Phenol Removal From Synthetic Wastewater by Adsorption Column

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Abstract: Adsorption column is used to perform the adsorption experiments of this work using continuous scheme. The operating parameters investigated in this work are: inlet pollutant concentration (10, 30, & 50 mg/L), Liquid hourly space velocity (5, 10, & 15 h⁻¹), and thickness of activated carbon layer (5, 15, & 25 cm). The aim of this work is to investigate the possibility of removing high phenol concentration from a synthetic wastewater since the nearby North Refineries Company, Baiji, (Iraq) wastewater treatment plant receives high phenol concentration. Moreover, to investigate the effects of various operating parameters on the adsorption capacity, breakthrough, and exhaustion times. The results of this work show that activated carbon can remove high concentration of phenol (up to 50 mg/L) efficiently. The results also indicated that the adsorption capacity depends on inlet pollutant concentration, activated carbon thickness, and liquid hourly space velocity. Actual adsorption capacity is calculated and found to be different from adsorption capacity found depending on the adsorption models. The lowest and highest adsorption capacities are 0.428 and 9.02 mg/g respectively, while the corresponding values for actual adsorption capacities are 0.216 and 32.4 mg/g.

Keywords: Phenol, Intended Adsorption, Velocity, Mass transfer zone, Adsorption Column.

1. Introduction
North Refineries Company, Baiji,( Iraq) discharges a wide range of pollutants including high phenol concentration to the wastewater treatment plant because this refinery is ancient and there are a lot of leaks besides a lack of adequate maintenance. These pollutants will find its way to the nearby Tigris river and groundwater. Since building new refinery or at least replacing many of the old units is not possible soon, thus it is important to use a method that can remove phenol or at least reduce its concentration in the outlet of the wastewater treatment plant.

Activated carbon is the most widely used adsorbent to remove many pollutants produced from many industries. Among these pollutants; organic materials and heavy metals. The removal of such pollutants using activated carbon are investigated [1-12]. However, other adsorbent materials such as Multi walled Carbon nanotube, Calcined Gypsum, and Natural and Modified Waste Rocks [2, 13-15] were used. In continuous adsorption scheme, the most important operating parameters affecting adsorption process are examined in many works which are: flow rate, adsorbent thickness (H), inlet pollutant concentration (Co), pH, and temperature.

Waadalla [1] found that breakthrough time (TB) is increased with the increase of thickness and decreased with the increase of inlet pollutant concentration. It is also found that breakthrough and exhaustion time (TB & TE) are directly proportional with thickness [2 & 16] while they are inversely proportional with inlet concentration and liquid hourly space velocity (LHSV) [2, 16 & 19]. Similar trend is got for the removal of other pollutants such as [Cr (VI)] using other adsorbents such as activated Tamirind seeds [17]. Bhakta et al. [12] found that adsorption capacity (ADC) is directly proportional to temperature and pH of 7 gave the best results. The results of Kanoosh [11] showed that adsorption capacity increases with the increase of inlet concentration and liquid hourly space velocity and with the decrease of thickness. Nouri and Ouederni [3]...
proved that adsorption capacity increases with the increase of thickness and inlet concentration while it decreases with the increase of flow rate. Radhika et al. [10] found that adsorption capacity increases with the increase of inlet concentration and with the decrease of thickness. They found that adsorption capacity decreased with the increase of liquid hourly space velocity. They found that breakthrough time is increased with the increase of thickness. Yang et al. [18] stated that the adsorption capacity varies with pore structure of the activated carbon. Weiwei et al. [8] mentioned that the adsorption capacity of phenol can reach up to 32.27 mg/g.

The data of adsorption are presented as a graph that takes "S" shape. The most popular adsorption models used to fit experimental data are Freundlich and Langmuir [20]. Kulkarni [21] stated that the adsorption capacity is found to be increased with the increase of inlet phenol concentration and activated carbon layer thickness while it decreased with the increase in flow rate. Issabayeva et al. [22] stated that adsorption capacity can reach as much as 1000 mg/g.

Different methods had been used for the removal of phenol and other organic pollutants [23 & 24]. Among these methods are: adsorption, oxidation, membrane separation, and biological methods [23]. Such methods can give about 80% phenol removal [24]. Phenol, which is a toxic compound, has a molecular weight of 94 and boiling point of 192 °C with a structure (\(\text{C}_6\text{H}_5\text{OH}\)). Phenols are widely used in household products and as intermediates for industrial synthesis. For example, phenol itself is used (in low concentrations) as a disinfectant in household cleaners and in mouthwash. In industry, phenol is used as a starting material to make plastics, explosives such as picric acid, and drugs such as aspirin. Other substituted phenols are used in the dye industry to make intensely colored azo dyes. Mixtures of phenols (especially the cresols) are used as components in wood preservatives such as creosote [25].

The aim of the present work is to perform a lot of experiments applying a continuous scheme to investigate: (i) the possibility of removing high phenol concentrations, (ii) to investigate the effects of various operating parameters on phenol removal and adsorption capacity, and (iii) to find out adsorption capacity and actual adsorption capacity\(\text{(AADC)}\) under various operating conditions.

2. Materials, Apparatus, and Method

2.1. Materials

- Distilled water is used to prepare the phenol polluted water. Phenol had been dissolved in this water to get the required phenol concentration.
- Activated carbon: Granular activated carbon (some of its properties are listed in Table 1). It is washed by distilled water and dried at 110 °C for 24 hours. Surface area of this activated carbon is measured at scientific and development center of oil ministry.
- Phenol: phenol of 99.5% purity obtained from North Refineries Company, Baiji, (Iraq) is used in this work. Some of its specifications are listed on Table 2.

| Property | Density, gm/cm³ | Porosity, fraction | Grain diameter, mm | Surface area, m²/gm |
|----------|-----------------|--------------------|-------------------|---------------------|
| Value    | 0.933           | 0.586              | 3.4               | 1175.62             |

Table 2. Some properties of phenol.

| Symbol | Structure | Molecular weight | Solubility in water | Chemical structure |
|--------|-----------|------------------|---------------------|--------------------|
| Ph     | \(\text{C}_6\text{H}_5\text{OH}\) | 94.11            | 66.7 m/L            | ![Chemical structure](image) |

2.2. Apparatus

- Thermometer (-10 to 360 °C) is used to measure temperature.
- pH-meter: Hanna pH-meter is used to measure pH. Germany manufactured.
UV-spectrophotometer: Spectro UV — VIS double beam PC UVD-3000 USA made (Figure 1) is used to measure phenol concentration. The calibration curve is prepared: Take 100 mg/L of phenol and dissolve it in 1 liter of distilled water. Then make several dilutions to get samples of 5 to 65 mg/L. The absorbance of these samples at wavelength of 280 nm are measured to plot the calibration curve as shown on Figure 2 which is used later to determine the concentration of phenol in the unknown samples.

Electric balance: (Adventure Pro AV 313C) of 0.001 sensitivity, Swiss made Ohaus corporation.

Drying oven: German made.

Adsorption Column: Lab scale adsorption column is designed and constructed as shown in Figure 3. The wastewater is pumped to an elevated tank mounted at 2 meter height of 20 liter volume. Then from this tank, water flow by gravity to a secondary tank of 9 liter volume mounted at 1.9 m. The secondary tank is equipped with a float to maintain constant flow rate to the adsorption column which is made of a plastic tube of 1.25 cm diameter and 125 cm length. Other accessories are shown on Figure 3.

2.3. Experimental Method
All experiments of this work are conducted at pH of $7 \pm 0.1$ and under constant temperature of 21 °C. For each experiment, the following steps are followed:

- All tanks, tubes, accessories are washed by tab water and distilled water.
- Prepare the suitable volume of polluted water of the required phenol concentration.
- Fill the adsorption column by distilled water to remove air.
- Pump the polluted water through closed circuit for 1 hour to get a homogenous water, then pump it to the main tank.
- Let wastewater enter the adsorption column at the desired adjusted flow rate.
- Take samples from the outlet of adsorption column at different time intervals. Each sample is tested three times to determine phenol concentration and the average value is taken.
- Stop the experiment when the outlet phenol concentration is equal to the inlet concentration. Then prepare the system for the next experiment.

2.4. Calculations
The necessary calculations performed in this work are done using Equations 1 to 4. Adsorption capacities are calculated using Langmuir model (Equation 1)[26]. According to this model, a plot of $C/(X/M)$ against $C$ will give a straight line. Enter X-axis with a concentration equal to the inlet pollutant concentration go
vertically to cross the straight line and read the value \([C/(X/M)]\) from y-axis. Then adsorption capacity \(q_e = X/M\) can be found.

\[
q_e = \frac{X}{M} = \frac{abC_e}{1+bcC_e} \quad \text{……..(1)}
\]

When:
\(a, b = \text{ constants}\).
\(C_e = \text{ equilibrium pollutant concentration in liquid, (mg/L)}\).
\(M = \text{ adsorbent mass, (mg)}\).
\(q_e = \text{ adsorbed pollutant mass per unit mass of adsorbent,(mg/mg)}\).
\(X = \text{ adsorbed pollutant mass, (mg)}\).

Actual adsorption capacities are calculated using Equation 2 [27]:

\[
AADC = \frac{(C_0 - C_f)V}{M} \quad \text{……..(2)}
\]

when:
\(AADC: \text{ Actual adsorption capacity (mg/g)}\).
\(C_0: \text{ inlet concentration of the pollutants (mg/L)}\).
\(C_f: \text{ final concentration of the pollutants (mg/L)}\).
\(M: \text{ Activated Carbon Weight (gram)}\).
\(V: \text{ volume of solution, (L)}\).

Mass Transfer Zone \([\text{MTZ}] = \delta\) & Adsorption Velocity \((V_{ad})\) are calculated using Equations 3 and 4 respectively [28].

\[
V_{ad} = \frac{H}{TE} \quad \text{……..(3)}
\]

\[
\text{MTZ} = H - TB * V_{ad} \quad \text{……..(4)}
\]

when:
\(H=\text{activated carbon thickness, (m)}\).
\(TB=\text{breakthrough time, (h)}\).
\(TE=\text{exhaustion time, (h)}\).
\(V_{ad}=\text{adsorption velocity, (m/h)}\).
\(\delta = \text{mass transfer zone, (m)}\).

3. Results and Discussion

The results of the present work are listed in Table 3 and represented graphically on Figures 4 to 6. Figures 4 to 6 represent the adsorption isotherms. Phenol adsorption follows a traditional trend. The time at which the outlet pollutant concentration reaches 5% and 95% of the inlet concentration is known as breakthrough and exhaustion time, respectively.

Figures 4 to 6 show that increasing inlet concentration will reduce both breakthrough and exhaustion times. Since the adsorbent mass is constant, thus increasing inlet concentration led to a decrease in breakthrough and exhaustion times due to faster saturation of the adsorption sites. Increasing inlet concentration will increase the driving force which increases the adsorption rate and saturates the adsorption sites more quickly. Similar trends are observed by [19, 29-31]. Breakthrough and exhaustion times ranges are (2 to 105h) and (79 to 590h) respectively. Longer breakthrough and exhaustion times will reduce the periodicity of regeneration and the environmental load since it allows more time for the column to be saturated leaving lower unused adsorption sites.
### Table 3. Experimental Results for Continuous Scheme.

| No | LHSV, (h⁻¹) | Co, (mg/L) | H, (cm) | TB, (h) | TE, (h) | ADC, (mg/g) | AADC, (mg/gm) | Vad, μm/s | δ, cm |
|----|--------------|------------|--------|--------|--------|------------|--------------|-----------|------|
| 1  | 5            | 10         | 5      | 28     | 259    | 1.824      | 3.7210       | 0.0536    | 4.46 |
| 2  | 5            | 10         | 15     | 57     | 370    | 1.5412     | 9.6300       | 0.1126    | 12.69|
| 3  | 5            | 10         | 25     | 105    | 590    | 0.4831     | 8.5830       | 0.1177    | 20.55|
| 4  | 5            | 30         | 5      | 7      | 206    | 7.4410     | 0.6390       | 0.0674    | 4.83 |
| 5  | 5            | 30         | 15     | 23     | 314    | 2.2750     | 4.9470       | 0.1327    | 13.90|
| 6  | 5            | 30         | 25     | 78     | 420    | 1.5760     | 15.6170      | 0.1653    | 20.36|
| 7  | 5            | 50         | 5      | 2      | 104    | 9.4610     | 0.5780       | 0.1335    | 4.90 |
| 8  | 5            | 50         | 15     | 17     | 237    | 4.2560     | 2.5800       | 0.1758    | 13.92|
| 9  | 5            | 50         | 25     | 66     | 312    | 2.7520     | 32.4020      | 0.2226    | 19.71|
| 10 | 10           | 10         | 5      | 13     | 188    | 1.7991     | 3.2260       | 0.0739    | 4.65 |
| 11 | 10           | 10         | 15     | 42     | 265    | 1.2064     | 6.6210       | 0.1572    | 12.62|
| 12 | 10           | 10         | 25     | 53     | 372    | 0.4546     | 10.4010      | 0.1867    | 21.44|
| 13 | 10           | 30         | 5      | 3      | 145    | 6.2280     | 0.8520       | 0.0958    | 4.90 |
| 14 | 10           | 30         | 15     | 16     | 242    | 2.2722     | 3.7920       | 0.1722    | 14.01|
| 15 | 10           | 30         | 25     | 39     | 300    | 1.5098     | 10.4110      | 0.2315    | 21.75|
| 16 | 10           | 50         | 5      | 0.333  | 94     | 9.0174     | 0.2880       | 0.1478    | 4.98 |
| 17 | 10           | 50         | 15     | 9      | 294    | 4.1454     | 2.5710       | 0.2148    | 14.30|
| 18 | 10           | 50         | 25     | 23     | 265    | 2.6970     | 28.2760      | 0.2620    | 22.83|
| 19 | 15           | 10         | 5      | 9      | 125    | 1.5969     | 2.2420       | 0.1111    | 4.64 |
| 20 | 15           | 10         | 15     | 26     | 200    | 0.7757     | 6.6460       | 0.2083    | 13.05|
| 21 | 15           | 10         | 25     | 41     | 230    | 0.4281     | 10.6020      | 0.3019    | 20.54|
| 22 | 15           | 30         | 5      | 0.666  | 104    | 6.1564     | 0.3200       | 0.1335    | 4.97 |
| 23 | 15           | 30         | 15     | 13     | 190    | 2.2194     | 5.7100       | 0.2193    | 13.97|
| 24 | 15           | 30         | 25     | 23     | 214    | 1.3883     | 8.3290       | 0.3245    | 22.31|
| 25 | 15           | 50         | 5      | 0.1666 | 79     | 8.2298     | 0.2160       | 0.1758    | 4.99 |
| 26 | 15           | 50         | 15     | 4      | 155    | 4.0119     | 1.9360       | 0.2688    | 14.61|
| 27 | 15           | 50         | 25     | 31     | 200    | 2.3558     | 22.9700      | 0.3472    | 21.12|

**Figure 3.** Schematic diagram of the adsorption unit.

**Figure 4.** Adsorption isotherms, H=5cm.
3.1. Effect of Thickness on Breakthrough and Exhaustion Times

Figure 7 represents the effect of activated carbon thickness on breakthrough and exhaustion times at liquid hourly space velocity of 15 h⁻¹. It is worth to mention that similar trend is obtained for LHSV of 5 & 10 h⁻¹. Inspection of this Figure and Table 3 showed that both times increased with the increase of thickness. These results agree well with that obtained by [1, 11, 16 & 17]. As the thickness increased, the adsorption sites are increased and delaying both TB and TE. Increasing thickness will reduce the left empty adsorption sites since higher thickness will increase the contact time. Increasing the contact time will allow more time for the adsorption mechanism to perform better in removing the pollutants since the adsorption process is controlled by the adsorption mechanism step having the lower speed. The activated carbon thickness in the field unit is over 25 cm, thus it is expected that higher TB & TE will be got in the field unit.

3.2. Effect of Inlet Concentration on Breakthrough and Exhaustion Time

Figure 8 represents the effect of phenol concentration on these times at Thickness of 25 cm. It is worth to mention that similar trend is obtained for thickness 5 and 15 cm. Inspection of this Figure and Table 3 indicated that both times decreased with the increase of inlet concentration because of the increase of the pollutant mass that will saturate the available adsorption sites faster. Increasing the inlet concentration will increase the driving force, giving faster saturation and shorter breakthrough and exhaustion times. This trend agrees with that of [1, 2, 16 & 17].
3.3. Effect of Liquid Hourly Space Velocity on Breakthrough and Exhaustion Times

Figure 9 represents the effect of liquid hourly space velocity on these times at a thickness of 25 cm. It is worth to mention that similar trend is obtained for thickness 5 and 15 cm. It is found that both times are inversely proportional with LHSV. Similar trend is obtained by [3, 11, 16 & 17]. Higher LHSV means lower available contact time for adsorption and higher pollutant mass passes through the same time leading to earlier saturation of the available adsorption sites giving lower TB and TE. It is preferable to operate the field units at lower flow rates as much as possible. This means that the increase of the produced wastewater volumes to be treated requires additional adsorption column to be constructed.

3.4. Adsorption Capacity

Nonlinear multi variable regression analysis technique using IBM SPSS statistics 24 is used to fit the experimental data by Langmuir and Freundlich models. The results showed that R² values for Langmuir model are higher than the corresponding values of Freundlich model. The ranges of R² for Langmuir and Freundlich models are (0.91 to 0.989) and (0.772 to 0.897) respectively. Therefore, Langmuir model (Equation 1) is used to find the adsorption capacity since it gives better fit with the experimental data. The calculated adsorption capacity values are listed in Table 3. The highest adsorption capacity is 9.461mg/g at LHSV of 5 hr⁻¹, H of 5 cm, and Co of 50 mg/L, while the lowest adsorption capacity is 0.4281 mg/g at LHSV of 15 hr⁻¹, H of 25 cm, and Co of 10 mg/L. This wide range of adsorption capacity indicated that ADC is very sensitive to the operating parameters. Thus, great care must be taken when designing and operating the field unit to get the highest pollutant's removal with the minimum cost.

3.5. Effect of Thickness on Adsorption Capacity

Figure 10 represents sample of the data concerning the effect of thickness on adsorption capacity at LHSV of 5 hr⁻¹. It is worth to mention that similar trend is obtained for LHSV of 10 and 15 hr⁻¹. Table 3 and Figure 10 show that adsorption capacity is inversely proportional with thickness because the amount of inlet pollutant concentration is constant and the mass of activated carbon is increased with the increase of thickness. Thus, the amount of pollutant concentration divided by the adsorbed pollutant per unit carbon mass [C/(X/M)] will increased with the increase of thickness, which means decreasing adsorption capacity. Similar trend is obtained by [10 & 11].

3.6. Effect of Inlet Concentration on Adsorption Capacity

Figure 11 represents sample of data concerning the effect of inlet concentration on adsorption capacity at a thickness of 25 cm. It is worth to mention that similar trend is obtained for a thickness of 5 and 15 cm. Table 3 and Figure 11 show that the adsorption capacity is increased with the increase of inlet pollutant concentration because the increase of the inlet pollutant concentration will increase the driving force which leads to an
increase of the adsorbed pollutant. Moreover, the quantity $C/(X/M)$ is increased as the nominator $(C)$ is increased which means increasing adsorption capacity. This trend agrees well with that of [3].

3.7. Effect of Liquid Hourly Space Velocity on Adsorption Capacity

Figure 12 represents sample of data concerning the effect of LHSV on adsorption capacity at a thickness of 25 cm. It is worth to mention that similar trend is obtained for a thickness of 5 and 15 cm. Table 3 and Figure 12 show that the adsorption capacity is inversely proportional with LHSV because there is not enough contact time for the adsorption process. This trend agrees well with that of [3 & 10].

3.8. Actual Adsorption Capacity (AADC)

The actual adsorption capacity is calculated using Equation 2 and listed in Table 3. Actual adsorption capacity is plotted on Figure 13 against the adsorption capacity calculated using Langmuir model. Adsorption capacity range based on Langmuir model is 0.4281 to 9.46 mg/g while the actual adsorption capacity range is 0.216 to 32.402 mg/g. There is a huge difference between them. There is no specific trend for this difference. Under certain operating conditions, AADC is greater than ADC [for run No. 9: ADC & AADC are 2.752 & 32.402 mg/g respectively] while under other operating conditions ADC is greater than AADC [for run No. 25: ADC & AADC are 8.2298 & 0.216 mg/g respectively]. This indicates that both ADC & AADC are very sensitive to the operating parameters. Inspection of Table 3 show that ADC & AADC for run No. 2 are 1.54 & 9.63 mg/g respectively. This means that to remove 1 kg of phenol, $1/(0.00963) = 103.84$ kg of carbon is required based on actual adsorption capacity. The corresponding value for carbon mass based on Langmuir model is $(1/0.00154) = 649.35$ kg. This finding indicated that the design of a field unit based on Langmuir adsorption capacity may be over or underestimated. Thus, the best way is to base the design depending on a pilot plant actual data.

The results concerning adsorption capacity range obtained from this work and that obtained by [32] (batch scheme) are listed in Table 4. This Table indicated that ADC & AADC ranges for batch scheme are higher than the corresponding ranges of continuous scheme. This is because two reasons: the first is the pollutant stay in contact with the adsorbent during all time of the experiment at batch scheme while in continuous scheme the polluted solution passes the adsorbent column at short time. The second reason is the adsorption capacity is reduced with the increase of adsorbent mass. This comparison indicated that the adsorption capacity is sensitive to the scheme of the experiment. These findings clarify that the design of field units based on adsorption capacity-based batch scheme may be underestimated. Thus, the expected actual range of the operating parameters of the field unit must be applied in the laboratory and pilot continuous adsorption column study to get the right field unit design.
Table 4 Comparison between the ranges of ADC & AADC for batch and continuous scheme.

| Adsorption capacity | Batch scheme | Continuous scheme |
|---------------------|--------------|-------------------|
| ADC                 | 1.8000-20.0260 | 0.42809-9.4610    |
| AADC                | 6.1456-63.7750 | 0.21600-32.402    |

### 3.9. Effect of Thickness, Liquid Hourly Space Velocity and Inlet Concentration on Adsorption Velocity and Mass Transfer Zone

Figures 14 to 16 show that both adsorption velocity and mass transfer zone are increased with the increase of thickness, LHSV, and inlet concentration. The results of [33-35] show that $\delta$ increases with the increase of thickness and inlet concentration while it decreases with the increase of LHSV.

Figure 14 show that increasing the thickness of activated carbon layer will increase both adsorption velocity and $\delta$. This is because the adsorbent mass is increased with the increase of thickness giving more available adsorption sites. The increase of the available adsorption sites will also increase the adsorption process rate, giving higher adsorption velocity and $\delta$.

Figure 15 indicated that $\delta$ and adsorption velocity are increased with the increase of LHSV. This is in good agreement with the results of [36] while it is in opposite trend with the results of [33-35]. The increase of LHSV will reduce contact time giving less chance for the adsorption process to be completed allowing the pollutant to pass deeper into adsorbent (reducing the adsorbed mass of pollutant through given adsorbent section). It will also reduce TB since more pollutant mass will pass through the same time as compared with that for lower LHSV. However, the net effect is an increase of adsorption velocity & $\delta$. The results of [37, 38] show that the pollutant removal increased with the increase of contact time. The increase of LHSV will reduce TE and according to Equation 3, adsorption velocity will increase. Although the increase of LHSV will reduce TB, it will increase the adsorption velocity. The net effect is an increase in $\delta$ according to Equation 4.

Figure 16 shows that increasing inlet concentration will increase adsorption velocity and $\delta$. The increase of inlet concentration will increase the driving force, thus increasing adsorption velocity. Increasing inlet concentration will increase the pollutant mass passing through unit time, which will allow the pollutant to travel larger distance. This will increase $\delta$. Similar trend is obtained by [33-35]. Higher inlet concentration gives low TE and according to Equation 3, higher adsorption velocity. Although higher inlet concentration gives lower TB, it will increase the adsorption velocity. The net effect is an increase in $\delta$ according to Equation 4.

Figure 13. AADC vs ADC based on langmuir model.  
Figure 14. Effect of H on $\delta$ & Vad, LHSV=5 h\(^{-1}\).
4. Conclusions

High phenol concentration (up to 50 mg/L) can be completely removed from highly polluted synthetic wastewater. However, breakthrough and exhaustion times vary greatly as the operating parameters are varied. It is found that both times are increased with the increase of thickness and inversely proportional with inlet concentration and LHSV. Adsorption capacity is found to be inversely proportional with LHSV and thickness and directly proportional with inlet concentration. Actual adsorption capacity differs greatly from adsorption capacity obtained from adsorption model, which is very sensitive to the operating parameters and the scheme of experiment. Therefore, designing field unit based on adsorption capacity calculated from adsorption model may give overestimated or underestimated unit. It is also found that adsorption velocity and δ are increased with the increase of thickness, LHSV, and inlet concentration. It is recommended to construct a pilot unit and test actual wastewater samples before proceeding to the field unit design.

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