same dispersion coefficient of 0.38. The eroded media presented less dead volume (74%) than the new media (83%).

It was observed that the filter with aeration presents a higher dispersion value \( (D_L/uL = 0.38) \) than the filter without aeration \( (D_L/uL = 0.003) \). As suggested by Martinov

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Filter with aeration</th>
<th>Filter without aeration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated HRT (min)</td>
<td>46</td>
<td>230</td>
</tr>
<tr>
<td>Calculated effective volume (L)</td>
<td>2.6</td>
<td>13</td>
</tr>
<tr>
<td>Dispersion coefficient (−)</td>
<td>0.38</td>
<td>0.003</td>
</tr>
</tbody>
</table>

Figure 5 | Tracer curves fitting to the Wolf and Resnick model before and after backwashing. (a) Without aeration, (b) with aeration.
et al. (2010), the degree of axial dispersion is influenced significantly by aeration. Based on the dispersion coefficient, for the filter without aeration, the hydraulic behaviour reflects more closely a plug flow reactor (Figure 4(b)). The observed dispersion coefficients are in the range between 0.002 and 0.005, which indicate an intermediate dispersion in the reactor according to the values reported by Tembhurkar & Mhaisalkar (2006) and Tay & Show (1998).

Wolf and Resnick model

Figures 5(a) and (b) show the experimental data for both filters, without and with aeration, and for both filter media, new and eroded. In these same figures, the curves resulting from the Wolf and Resnick model are also shown. Contrary to the axial dispersion model, the Wolf and Resnick model does not allow a ‘better fitting’ of the experimental results. The experimental data are introduced in the model and the obtained coefficients define the resulting curves (see the mathematical model in Table 4 and the modelled curves in Figures 5(a) and 5(b)).

Table 4 shows the estimated flow types, dead volume fractions and the mathematical expressions that describe the hydraulic behaviour of the filter, with and without aeration, for new and eroded filter media. The filter without aeration has a predominantly plug flow behaviour while the filter with aeration has a predominantly complete mixed flow behaviour with a higher fraction of dead volume.

The filter with new media and aeration presents a much higher dead volume (83%) than the filter without aeration (19%). Short circuiting and high dead volume in the filter with new media result from the irregular particle distribution inside the filter. Backwashing is the cause for rounding of the particle edges and, consequently, better distribution inside the filter where the void and dead volumes decrease. However, the filter with aeration presents a higher dead volume fraction (79%) than the filter without aeration (8%).

At the beginning of the experiment, gas hold up was considered to be the main cause for the large dead volume in the filter with aeration. Gas hold up was determined as the difference of the water volume inside the filter without and with aeration; in the case of new media, the air volume inside the filter was 6%, and 5% in the case of the eroded media. These values indicate that the volume occupied by air is not the main cause for the effective volume reduction. Based on Figure 4(b), the tracer concentration inside the filter with aeration increases almost linearly with time indicating effective mixing inside the filter and along the filter height; this mixing is considered to be the cause of the dead volume as described by the models.

In the filter without aeration, the dead volume zones are attributed to the channelling of the fluid due to irregularities of the filter media. The channelling and dispersion of the tracer was higher in the filter with new media than the one with eroded media.

CONCLUSIONS

Backwashing causes rounding of the particle edges, resulting in better fluid distribution and decreasing dead volumes in the filter. In both cases, without and with aeration, the hydraulic retention times with the new media are shorter than with the eroded one. Different air flow rates did not significantly affect hydraulic behaviour inside the filter.

Formation of ‘channels’ during the tracer tests was observed. Through these channels, or preferential paths, in both new and ‘rounded’ particles, the fluid flows faster than in the rest of the bulk, making the tracer appear in the effluent shortly after beginning the tests. The fluid is replaced in the filters in a much shorter time than estimated.

With aeration, the new media allows constant fluid replacement in the filter; with the eroded media, the fluid follows a more predictable behaviour according to the theoretical models. Short circuiting and high dead volume in the
filter with new media result from the irregular particle distribution in the filter. In the filter without aeration, dead volume zones are attributed to the channelling of the fluid due to the irregularities of the filter media. The channelling and dispersion of the tracer was higher in the filter with new media than the one with eroded media.

Although the axial dispersion model does not consider the influence of dead volume zones, these can be calculated as the difference between the effective experimental and calculated volumes.

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REFERENCES


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