Effect of full and partial-bed configuration on carbon removal performance of biological aerated filters
Fatihah Suja and Tom Donnelly

ABSTRACT
A comparative study to explore the characteristics of partially and fully packed biological aerated filters (BAFs) in the removal of carbon pollutant, reveals that the partial-bed reactor can perform comparably well with the full-bed reactor. The organic removal rate was 5.34 kg COD m\(^{-3}\) d\(^{-1}\) at Organic Loading Rates (OLR) 5.80 ± 0.31 kg COD m\(^{-3}\) d\(^{-1}\) for the full-bed, and 5.22 kg COD m\(^{-3}\) d\(^{-1}\) at OLR 5.79 ± 0.29 kg COD m\(^{-3}\) d\(^{-1}\) for the partial-bed. In the partial-bed system, where the masses of biomass were only 41–51% of those of the full-bed, the maximum carbon removal limit was still between 5 to 6 kg COD m\(^{-3}\) d\(^{-1}\). At organic loadings above 5.0 kg COD m\(^{-3}\) d\(^{-1}\), the carbon removal capacity in both systems was limited by the mass and activity of microorganisms. The SRT in the full and partial-bed reactors was primarily controlled by the biomass loss in the effluent and during backwash operation. The SRT was reduced from 20.08 days at OLR 4.18 ± 0.20 kg COD m\(^{-3}\) d\(^{-1}\) to 7.62 days at OLR 5.80 ± 0.31 kg COD m\(^{-3}\) d\(^{-1}\) in the full-bed, and from 7.17 days to 4.21 days in the partial-bed. After all, SRT values in the partial-bed were always lower than those in the full-bed.

Key words | biofilm, biological aerated filters, carbon removal, suspended growth biomass

LIST OF SYMBOLS

- \(\varepsilon_{aw}\): porosity after backwash
- \(\varepsilon_{bw}\): porosity before backwash
- \(\varepsilon_{cb}\): clean bed porosity
- \(\varepsilon_{o}\): porosity during operation
- \(m_{wb}\): masses of washed biofilm
- \(N_m\): number of media
- \(\theta_c\): sludge retention time
- \(\theta_h\): hydraulic detention time
- \(S_e\): effluent substrate concentration
- \(SS_{eff}\): suspended solids concentrations in the effluent
- \(V_b\): biofilm volume
- \(V_c\): volume collected
- \(V_m\): media volume
- \(V_s\): media specific volume
- \(V_{SS}\): suspended biomass volume
- \(V_{pb}\): packed bed volume
- \(V_T\): total volume
- \(V_{vl}\): void volume filled with liquid
- \(X\): biomass concentration
- \(Y\): biomass growth yield

INTRODUCTION
In the past, there has been considerable work on biological aerated filters (BAFs) focused on the optimisation of their design and operation (Le Tallec et al. 1999; Mann et al. 1999; Moore et al. 2001). However, this has left a gap in understanding the role of the attached and suspended biomass in the reactor. Insights on such related matters might offer cost reduction opportunities giving the BAF process wider applicability.

The solid phase that acts as the support medium for biofilm growth is still a subject of much debate. A high media surface area would seem to be desirable in packed...
bed applications to maximize the active biomass in the form of a biofilm. The presence of more biomass might be expected to result in the ability of the reactor to remove higher rates of organic loads per unit volume. However, several research findings have revealed that increase in biofilm mass does not necessarily improve the performance efficiency of fixed bed reactors. Young & Dahab (1982) and Song & Young (1986) noted that COD removal was not directly related to the media specific area. A significant portion of the active biomass is present, not as attached film, but as unattached dispersed growth in the interstices (voids) of the medium. This is in accordance with the results obtained by Show & Tay (1999), who detected that doubling the media surface in an anaerobic reactor shows only less than 5% improvement in COD removal. The above findings led to the concept of reducing the amount of media packed in the BAF thereby creating a hybrid BAF.

A new breed of reactor with less media is expected to reduce its capital and operational costs. In BAF, not only that, the costs of the media contributes a significant portion of the initial capital outlay (Kent et al. 1996), but also a large surface area of media leads to a higher accumulation of biofilm, and so more aeration is needed for endogenous decay of biomass. A high media volume also means that more energy is lost to frictional forces that, in return, can reduce the mixing intensity in the reactors. In addition, higher washing rates are needed to provide shear forces to dislodge the clogging biofilm. These require high-rate pumping facilities and add to the energy usage. Rogalla & Sibony (1992) noted that backwashing could account for up to 15–20% of the total daily energy consumption in a full-scale BAF. An increased in the amount of biofilm that needs to be backwashed also adds to the cost of solids management.

To fully measure the success of a design, Metcalf and Eddy (1991) concentrated on monitoring plant performance either in terms of effluent quality or of the percentage removal obtained from the constituents of concern. Of primary importance is to look at the effects on carbon removal characteristics as it is the major target for almost all wastewater treatment processes. The reduced media volume would also affect the distribution of both cultures in the reactors. This study is therefore looking at the COD removal performance of biological reactors with different media volume.

Theoretical considerations

In terms of substrate removal, the rate of carbonaceous oxidation depends on the rate of microbial growth. It is well known that the growth rate of a population is affected by the availability of nutrients and increases indefinitely to a maximum specific growth rate with increasing substrate availability (Horan 1990).

Theoretically, the efficiency of a reactor will be increased as the biomass concentration is increased. Nevertheless, in heterogeneous reactors, the increase in biomass concentration may represent an increase in the biofilm depth, thus resulting in increased solid-phase mass transfer resistance. Therefore, the increase in biomass concentration may represent a problem to the system. The improvement in organic matter removal efficiency will not be a direct relationship as postulated. In mixed growth reactors in which the biomass is suspended and attached, the phenomena are more complex.

MATERIALS AND METHODS

Reactor operation

The experimental apparatus and backwashing scheme of the reactor is explained in Fatihah & Donnelly (2008). Activated sludge and settled sewage obtained from a local municipal wastewater treatment plant were used for the seeding. To facilitate microbial adhesion and to prevent washout of bacteria after inoculation, the system was placed on a full internal recycle for 7 days before starting to feed the reactors. During this period, the reactor was run as a batch process. A volume of 1L synthetic feed with 500 mg l⁻¹ COD concentration was fed daily to the reactor to keep the biomass sustained. Daily monitoring of pH and DO was carried out to ensure that conditions for biomass growth were maintained. The pH was kept at around 7 by adding 1 N NaHCO₃ solution to the feed when necessary. The DOs in the reactors were kept at 2 to 4 mg l⁻¹ by means of flowmeters to ensure that the process is not oxygen limited. However, since online monitoring facilities were not available, the DO measurement was only made once a day.

After completing a seven-day recycle with activated sludge, the reactors were subsequently fed at a very low
organic loading rate (OLR) of 0.5 kg COD m$^{-3}$ d$^{-1}$. This was to allow acclimatization of biomass to the new environment with minimal organic and hydraulic stresses during the sensitive start-up period. The influent COD concentration was around 2,000 mg l$^{-1}$ corresponding to a TOC value of 800 mg l$^{-1}$. During this period, the reactor was not backwashed, again in order to promote a stable growth of biofilm without any disturbance.

After the start-up, the reactors were operated in parallel at the same hydraulic and organic loading rates. Step-increased loadings were achieved by increasing the flowrate of the influent. The range of flowrates used were 3.30 l d$^{-1}$ to 43.20 l d$^{-1}$. Table 1 lists the applied loadings and backwash procedures used in the study.

For each step loading, the influent and effluent of the reactor were analysed during the period of unsteady and steady-state operations. However, for determining the removal rates, the reactors were operated until a steady-state performance was reached, as indicated by constant effluent TOC concentrations (within 5% fluctuation of the values). Backwashing of the filters was carried out on an elapsed time basis with a frequency of once every two or three days. The feed strength was determined with a spot sample every day. The effluent samples were collected 1–4 hours before backwashing operation.

**Sludge retention time (SRT) determination**

SRT is determined as the total amount of sludge solids in the reactor divided by the rate of sludge loss from the reactor (Gray 1989). In the full- and partial-bed reactors, the amount of solid loss was based on the amount of suspended biomass lost in the effluent and the biomass lost due to backwashing operation. The sludge retention time was then determined by the following equation:

$$\text{Mean SRT} (d) = \frac{A}{B + C}$$

where $A$ is total reactor biomass before backwashing; $B$ is mass lost due to backwashing divided by the number of days since last backwash and $C$ is average daily mass lost in treated effluent.

Total reactor biomass before backwashing comprised of the amount of biofilm and suspended growth in the reactors. Measurement of this retained biomass was only made at the end of a steady-state period of a specified loading when all other experiments related to that loading were completed. The amount of biofilm in the reactors was quantified according to the reactors' porosity and the solids loss during backwashing operation.

Porosity is a measure of the fraction of the space between solid particles in the bed compared to the space the particles themselves take up. Porosity of a packed bed can be assessed experimentally. For a clean bed, the formula is

$$\varepsilon_{cb} = \frac{[V_T - (N_m \times V_S)]}{V_T}$$

The specific volume of the media was determined by measuring the increase of water volume in a cylindrical column due to the insertion of known pieces of media. Thus, the specific volume of a media is simply the increase in liquid volume divided by the number of media used.

**Table 1 | Applied organic loadings and backwash procedures for the full and partial-bed reactors**

<table>
<thead>
<tr>
<th>Flow rates</th>
<th>OLR (kg COD m$^{-3}$ d$^{-1}$)</th>
<th>Partial-bed</th>
<th>Backwash Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Full-bed</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.04</td>
<td>1.42 ± 0.06</td>
<td>1.49 ± 0.07</td>
<td>2 min air at 5 l min$^{-1}$</td>
</tr>
<tr>
<td>13.39</td>
<td>2.25 ± 0.15</td>
<td>2.30 ± 0.15</td>
<td>3 min air at 5 l min$^{-1}$ + water at 4 l min$^{-1}$</td>
</tr>
<tr>
<td>19.57</td>
<td>3.35 ± 0.22</td>
<td>3.35 ± 0.22</td>
<td>2 min rest</td>
</tr>
<tr>
<td></td>
<td>2 min water at 4 l min$^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24.20</td>
<td>4.18 ± 0.20</td>
<td>4.19 ± 0.18</td>
<td>3 min air at 40 m$^3$ m$^{-2}$ h$^{-1}$</td>
</tr>
<tr>
<td>32.40</td>
<td>5.80 ± 0.31</td>
<td>5.79 ± 0.29</td>
<td>(12 l min$^{-1}$) and water at 24 m$^3$ m$^{-2}$ h$^{-1}$</td>
</tr>
<tr>
<td>45.20</td>
<td>7.95 ± 0.40</td>
<td>7.95 ± 0.40</td>
<td></td>
</tr>
</tbody>
</table>
In order to measure the porosity of the reactor in operation, the liquid that occupied the bed was decanted from successive layers of the reactor in order to lessen the effect of suspended solids accumulation on the attached biofilm. The volume of the liquid was then physically measured to improve the accuracy of the figure when calculating the bed porosity:

\[ e_o = \frac{(V_T - (V_m + V_b + V_{SS}))}{V_T} = \frac{V_T - (V_T - V_C)}{V_T} \quad (3) \]

The volume contributed by the suspended solids was ignored due to its much lower proportion compared to that contributed by biofilm and media.

From equations (2) and (3) above, the total attached solids in the reactor is,

\[ \text{Attached solids} = (e_{cb} - e_o) \times (e_{bw} - e_{aw}) \times m_{wb} \quad (4) \]

The masses of suspended solids in the reactors were estimated by multiplying the void volume in the column by the concentration of suspended growth extracted from the middle port of the reactor. A sufficient volume (about 50 ml) of reactor liquor was first wasted to remove any attached solids residing in the sampling pipe before the actual sample was taken. Total suspended biomass in the reactor is determined by the following,

\[ \text{Total suspended biomass} = (V_{pb} \times e_o + V_e l) \times SS_{eff} \quad (5) \]

Biomass loss in the treated effluent should have been studied using real time data since the rate of loss varies from time to time during each backwash cycle. However, for comparison to be made between the two reactors, the SS concentrations were measured only once a day, before being multiplied by the flow rate to obtain the total loss for that day. It was later found that this assumption was reasonable, since the masses of biomass in the effluent calculated using the real time data or daily taken data did not vary substantially. Total mass of solids lost due to backwash was obtained simply by multiplying the concentration of SS in the backwash water by the volume of water used for the backwash operation.

## RESULTS AND DISCUSSIONS

### Carbon removal performance

The percentage TOC removals of filtered effluent samples at each organic loading are illustrated in Figures 1 and 2.

The removal rate for each loading was calculated according to the mean TOC removal efficiencies and the mean OLRs applied. To obtain the mean values, only data taken approximately after two weeks of a new loading application were used. This was to ensure that these data represent a steady-state condition in the system. Table 2 tabulates the removal rates at successive increased loadings of the full- and partial-bed reactors.

For the full-bed reactor, apart from a brief drop of efficiency after each increase in OLR (indicated by circles in Figure 1), highly satisfactory performance was achieved with a removal efficiency of 92.1 ± 6.5% at OLR 5.80 ± 0.31 kg COD m⁻³ d⁻¹ (organic removal rate of 5.34 kg COD m⁻³ d⁻¹). The efficiency dropped to 73.6 ± 6.1% at an increased loading of 7.95 ± 0.40 kg COD m⁻³ d⁻¹, giving a removal rate of 5.85 kg COD m⁻³ d⁻¹. For the partial-bed, the removal efficiencies were over 90% at all loadings with a percentage of 90.2 ± 6.3% at OLR 5.79 ± 0.29 kg COD m⁻³ d⁻¹. Meanwhile, at OLR 7.90 ± 0.40 kg COD m⁻³ d⁻¹, the percentage decreased to 68.0 ± 7.9%, which resulted in a removal rate of 5.41 kg COD m⁻³ d⁻¹.

### Sludge retention time (SRT)

Table 3 illustrates the flow of SRT calculation. The ratio of the estimated total biomass retained in the partial bed (111,220 mg) as compared to that of the full-bed (273,840 mg) is 0.41:1 at OLR 4.18 kg COD m⁻³ d⁻¹ and

![Figure 1](https://iwaponline.com/wst/article-pdf/58/5/977/436295/977.pdf)
0.51:1 at OLR 5.80 kg COD m$^{-3}$ d$^{-1}$. The masses of the suspended biomass were in the range of 1% to 11% those of attached biofilm in the full and partial-bed reactors.

The SRT was reduced from 20.08 days at OLR 4.18 kg COD m$^{-3}$ d$^{-1}$ to 7.62 days at OLR 5.80 kg COD m$^{-3}$ d$^{-1}$ in the full-bed and from 7.17 days to 4.21 days in the partial-bed. It also shows that SRT values in the partial-bed were always lower than those in the full-bed. Also, the SRTs of the system were lower in both the full and partial-bed reactors at higher loadings.

Interestingly, although the amount of media in the partial-bed reactor was reduced to half of that in the full-bed, the removal efficiency is almost comparable. Both the reactor configurations demonstrated almost the same maximum organic removal rate of about 5 to 6 kg COD m$^{-3}$ d$^{-1}$. Applied OLRs above 6 kg COD m$^{-3}$ d$^{-1}$ did not increase the removal rate significantly, and so the apparent efficiency fell.

In a continuous system, the specific growth rate is dependent on the mass rate of the limiting substrate in a reactor. Therefore, by controlling the flow of medium into a reactor at a constant known rate, an organism may be grown at any required specific growth rate, provided that this does not exceed its maximum specific growth rate ($\mu_{\text{max}}$). The high removal rates at successive loadings of 1 kg COD m$^{-3}$ d$^{-1}$ to 6 kg COD m$^{-3}$ d$^{-1}$, obtained in the full- and partial-bed reactors (Table 2) could be attributed to the occurrence of varying specific growth rates at each steady-state phase of different OLRs.

However, this does not imply that a sudden shock-loading of substrate will not influence the magnitude of the effluent substrate concentration. Consequently, there will be a lag period before the growth rates acclimate to the new substrate concentration and the cell concentration in the reactor increases. Horan (1990) noted that this observation has been confirmed experimentally and it has been shown that the specific growth rate experiences a dynamic lag in responding to changes in the concentration of rate-limiting substrate in the culture vessel. A small increase in growth rate is generally observed immediately, but further increases to a new higher steady-state value may take several solids

![Figure 2](https://iwaponline.com/wst/article-pdf/58/5/977/436295/977.pdf)

**Figure 2** | TOC removals in the partial-bed reactor at step increased organic loadings.

---

<table>
<thead>
<tr>
<th>OLR (kg COD m$^{-3}$ d$^{-1}$)</th>
<th>Full-bed</th>
<th>Partial-bed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TOC removal efficiency (%)</td>
<td>Removal rate (kg COD m$^{-3}$ d$^{-1}$)</td>
</tr>
<tr>
<td>1.42 ± 0.06</td>
<td>93.2 ± 1.0</td>
<td>1.32</td>
</tr>
<tr>
<td>2.25 ± 0.15</td>
<td>89.7 ± 7.7</td>
<td>2.02</td>
</tr>
<tr>
<td>3.35 ± 0.22</td>
<td>95.9 ± 1.3</td>
<td>3.14</td>
</tr>
<tr>
<td>4.18 ± 0.20</td>
<td>91.5 ± 5.1</td>
<td>3.82</td>
</tr>
<tr>
<td>5.80 ± 0.31</td>
<td>92.1 ± 6.5</td>
<td>5.34</td>
</tr>
<tr>
<td>7.95 ± 0.40</td>
<td>73.6 ± 6.1</td>
<td>5.85</td>
</tr>
</tbody>
</table>

---

Table 2 | Removal rates at successive increased loadings in the full and partial-bed reactors
retention times to accomplish. A lag in the responses of the specific growth of the population to rapid increases or decreases in substrate concentration is known as a ‘hysteresis effect’. This effect was seen at every step increase of organic loadings in the full-bed reactor (Figure 1).

Since dissolved oxygen concentrations remained at approximately 2 to 4 mg l\(^{-1}\) in both reactors, and other conditions, such as recycle rate and backwash procedures, were also controlled to be almost the same in both reactors, the explanation for a maximum organic removal of about 5 to 6 kg COD m\(^{-3}\) d\(^{-1}\), turns to possible limitations in the retention of biomass within the reactors. Comparing Figures 1 and 2, it is interesting to note that the shock effect of the step- increased organic loading rate observed in the full-bed reactor, was not detected at all in the partial-bed reactor. In theory, the sludge loading (F:M ratio) is related to sludge retention time (SRT) because sludge activity increases if the organic loading is increased followed by the increase of sludge growth. It was hypothesized that lower SRTs in the partial-bed reactor resulted in higher mean bacterial growth rates, and cancelled the lag phase effects. The SRTs for the full- and partial-beds were then compared.

At steady state, even though effluent substrate concentration is not affected by influent concentration, the solids concentration in the reactor will increase in responses to increases in the influent substrate concentration. Meanwhile, the SRT in the full- and partial-bed reactors was pretty much controlled by the biomass loss in the effluent and during backwash operation. Increase in OLRs in the full- and partial-bed reactors resulted in a larger demand for the available dissolved oxygen, i.e. the aeration rate, and thereby increased the turbulence in the reactors. The thicker and more filamentous biofilm formed at higher loadings was easily sloughed by the increased fluid upflow velocity and during the, reducing the SRT (Table 3).

**Table 3** | SRT determination using measured and calculated parameters

<table>
<thead>
<tr>
<th>Measured and calculated values</th>
<th>OLR 4.18 kg COD m(^{-3}) d(^{-1})</th>
<th>OLR 5.80 kg COD m(^{-3}) d(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full-bed</td>
<td>Partial-bed</td>
</tr>
<tr>
<td>Total SS effluent (mg)</td>
<td>222,400</td>
<td>394,300</td>
</tr>
<tr>
<td>Total backwash solid (mg)</td>
<td>268,600</td>
<td>164,100</td>
</tr>
<tr>
<td>Total biomass loss (mg)</td>
<td>491,000</td>
<td>558,400</td>
</tr>
<tr>
<td>Clean bed porosity</td>
<td>0.93</td>
<td>0.93</td>
</tr>
<tr>
<td>Operational bed porosity</td>
<td>0.471</td>
<td>0.579</td>
</tr>
<tr>
<td>Estimated attached solids (mg)</td>
<td>270,200</td>
<td>109,600</td>
</tr>
<tr>
<td>Packed bed void volume (l)</td>
<td>10.89</td>
<td>5.50</td>
</tr>
<tr>
<td>Bed filled with liquid (l)</td>
<td>3.00</td>
<td>8.38</td>
</tr>
<tr>
<td>SS from reactor middle port (mg l(^{-1}))</td>
<td>460</td>
<td>140</td>
</tr>
<tr>
<td>Estimated SS in the reactors (mg)</td>
<td>3,740</td>
<td>1,620</td>
</tr>
<tr>
<td>Total biomass retained (mg)</td>
<td>27,3840</td>
<td>111,220</td>
</tr>
<tr>
<td>Days of operation</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>SRT (day)</td>
<td>20.08</td>
<td>7.17</td>
</tr>
</tbody>
</table>

Note: m and n values are obtained from backwashing study at OLR 2.25 kg COD m\(^{-3}\) d\(^{-1}\).

**Figure 3** | Microscopic profile of microorganisms in the full-bed reactor (× 100).
The SRTs in the full- and partial-bed reactors were both dropped when measured at OLR 4.18 kg COD m\(^{-3}\) d\(^{-1}\) and at OLR 5.80 kg COD m\(^{-3}\) d\(^{-1}\). High F:M and low SRT conditions increases the chances of filamentous bacteria to proliferate (Gerçeker 2002). The view on the occurrence of filamentous bacteria matches the microorganism profiles monitored by microscopic examination throughout the operation. Sample of the view is shown in Figure 3 taken at OLR 5.80 kg COD m\(^{-3}\) d\(^{-1}\).

With the onset of a very serious excessive growth of filaments in the reactors, backwashing operation could easily wash out the filamentous bacteria attached to the media.

The above condition may underline the importance of suspended biomass in BAF systems, the retention of which will be heavily dependent upon their flocculation and settling characteristics, and how this would be affected by OLR and localized upflow wastewater velocities in the packed bed. Once biomass washout approached the critical value, the effluent substrate concentration became higher, thereby reducing the organic removal rate obtained. That is, the biomass concentration within the reactor rises as the load increases until it reaches the point at which, due to porosity limitations, flow distribution limitations or higher gaseous flows, it reaches an equilibrium level beyond which increases in organic load (thus increase in air flow and feed flow) will generate biomass that can not be retained within the reactor.

Biomass washout could have affected the SRT of the system (Table 3). The higher retention of biomass can also lead to a lower specific growth rate of the mixed microbial population within the system. The partial-bed configuration would therefore provides an effective condition for higher respiration activity of biomass.

CONCLUSIONS

Greater concentration of biomass in the full-bed reactor does not significantly improve the efficiency of the reactor for the removal of soluble pollution. The SRT values in the partial-bed were always lower than those in the full-bed. Since SRT is the reciprocal of the net specific growth rate of the sludge, it can be considered as an overall measure of sludge activity. This means that, in each step of increased loading, the sludge growth rate was higher in the partial-bed than in the full-bed.

REFERENCES


