Head loss performance and modeling of burnt oil palm shell in deep bed filtration


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Abstract Filtration is a common unit operation in a water treatment plant. The effectiveness of granular filter media in treating surface water and removing suspended solids is already well established. However, less effort in the mathematical modeling towards the design of the filtration unit is observed. The current study involved head loss performance evaluation and development of a mathematical model to correlate maximum service time of filter at a maximum allowable head loss with various effective sizes and flow rates. Sand and burnt oil palm shell (BOPS) used as filter media in single and dual media filters were subjected to different effective sizes and flow rates. The average influent water turbidity for each filter (at specific effective size and flow rate) before entering the filtration unit was from 1 to 5 NTU. This was a pilot study on settled water that was conducted in a Malaysian water treatment plant. Results suggest that all filters are capable of producing water with acceptable turbidity unit (< 1 NTU). The total running time and filtrate water quality produced by BOPS/sand dual media filter was much better (i.e. the running time of BOPS/sand was four to nine times greater than sand single media filter) than BOPS and sand single media filters. The experimental data were well represented by a newly developed model and results of fitting show a high correlation coefficient ($R^2$) of 0.991. The maximum allowable head loss was selected as 240 cm with an acceptable filtrate water quality (less than 1 NTU). In addition, the current results will be a supplementary tool for engineers in designing a proper filtration unit.

Keywords BOPS; head loss; mathematical modeling; rapid filtration; sand; turbidity

Introduction

In water treatment, filtration is commonly used for the removal of relatively small flocs or particles after the sedimentation process. In addition, filters are also used to remove particulates, bacteria, chemical added in the pre-treatment, algae, iron and manganese oxides, colloidal humic compounds, viruses, radioactive particles, asbestos fibers, heavy metals, colloidal clay particulates, etc. The selection and design considerations for depth filters are based on knowledge of types of filters that are available, general understanding of the performance characteristic and appreciation of process variables controlling depth filtration.

The granular media filter is the most common method of removing colloidal impurities in water processing. Precisely, granular media filters can be classified into filter type (conventional, deep bed, pulsed bed, fuzzy filter and traveling bridge), filter operation (semi-continuous and continuous), filter bed (single media, dual media, mixed media, stratified and un-stratified), filtering medium (sand, anthracite, garnet, synthetic fiber, coal, magnetite and coconut shells), bed depth, direction of fluid flow (upward and downward), backwash operation (batch, continuous and semi-continuous), flow rate through filter (constant or variable) and solid storage location (internal and surface) (Metcalf and Eddy, 2003).
Pilot studies are mostly conducted to evaluate the effectiveness of different filter media, effective sizes, flow rates, filter beds and bed depths. However, these are limited to the experimental data studied. The limitation of experimental data has encouraged the current study to develop empirical mathematical models. The development of this new empirical model leads to a proper design of filtration unit. It can also be used as a supplement to the theoretical studies which have difficulties in obtaining a relatively accurate model (Chang-upp and Chi, 1995; Rodier et al., 1997; Guo et al., 2002).

Studies carried out by Bai and Tien (1997) proved that particle detachment in deep bed filtration is dependent on particle size, filter grain size and head loss gradient, but in the current studies the particle detachment has taken into account as a part of the effect contributing to the total effectiveness of the system removal efficiency. When both the particle and pore size distribution are of the Raleigh type, it is reported that particles with Brownian motion behavior are easier to be retained at small pores, and resulted in higher permeability reduction (Chang et al., 2004; Chan et al., 2005). In contrast, the current study was only subjected to settled water where flocs are considered non-Brownian motion. Eventually, it causes lower permeability reduction and results in a longer of filter running time.

The filtration optimization stage is defined as a total running time in achieving both limiting head loss and a specific effluent quality (Tchobanoglous and Schroeder, 1985). A stage when the production of water reaches optimum level. However, it is difficult to determine the exact filtration optimization stage. This is mainly due to variation of effluent water quality from the sedimentation tank that were varied from time to time.

In order to maximize the usage of existing experimental data, an alternative mathematical modeling was proposed. It was observed that the head losses for all filters increase when running time increases with curve concave downward (Figures 1, 2 and 3). Therefore, the variation of head loss with running can be represented in the following model:

\[ H_L = H_0 + aT^\beta \]  

where \( H_L \), \( H_0 \), \( T \), \( a \) and \( \beta \) are operational head loss (cm), initial head loss (cm), running time (hr), constant (cm.hr\(^{-\beta}\)) and constant (dimensionless), respectively. This model is also similar to the model developed by Ives (1970). Moreover, Stevenson (1997) found a linear increase in head loss with time.

Boller and Kavanaugh (Boller and Kavanaugh, 1995) have demonstrated that the rate of head loss build-up in a granular media filter, for a constant mass of solids being
removed, is strongly dependent on the size of the particulates in suspension and the size of the granular media. Besides, Bai and Tien (2000) found that deposition in deep-bed filtration depends on both particle size and influent concentrations. However, in this experiment, only the size of particulate was kept constant.

**Methods**

The current study was limited to conventional down-flow filters that include only single and dual media filters. Type of filter operation was semi-continuous since it must be taken off-line periodically for backwashing. The filtering medium selected for the current study was limited to sand and burnt oil palm shell (BOPS). BOPS was used as new granular filter media and was reprocessed from local solid waste material that was abundantly available at the end of the palm oil industry process. The bed depths and effective sizes of the filter vary from 58 to 70 cm and 0.4 to 2.0 mm, respectively, depending on the types of media and filter bed used.

Palm shells were burnt in a furnace at 300°C without oxygen and then ground into granules before sieving to establish the particle size distribution curve. The effective sizes of sand were 0.4 and 0.6 mm. For BOPS, the effective sizes were 1.0 and 2.0 mm. Both sand and BOPS had the same uniformity coefficient (UC) of 1.5. The effective sizes \(E_s\) for BOPS/sand were 1.0 mm/0.5 mm and 2.0 mm/0.5 mm. The specific gravity for sand and BOPS were 2.65 and 1.40, respectively.

There were six filters prepared for the study. Two were sand single media filters. Two were BOPS single media filters and two were BOPS/sand dual media filters. Each of the

![Figure 2](image2.png)

**Figure 2** The variation of head loss with running time at particular effective size and flow rate for sand in single media filter

![Figure 3](image3.png)

**Figure 3** The variation of head loss with running time at particular effective size and flow rate for BOPS/sand in dual media filter
filter media was placed into a filtration unit to determine the optimum bed depth of filtration for their specific effective sizes. Settled and domestic water were used during the filtration process and backwashing operation, respectively. A water pump was used to lift the settled water to the top of the filter before the flow system governed by gravity force. The hydraulic requirements of the pilot-scale were designed similar to a proper unit operation in water treatment plant. The respective optimum bed depths for various effective sizes were then subjected to two different operating flow rates, i.e. 10.0 and 15.0 m$^3$/m$^2$/hr.

The turbidity of the influent and effluent of the filter and the head loss of the filter at different heights of bed depth were recorded at different time intervals. The filtration system was backwashed when either pre-selected filtrate turbidity (1.00 NTU) or head loss (240.0 – 300.0 mm) was exceeded. All these experiment were carried out in a water treatment plant in Malaysia.

Mathematical modeling was conducted by Mathematica version 4.2. The head loss was correlated with running time. The correlation coefficient ($R^2$) was determined for each modeling exercise to determine the accuracy of the model.

**Results and discussion**

The evaluation of the rapid filtration performances of single and dual media filters using sand and BOPS as filter media was focused on running time and head loss. These were indirectly incorporated with the effects of flow rate and effective size. Running time is defined as time between the beginning of filtration until either the filter head loss reaches 240.0 – 300.0 mm or filtrate water turbidity reaches 1.00 NTU. Apart from this, running time is affected by grain size or effective size, filter bed depth, flow rate of settled water, concentration of settled water, floc strength, deposit density, porosity and types of media used. However, the current study was only concentrated on effective size, influent water flow rate and media filter types.

Table 1 shows the total running time achieved for single and dual media filters for particular total head loss and final filtrate turbidity values. It was collectively observed that filter medium with smaller effective size has shorter total running time and vice versa on smaller flow rate, except 0.4 mm effective size of sand. Based on the effective sizes and flow rates of dual media filter, the results have shown that BOPS/sand filter media has the highest total running time when compare to single media filters.

The results of fitting experimental data of sand and BOPS in single and dual media filters into Equation (1) are presented in Table 2. Overall, the experimental data were

<table>
<thead>
<tr>
<th>Media</th>
<th>$E_s$ (mm)</th>
<th>Flow rate (m$^3$/m$^2$/hr)</th>
<th>Total running time (hours)</th>
<th>Total head loss (cm)</th>
<th>Initial filtrate turbidity (NTU)</th>
<th>Final filtrate turbidity (NTU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>0.4</td>
<td>10.0</td>
<td>14.30</td>
<td>163.0</td>
<td>0.14</td>
<td>1.11</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>15.0</td>
<td>15.18</td>
<td>280.0</td>
<td>0.85</td>
<td>0.12</td>
</tr>
<tr>
<td>BOPS</td>
<td>1.0</td>
<td>10.0</td>
<td>21.30</td>
<td>274.0</td>
<td>0.62</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>15.0</td>
<td>21.00</td>
<td>268.0</td>
<td>0.34</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>10.0</td>
<td>53.42</td>
<td>265.0</td>
<td>0.80</td>
<td>0.26</td>
</tr>
<tr>
<td>BOPS/sand</td>
<td>1.0/0.5</td>
<td>10.0</td>
<td>123.50</td>
<td>265.0</td>
<td>0.30</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>1.5/0.5</td>
<td>15.0</td>
<td>132.00</td>
<td>249.5</td>
<td>0.80</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>2.0/0.5</td>
<td>10.0</td>
<td>164.25</td>
<td>247.0</td>
<td>0.60</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Table 1 Running time, total head loss, final filtrate turbidity for single and dual media at different effective sizes and flow rates.
well fitted by Equation (1), since the correlation coefficients obtained were in the range of 0.97–1.00. A clearer view of comparison between experimental and predicted head loss is presented in Figure 4.

The parameters obtained from fitting model, Equation (1), can be used to estimate the maximum service time of filter at maximum allowable 240 cm head loss for specific effective size and flow rate. In order to apply the current results to design a filtration unit at specific location, variables such as influent quality, acceptable effluent quality, effective size, flow rate, bed depth, uniformity coefficient and the types of filter media to be used may need to be further considered. If any of these criteria that will be used to design a filtration unit at particular location fail to comply with the variables set within the experimental study, it will not be reliable to use the current results to conduct estimation on design of any filters at that particular location.

It is known that pressure of liquid increases linearly as depth of liquid increases. But when filter media was placed into the filter column, a pressure drop was observed (at a particular flow rate) which is known as initial head loss. As the filters continue the filtration, the removal of turbidity on the filter media generates pressure curves that are concave to the left. All these were observed for BOPS and sand in single and dual media filters (Figures 5, 6 and 7). Boller and Kavanaugh (1995) have demonstrated that the rate of head loss build-up in a granular media filter, for a constant mass of solids being removed, is strongly dependent on the size of the particulates in suspension and the size of the granular media. Besides, Bai and Tien (2000) found that deposition in deep-bed filtration depends on both particle size and influent

Table 2 Different types of filters fitted by Equation (1) at different effective sizes and flow rates, and parameters obtained

<table>
<thead>
<tr>
<th>Filter media</th>
<th>$E_s$ (mm)</th>
<th>Flow rate (m$^3$.m$^{-2}$.h$^{-1}$)</th>
<th>$\alpha$ (cm.hr$^{-b}$)</th>
<th>$H_o$ (cm)</th>
<th>$\beta$ (dimensionless)</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>0.4</td>
<td>10.0</td>
<td>2.45</td>
<td>30.2</td>
<td>1.48</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>15.0</td>
<td>2.70</td>
<td>41.5</td>
<td>1.64</td>
<td>1.00</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>10.0</td>
<td>0.993</td>
<td>38.5</td>
<td>1.77</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>15.0</td>
<td>1.87</td>
<td>37.6</td>
<td>1.59</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>BOPS</td>
<td>1.0</td>
<td>10.0</td>
<td>1.80</td>
<td>5.00</td>
<td>1.03</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>15.0</td>
<td>2.14</td>
<td>17.6</td>
<td>1.18</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>10.0</td>
<td>0.0303</td>
<td>2.87</td>
<td>1.76</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>15.0</td>
<td>0.0907</td>
<td>2.00</td>
<td>1.81</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>BOPS/sand</td>
<td>1.0/0.5</td>
<td>10.0</td>
<td>0.247</td>
<td>14.3</td>
<td>1.42</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>15.0</td>
<td>1.59</td>
<td>10.5</td>
<td>1.18</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.0/0.5</td>
<td>10.0</td>
<td>0.828</td>
<td>4.44</td>
<td>1.08</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>15.0</td>
<td>0.0490</td>
<td>26.2</td>
<td>1.80</td>
<td>1.00</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4 Comparison between experimental and predicted head loss of sand and BOPS in single and dual media filters by Equation (1)
concentrations. However, in this experiment, the size of particulates and granular media were kept constant, except for influent concentration.

From BOPS single media filter (Figure 5), it was observed that the active zone takes place in the middle of the filter bed depth, which revealed the filtration process was well distributed from the surface and increased to peak in the middle of the filter bed depth. However, when referring to sand single media filter (Figure 6), it was observed that the peak was slightly lower or closer to the surface of the filter. This suggests that most of the filtration process was happening on the shallow surface of the filter. The flocs entrapped on the top of the sand single filter media eventually acted as a new layer of filter and therefore, filtrate quality became better until an optimum storage level was achieved before breakthrough.

In BOPS/sand dual media filter (Figure 7), it was found that the head loss for sand increases more rapidly than BOPS. This might be due to the fact that the effective size of sand was smaller than BOPS. Moreover, the peak of head loss for sand in dual media filter was nearly in the middle of sand media height. During the filtration process, the flocs with bigger size were entrapped by BOPS media in the upper layer and the flocs with smaller size were enabled to travel deeper in the filter bed. This could possibly lead to development of an active zone at deeper filter bed height. Subsequently, it was found that the active zone for sand was transferred from the shallow surface into the middle of the sand height and therefore, increased the running time for the operation unit significantly.

**Figure 5** Profile terminal head loss of BOPS single media filter at 10 m³/m²/hr flow rate and 1.0 mm effective size

**Figure 6** Profile terminal head loss of sand single media filter at 10 m³/m²/hr flow rate and 0.6 mm effective size
Conclusions

It was found that BOPS/sand dual media filter was a better solution in treating turbid water with respect to total running time and filtrate water quality, since it consists of BOPS as top filter media layer (capable of removing flocs of bigger size) and sand as bottom filter media layer (removing flocs of smaller size). With this combination, the operation time of the filter was extended and the quality of water produced was within the acceptable limits. Eventually, the cost of operation reduces and the quantity of water produced increases significantly. The development of the head loss model can be used as a guideline to design the total running time of the filtration unit at specific allowable head loss for specific effective size and flow rate, without sacrificing the quality of water produced at the effluent of filter. The advantages of such models include ease of use, much information in little space and accurate data giving high correlation coefficients. The new data estimated by interpolation, extrapolation and identification of grossly inaccurate (non-fitting) data could be avoided.

References