Dynamic Modeling Process from the Hexane Removal of Contaminated Air Bio Filtration Method

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Abstract

Purification of polluted air from volatile organic compounds by means of biologic methods has been considered due to great advantages. Biofiltration is one of the best biologic methods for doing such processes. In this research, a mathematical model has been presented in order for Biofiltration process of polluted air in which limiter effects of oxygen and humidity have been considered. Since, microbe’s inclination to substrate and microbial growth and production output of biomass are effective on bio filter’s performance, evaluating the effect of these quantities is necessary. Dynamic modeling of Biofiltration process of polluted air in stable and unstable conditions was conducted by emphasizing on humidity in the equations of mass transfer and sensitivity analysis in order for determining change effect of this parameter on the performance of model. The results show that the maximum amount of special growth results in the increase of absorption capacity, and also the model rightly confirms that constant increase of saturation
reduces the absorption capacity; whilst by means of this model, we can show that special surface switch and thickness change of biofilm are effective on absorption capacity.

**Keywords**: Biofiltration, dynamic modeling, moisture balance, numerical solution

1. Introduction

Microbial reactions from the early of 20th century up to now have widely been used in order for purifying the sewage and waste, but it was only in 1950 that biological approaches were used in order for purification of gaseous waste. In historical terms, biofiltration has in common been used in order for omitting odorous compositions such as hydrogen sulfide from the air in sewage refinement units. In 1970, when binding regulations were ordained in order for air pollution control and its implementation, the interest for using bio filters increased. There was a need for progressed bio filters that had the ability of purifying a high volume of smelly and infected by volatile organic compounds air. For the first time, new systems expanded in Germany and Netherlands. These bio filters had new air distribution system and in order for their performance improvement as compared with former bio filters, different fundaments were used like barks and sawdust and polyester bullets and peat (hollow and porous marshy wastes) and etc. In this way, platform compression reduced and air distribution became more uniform; however, yet there were some problems like drought and compression and acidification of platform [1].

Although, from 1980, biofiltration has been used in order for omitting volatile organic compounds in spread gases from different processes [2, 3], this technology is appealing in the environment temperature due to many reasons such as convertibility of pollutants to (CO2 + H2O) ineffective products. The other advantage of bio filters is non-production of secondary pollution and due to this reason, they are environment lover. Also, bio filters and biotrickling filters can be a more effective option as compared to old methods of air pollution control for high volumes and gas flows with low concentration that include biological biodegradable pollutants.

Also, since these systems work at ambient temperature and they don’t need high temperature environments, they need less energy.

Three primary arrangements in biological purification technologies usually include bio filter, biotrickling, and bio scrubber. Operation mode is similar in all of them. Humid polluted airflow is ferried through a loaded porous on which a combination of destructive organisms of pollutants have been stabilized.

Microorganisms constitute a lamina named biofilm that pollutants are consumed by permeating this layer in order for growth and survival of microorganisms. Biological destruction of pollutant occurs when microorganisms consume the pollu-
tants as carbon source or electron donor and produce accommodated compositions such as CO2, H2O and biomass and etc. Activity domain of biological purification processes is basically determined through physical and chemical properties of pollutants and inherent capabilities of microbe and environmental and operational conditions of the system.

In the following, there is a comparison of operation mode in these three purification arrangements.

<table>
<thead>
<tr>
<th>Aqueous phase</th>
<th>Microorganisms</th>
<th>Type of reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>Fixed bed</td>
<td>Biofilter</td>
</tr>
<tr>
<td>Fluent</td>
<td>Fixed bed</td>
<td>BiotricklingBiofilter</td>
</tr>
<tr>
<td>Fluent</td>
<td>Floating</td>
<td>Bio scrubber</td>
</tr>
</tbody>
</table>

In spite of this, bio filters’ modeling got started in order for biological purification of volatile organic compounds in air from 1980 by Ottengraf 1 which considered biological infiltration and destruction of pollutants in bio film [5]. During this time, zero and first surface kinetic phrases were introduced as the destruction process of model [6]. Disk and Ottengraf (1991) also studied the omission of dichloromethane vapors in a biotrickling bio filter. Gradually, the models became more complicated and durable and non-durable models were developed in order for providing a description of biomass degradation and aggregation mechanisms in biofiltration processes. Monod kinetic models including substrate inhibition were used by Zarok et al (1993) and Zilli et al (1993).

Also, for the first time, Zarok et al (1993) used a phrase for response rate that included limited effects of oxygen explicitly [6].

1.1. Biofiltration process mechanism

Biofiltration process is developed based on two basic phenomena:
- Transference of pollutant from air to the aqueous phase or carrier medium. Transference of pollutant from gas phase to liquid phase occurs according to physical regulations (figure 1-18). Concentration in water will be a proportion of concentration in air and it has Henry proportion stable. Generally, bio filters have the highest rate of omission for the compositions which are soluble in water and they are dissoluble biologically. Mathematical models usually provide this issue. Because, they evaluate biofilm similar to water using Henry fixed law in order to predict mass transfer to bio film, where decomposition occurs. Balance is a local phenomenon. Even, when each one of the concentrations in air and water are quite different based on height and depth, it is very likely that concentrations in Biofilter are in balance.
Figure 1: a close exponential from airway among fillers and transfer quality of pollutant from gas phase

Distribution of gaseous pollutant to biofilm phase is the first step for the destruction of pollutant (in bio scrubber and biotrickling bio filter, there is a liquid phase which is the connection limit of gas phase and biofilm that pollutant is initially transferred to this phase and then it is transferred to biofilm phase). In describing mass transfer of gas-biofilm, surface resistance between gas and biofilm is often ignored. Due to practical reasons, it is usually assumed that direct transfer of pollutant occurs between two phases and the obtained concentration is in balance in both gas and biofilm phase. Equilibrium distribution is to a much extent dependent on Henry’s law of pollutant [7].

Pollutant concentrations in gas and liquid phases are connected to each other by the following equation:

\[ K_H = \frac{C_g}{C_b} \]

Wherein \( K_H \) is dimensionless Henry’s law and \( C_g \) (gm-3) is the concentration of gas phase and \( C_b \)(gm-3) is the concentration of bio film phase. Regarding the pollutants with high Henry’s law, the distribution of pollutant to bio film phase is so little. In table 2, some Henry laws regarding different types of pollutants have been compared [7].

In a bio filter, there is less water content (40%-60%) and therefore, mass transfer of gas/bio film occurs with less surface resistance as compared to biotrickling Biofilter and bio scrubber that have high water content. In membranous bio reactor, there is no surface resistance of gas/ bio film. Therefore, having a relatively non-polar membrane like silicone membranes, this reactor can be very suitable for the pollutants with high Henry ratios [7].
In spite of fitness phenomenon, mass transfer also occurs. Some compositions which are practically insoluble in water are refined well. This high rate of removal in hydrophobic compounds specifies that current models don’t describe bio film transfer and its reaction well, because they predict weak mass transfer of these compositions and low removal rate. The research showed that mass transfer of hydrophobic compositions in biofilm was more than water and it justified high removal rate. Due to the consumption of pollutant in bio film, concentration of pollutants in that remains little. Therefore, transfer from the areas with high concentration to the areas with low concentration occurs easily; however, since bio film phase is disordered, permeating that is considered as limiter. Therefore, penetration in bio film might be prevented by the cells and polysaccharides.

Table 2: related Henry’s laws of different kinds of pollutants [7]

<table>
<thead>
<tr>
<th>Compound</th>
<th>$D_{\text{air}}$ (m$^2$s$^{-1}$)</th>
<th>$D_{\text{water}}$ (m$^2$s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen(25°C)</td>
<td>$1.4 \times 10^{-5}$</td>
<td>$2.5 \times 10^{-9}$</td>
</tr>
<tr>
<td>Ethanol</td>
<td>$1.24 \times 10^{-5}$</td>
<td>$1.13 \times 10^{-9}$</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>$1.64 \times 10^{-5}$</td>
<td>$2.0 \times 10^{-9}$</td>
</tr>
<tr>
<td>Benzene</td>
<td>$1.2 \times 10^{-5}$</td>
<td>$1.3 \times 10^{-9}$</td>
</tr>
<tr>
<td>Hexane</td>
<td>-----</td>
<td>$7.22 \times 10^{-10}$</td>
</tr>
</tbody>
</table>

Figure 2 shows concentration profile in gas phases and bio film inside the bio filter.

![Figure 2: concentration profile in gas phases and bio film inside the bio filter](image-url)
Transference of pollutant from common surface to the active biological phase is implemented through penetration which is describable with Fick's law:

\[ J = -D \frac{dC_b}{dx} \]

In which (mol.m\(^{-2}\).s\(^{-1}\), g.m\(^{-2}\).s\(^{-1}\)) is Jeremy reflux and D (m\(^2\).s\(^{-1}\)) is penetration and x (m) is the distance inside bio film. The amount of effective penetration ratio is so variable depending on the environment. Penetration inside the water is much slower than air and penetration inside the solution is slower than water. Approximately, penetration in a bio film is (0.5-0.7) of penetration in water; though exact amounts of penetration ratios are important in modeling. The important point is that needed concentration gradient for penetration is retained through a constant entrance of gas phase and pollutant removal is retained through microbial degradation reaction in bio film phase. Figure 4 shows concentration gradient between gas phase and bio film. Although microorganisms have a high tendency to most of biodegradable pollutants, they face problem in consuming the pollutant in concentrations less than \(\mu g.l^{-1}\) of water [7].

- Biological transformation of pollutant to biomass and final products of metabolism or carbon dioxide or water.

Pollutant in bio film which includes different grown organisms on solid carrier is decomposed biologically.

![Figure 3: a view of internal mechanisms of bio filter](image)

When pollutants are used as the power source, microbial metabolism of pollutants occurs easily. For example, toluene is consumed as the carbon source and electron donor by means of several organo-trophic bacteria. These bacteria use the oxygen as electron acceptor. Suitable access to nutrients such as minerals and vitamins and growth factors are necessary for suitable growth of microbial population. Therefore, microbial biomass functions as a biocatalyst which always retains its survival (through death and regrowth) [7].

Microorganism growth in Biofiltration process is so important. Growth rate depends on substrate access and temperature and PH and presentment of toxins.
and inhibitors. Biomass efficiency is related to the proportion of produced biomass and consumed substrate for its production:

\[ Y = \frac{dX}{dS} \]

\( Y \) (g.g\(^{-1}\)) is dry cell weight output to the mass of consumed substrate (polluter). \( X \) (gm\(^{-3}\)) is dry weight of biomass in bio film or suspension and \( S \) (gm\(^{-3}\)) is substrate weight. Output depends on bacterial species and specific substrate. If \( S \) substrate is the limiter of microorganism growth, Monod equation might be written so that specific growth rate (h\(^{-1}\)) \( \mu \) is related to substrate concentration:

\[ \mu = \mu_{\text{max}} \cdot \frac{S}{K_s + S} \]

In which \( \mu_{\text{max}} \) is the maximum growth rate and (h\(^{-1}\)) and \( K_s \) are half speed Monod constant for \( S \) substrate. In this equation, if the concentration is low, the equation is first level. Also, if the concentration is high, the equation will be zero level and it won’t be dependent on substrate concentration. By combining two former equations, a phrase will be obtained that relates consumption rate of substrate to substrate concentration and biomass:

\[ r = \frac{dS}{dt} = - \frac{\mu \cdot X}{Y} = - \frac{\mu_{\text{max}} \cdot X \cdot S}{(K_s + S) \cdot Y} \]

Microorganisms (biomass) can enter the reactor to different methods. In some cases, natural resources like soil or activated sludge of factories’ treatment unit is used in order for inoculation in reactor. Specific bacterial species or combinations of them which have been separated from the nature and have consumption capability of the intended material are also used. Also, regarding the pollutants which are used hardly, genetically modified species are usable [7]. Generally, inoculation of Biofilter with suitable bacteria reduces the beginning of the process significantly. Although operational conditions and common environmental factors have a specific effect on the existent microorganisms in reactor which result in the development of a specific microbial collection, this collection might be different from the inoculated collection in reactor. Following the change of microorganisms, all parameters of reactor also change [7].

### 2. Methodology

In the recent research, Biofilter is a filled column for removing a pollutant composition from air. In Biofiltration process, air results in the transference of pollutant to bio film phase by crossing the bed. The composed bio film on filling particles includes a collection of microorganisms that have the responsibility of pollutant destruction in a biological reaction. This phenomenon along with pene-
tration rate of pollutant to bio film creates the limitations of Biofiltration process. In order for the development of model, initially mass transfer equations including the pollutant and humidity are established inside the differential Element of the system and after discretization, they are solved by coding in MATLAB software environment. The basic equation of mass transfer based on the balance of mass conservation is as the following:

\[(\text{Rate of accumulation}) = (\text{entrance}) - (\text{exit}) - (\text{consumption})\]

This equation has the capability of establishment with different norms for each one of gas and bio film phases. Initially, equations for steady-state conditions are presented for modeling that a simpler condition is applied for modeling. Then, equations development is made for unsteady conditions and modeling is implemented under more complex situations.

- Mass balance of contaminant in gas phase in steady-state conditions:

Figure 4 shows \(\delta z\) differential element which has been considered in the direction of Biofilter height with \(z\) coordinate. The entrance air arrives the element with the constant speed of \(u_g\) (m/s) and pollutant concentration of \(C_g(z)\) (g/m³) and it exits that with \(C_g(z + \delta z)\) (g/m³) concentration. Also, moisture exchange takes place in this element. Inside the element, pollutant is consumed through \(-r_A\) biological reaction, by means of microorganisms. So, we have:

\[
\Delta u_g A_{cylinder} C_g(z) - u_g A_{cylinder} C_g(z + \delta z) - r_A V_{cylinder} = 0
\]

According to the presented explanations, we have:

\[
\Delta u_g A_{cylinder} C_g(z) - u_g A_{cylinder} C_g(z + \delta z) - r_A V_{cylinder} = 0
\]

In this equation, \(A_{cylinder}\) shows cross-section of element and \(V_{cylinder}\) shows element size. Concentration changes during the element occur due to biological reaction.
As it is clear, the amount of the transferred pollutant through penetration in the first layer in bio film equals to the amount of omitted pollutant through reaction by means of microorganisms. As a result, in mass balance equation, instead of response rate, we can replace the amount of penetration to bio film from the first layer which is expressed by Fick’s law.

Following the replacement of reaction norm in the above equation, we have:

\[
\frac{u_g A_{cylinder} C_{g}}{\delta z} - u_g A_{cylinder} C_{g} \bigg|_{x=0} + A_{cylinder} \delta z \left( A_{b} D_{b} \frac{\partial C_{b}}{\partial X} \bigg|_{x=0} \right) = 0
\]

By dividing the parties of the above equation on surface and \( \delta z \), we have:

\[
\frac{u_g C_{g}}{\delta z} - u_g C_{g} \bigg|_{x=0} + (A_{b} D_{b} \frac{\partial C_{b}}{\partial X} \bigg|_{x=0}) = 0
\]

Finally, by leading \( \delta z \) to zero and establishing boundary conditions, the following differential equation is obtained:

\[
-u_g \frac{\partial C_{g}}{\partial z} + A_{b} D_{b} \frac{\partial C_{b}}{\partial X} \bigg|_{x=0} = 0
\]

\[
C_{g}(0) = C_{fb}
\]

In the above equation, \( u_g \) (m/s) is polluted air stream flow and \( A_s \) (m\(^2\)) is specific surface of bio film and \( D_{b} \) (m\(^2\)/s) is effective penetration rate of pollutant in bio film and \( C_{g} \) (gr/m\(^3\)) is pollutant concentration in gas phase and \( C_{b} \) (gr/m\(^3\)) is pollutant concentration in bio film phase.

Also, \( C_{g}(0) \) (gr/m\(^3\)) is pollutant concentration in the first point inside bio filter.

Pollutant mass balance in bio film phase:

\[
D_{b} \frac{\partial^2 C_{b}}{\partial X^2} - X_s \frac{\nu_m C_{b}}{Y_{S}, K_s + C_{b}} + C_{b} = 0
\]

\[
C_{b}(0, z) = \frac{C_{g}(z)}{m}
\]

\[
\frac{\partial C_{b}(x, z)}{\partial X} = 0
\]

In this equation, \( X_s \) (gr dry cells/m\(^3\) biofilm) is cell density inside bio film and \( \nu_m \) (s\(^{-1}\)) is the maximum specific growth rate of microorganism inside the bio film and \( Y_{S}, \) (gr biomass/gr substrate) is biomass production output toward the pollutant of consumed substrate and \( K_s \) (gr/m\(^3\)) shows saturation constant. Also, \( m \) (with no dimension) is Henry’s law of the pollutant and \( x_n \) (m) is biofilm thickness. In reviewing boundary conditions of this equation, it is clarified that the first condition represents lack of resistance for pollutant transfer among the phases.
and balance among the phases. Also, the second boundary condition shows impermeability inside the filling particles.

- Moisture balance in gas phase in steady-state conditions:

\[
-u_s \frac{\partial H_g}{\partial z} - A_{D_{H_2O}} \frac{\partial H_g}{\partial x} \bigg|_{x=0} = -u_s \frac{\partial H_g}{\partial z} + K_s \alpha (H^* - H_g)
\]

\[H_g(0) = H_{w_0}\]

In this equation, \(H_g\) (kg \(H_2O/m^3\) air) is water density in gas phase and \(D_{H_2O} \) (m\(^2\)/s) is penetration ratio of water in air and \(H_b\) (H\(2O/m^3\) biofilm kg) is water density in bio film phase and \(H^*\) (kg \(H_2O/m^3\) air) is water saturation density in gas phase under environmental conditions and \(K_s\) (m/s) is mass transfer coefficient for evaporation and water transfer and \(a\) (m\(^{-1}\)) is specific surface of mass transfer by assuming spherical particles.

Paying attention to moisture balance equation in gas phase, it is clarified that the amount of water entrance to gas phase from the composed lamina around filling particles (penetration norm in point \(x=0\)) is equal to mass transfer relation between two points in gas phase. One of these two points is in gas phase and the other one is on the composed film on the particle and it is considered as full saturation.

Since, measurement of some parameters like special surface and bio film thickness and minor ratio (Henry’s law) and effective penetration ratio and all parameters of microbial kinetic are independently hard with experiment, in most cases, parameters are obtained by fitness. This affair, overall, inflicts massive and impartible error to the model.

For example, in order for simplification of modeling process, biofilm property inside Biofilter such as penetration ratio of pollutant and minor ratio is modeled with water properties. Although this affair might offer acceptable results to soluble and hydrophilic materials, it seriously affects determination of ratios for hydrophobic materials so that it makes the accuracy of model results unreliable. This problem was clarified in comparison with lab results for hydrophobic materials. For example, regarding Hexane pollutant, in spite of having slight solubility in water, lab results showed high removal [8].

In the current modeling, reliable and measured data with high accuracy of resources were utilized [8, 9] all of which attended in bio filters of Hexane purification. In order for determining the accuracy of model predictions of this research, Biofiltration results of the resources are evaluated at steady state and utilized in unsteady model.

The utilized Biofilter information [8] and the filled glass column to the height of one meter and inner diameter of 70 mili meters consisted of three parts and 4 sampling port. Any section’s mass was 850 mili liters which was filled with 96 gram perlite with the average diameter of 4 mili liters. Saturated air from Hexane entered from the top of the column with 2.5 l/min stream flow.
- Mass balance of pollutant in gas phase in unreliable conditions:

\[
\frac{\partial (e_x C_x)}{\partial t} = -u_g \frac{\partial C_x}{\partial z} + A_D \frac{\partial}{\partial x}\left|_{x=0} C_x\right.
\]

\[C_x(0,t) = C_{pm}\]

\[C_x(x,0) = C_{x_0}(x)\]

- Mass balance of pollutant in bio film phase in unreliable conditions:

By establishing the above balances similarly for bio film, we have:

\[
\frac{\partial C_b}{\partial t} = D_{hex} \frac{\partial^2 C_b}{\partial x^2} - \frac{X_g \cdot V_C}{y_g} C_b + C_b
\]

\[C_b(0,z,t) = \frac{C_x(z,t)}{m}\]

\[\frac{\partial C_b(x,z,t)}{\partial x} = 0\]

\[C_b(x,z,0) = C_{b_0}(x,z)\]

- Moisture balance in gas phase in unreliable conditions:

\[
\frac{\partial (e_x H_x)}{\partial t} = -u_g \frac{\partial H_x}{\partial z} - A_f \frac{\partial H_x}{\partial x}\left|_{x=0} = -u_g \frac{\partial H_x}{\partial z} + K_a (H' - H_g)\right.
\]

\[H_x(0,t) = H_{pm}\]

\[H_x(z,0) = H_{pm}(z)\]

Alongside these equations, the descriptive equation of the water content in filler in any element has been applied:

\[
\frac{\partial m}{\partial t} = -K_a (H' - H_g) \quad t = 0, m = m_0
\]

In which \(a(m^{-1})\) shows special surface of water mass transfer in filler and \(m\) (kg H2O/m3 air) shows the total water storage in Biofilter and \(m_0\) (kg H2O/m3 air) is water Filler storage at the beginning of unsteady conditions. Also, according to the usual introduced data for filler materials, calculations of water absorption rate of such particles were done in order for determining primary water supply of this column at the beginning of unsteady conditions.

In order for investigating the accuracy of model predictions in unstable state, reference data are used [10]. The filled glass column’s heath was 60 centimeter and its internal diameter was 50 milimeter. Column was filled with perlite and absorbent super with the size of 1 to 1.4 milimeter (figure 5). Air entered the column with different pollutant densities and air flows and its output densities were evaluated. Until 37th day, water
and minerals were added to both columns. The present model is used in order for predicting the days after dissection of bedewing.

Figure 5: a view of two used Biofilter column one of which is filled with perlite and the other one is filled with the mixture of absorbent super and perlite.

![Figure 5: a view of two used Biofilter column one of which is filled with perlite and the other one is filled with the mixture of absorbent super and perlite.](image)

Figure 6: concentration change under reliable and unreliable conditions in different entrance concentrations

All used parameters for predicting Biofiltration data have been mentioned in the following table:

Table 3: offered model’s parameters (Espingo et al, 2004 and 2005)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Amount</th>
<th>Parameter</th>
<th>Unit</th>
<th>Amount</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m^2 s^{-1}$</td>
<td>$1.22 \times 10^{-4}$</td>
<td>$D'$</td>
<td>$kg kg^{-1}$</td>
<td>1.313953</td>
<td>$Y_{x/p}$</td>
</tr>
<tr>
<td>$gm^{-3}$</td>
<td>78.94</td>
<td>$K_p$</td>
<td>$\mu m$</td>
<td>387</td>
<td>$\delta$</td>
</tr>
<tr>
<td>$gm^{-3}$</td>
<td>0.02</td>
<td>$k_p$</td>
<td>$gm^{-3}$</td>
<td>9744</td>
<td>$X_p$</td>
</tr>
</tbody>
</table>
Table 3: (Continued): offered model’s parameters (Espingo et al, 2004 and 2005)

<table>
<thead>
<tr>
<th></th>
<th>9.14</th>
<th>$m_p$</th>
<th>$h^{-1}$</th>
<th>$5.83 \times 10^{-5}$</th>
<th>$\mu_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>m$^2$s$^{-1}$</td>
<td>2.58$\times 10^{-10}$</td>
<td>$D_p$</td>
<td>-------</td>
<td>0.45</td>
<td>$\varepsilon$</td>
</tr>
<tr>
<td>-------</td>
<td>------</td>
<td>-------</td>
<td>---------</td>
<td>-------------------</td>
<td>--------------------</td>
</tr>
</tbody>
</table>

3. Results

3.1. Reliable modeling results

By solving mass transfer equations, model is able to present output results of biofiltration. One of the obtained data from modeling is predicting concentration changes of pollutant in different elements in bio filter. As it was explained in modeling part, bio filter’s height has been distributed to different elements that following the beginning of numerical solution process, mass and humidity transfer equations from close to border elements enter all internal elements and concentrations start convergence in order to reach the concentration number in stable state and in order for the changes to vanish. This process continues as long as any element converges and as a result Biofilter output attains convergence. Figure 8 shows these changes in the primary element inside the bio filter.

Figure 7: concentration changes in the primary element inside the bio filter.

Figure 8 shows concentration changes of pollutant in the last element. Following any repetition in the plan, gradually, the equations converge and reach their stable amount. The reason of this concentration increase to a maximum amount is the dependence of this concentration to the former elements inside Biofilter which occurs through the coefficients of mass transfer equation. Also, by comparing the amounts of this figure with the former figure, it is clarified that gradually, concentrations decline and it means that modeling process during the height has been
modeled well. This is because; bacterial biofilm during the height gradually results in the concentration reduction.

![Figure 8: concentration changes in the final element inside bio filter](image)

During Biofiltration at steady state, the amount of moisture in Biofilter is a constant number. Also, air moisture inside Biofilter is also a number between saturation moisture and dry conditions. With this account, During the numerical solution, the model has earned a constant amount for moisture and retained that. This is because postulating the equations’ solution at steady state is that moisture is supplied continuously and there is no water shortage in bed. The following figure shows humidity changes diagram during the time at steady state which has been modeled well. In fact, assuming bedewing of bed, there is humidity since the beginning of Biofilter operation and we don’t have gradual process for that.

![Figure 9: moisture chart inside bio filter](image)
In order for evaluating the accuracy of modeling at steady state, we use the article data. Figure 11 shows a sample of reference data [8] which has been predicted by means of the model.

![Figure 10: data modeling of Arriaga et al [8]](image)

Modeling results confirm the accuracy of applied parameters for modeling. This modeling’s error is so little.

Also, the assumptions of the present model are more complete as compared to the reference model. Because, in this reference, modeling has been conducted by approximating Monod equation with the kinetics of zero-order reaction which is only possible in high concentrations, but the present model, by considering both penetration resistance and Monod reaction has presented a better result. So, the mentioned assumption for approximation has not presented a good fitness.

In the following, prediction of Biofiltration process data of the second reference [10] at steady state has been conducted. Hexane as the pollutant has entered the Biofilter in three 1.5 and 1 and 0.5 gr/m³ concentrations in order to establish steady conditions. The present model along with the confirmed parameters from the former modeling was used in order for data prediction. Figure 12 shows the comparison of the obtained results from model prediction and concentration change data of input pollutant. As it is observed in the figure, the model is able to predict the data with an acceptable error (on average 10.6 percent).

![Figure 11: model prediction for Biofiltration data in different entrance concentrations](image)
3.2. The results of unsteady modeling

Figure 13 shows unsteady modeling of reference data [10] in the entrance concentration of 1 and stream flow of 0.3. In this Biofiltration, after interrupting bed bedewing, microbial bio film wastes gradually and as a result, output concentration increases gradually. Due to the conduction of biological reaction of the pollutant destruction which is among exothermic reactions, evaporation rate inside the bed is high. Gradually, following water evaporation and bed drought, the activity of microorganisms responsible for pollutant destruction reduces and concentration increases. Fresh air with the moisture less than saturation slowly dries some parts of the bed which are exposed to moisture and deactivates them. Interruption of bedewing has been implemented from 37th day in reference Biofiltration (by omitting steady days at the beginning of the following diagram, bedewing has been equalized from zero day of this diagram) that the model has predicted this concentration increase process well and in spite of that the continuation of predictions has been made up to gaining the entrance concentration in the model (there are no reference data).

![Figure 12: predicting experimental data by the model in entrance concentration 1 and stream flow 0.3.](image)

Figure 13 shows unsteady modeling of reference data [10] in the entrance concentration 1 and stream flow 0.5. As, it is clear from the figure, modeling of this process has been conducted well.

![Figure 13: predicting experimental data by the model in entrance concentration 1 and stream flow 0.5](image)
Figure 15 shows the entrance concentration 1 and stream flow 0.7. The increase of stream flow has resulted in more rapid changes in the model. As a result, the model in this stream flow has not been able to predict concentration increase process well the results of which can be analyzed according to the presented model by Kumar that in the intensity of above flows corrects biomass density [11].

Figure 14: predicting experimental data by the model in the entrance concentration 1 and stream flow 0.7

Figure 15 shows moisture changes (water content) of bed in elements. As long as further elements are on the way of air stream, the moisture of next elements is supplied through evaporation in this element. The effect of moisture loss in the previous element and the result of low humidity of gas phase in the same element are slowly transferred to the next element in order for the mentioned element to exit the calculations route eventually by losing its available water quietly. This figure has modeled moisture reduction process well.

Figure 15: moisture changes of bed in an element

Figure 16 shows the effect of sudden change of entrance concentration on the output concentration of Biofilter which is reminisced as concentration shock. As it is obvious in the figure, following the change of entrance concentration, another
non-reliability factor in the system results in the changes in side Biofilter. Finally output numbers change. These three conditions have been predicted by the model well that during 6 days, the condition achieves its new reliable state.

Figure 16: the effect of concentration shock in Biofilter output

Figure 17 shows concentration profile inside Biofilter in three different air flows. In spite of the fact that concentration has been modeled well in the final point of height (0.6 meter) in three flows, the change process of concentration profile is also significant. Under constant conditions (the same height), the more flow, due to time reduction, has resulted in the increase of concentration limitation inside bio filter, whereas the less flow has resulted in more decomposition of the pollutant.

Figure 17: concentration profile inside Biofilter in three different flows

3.3. Sensitivity analysis

The used parameters in modeling can be effective in model performance and in order for confirming the model; we should evaluate model sensitivity to each one of them. Constant saturation changes and changes in microbe inclination to the consumption of the intended pollutant and some other parameters can be effective
on Biofilter performance. Evaluation of the effect of these quantities on the performance of model results in better understanding of model changes and determining model sensitivity to that parameter.

Figure 18 shows the effect of the changes of specific growth maximum on the predicted removal capacity by the model. According to this, the increase of the amount of specific growth maximum results in the increase of removal capacity. The reason is that following the increase of this quantity, bacteria production increases and as a result it is accompanied with the Increase of pollutant consumption and as a result, removal capacity increases slowly. Also, if the kind of bacteria is replaced with a bacteria having more specific growth maximum, removal capacity will increase that this problem specifies the importance of using rapid growth bacteria.

Figure 18: the effect of the changes of specific maximum growth on removal capacity

Figure 19 shows the effect of constant saturation changes on the predicted reliable removal capacity by the model.

As it is clear in this figure, following the increase of constant amount of saturation, removal capacity decreases slowly. The reason is that following the constant increase of saturation, microbe’s inclination to pollutant destruction is less and as a result, removal capacity reduces. This means that if the intended microbe has more tendencies to the decomposition of pollutant, removal capacity increases. Therefore, appropriate initial inoculation from the microbe desiring pollutant omission reduces the time of Biofiltration process and increases removal capacity of bio filter.
Figure 19: the effect of constant saturation changes on reliable removal capacity

Figure 20 shows specific surface changes of bio film on removal capacity. Specific surface equals to the active surface of mass transfer of pollutant so that following the specific surface increase, transfer rate of pollutant increases because removal capacity of Biofilter increases. Also, the change effect in specific surface can determine the kind of used filler in order to facilitate mass transfer of pollutant. The more is the porosity (in fact, if the surface increases in volume unite), the specific surface increases.

Figure 20: the effect of specific surface changes of bio film on removal capacity

Figure 21 shows the effect of thickness change of bio film on removal capacity. Although, no change occurs in bio film thickness during Biofilter operations, model sensitivity was evaluated by changing this parameter. Following the increase of bio film thickness, removal capacity reduces the reason of which is the obstruction of bed and high pressure drop and inappropriateness of this increase in the model is shown to the form of reducing removal amounts.
Figure 21: the effect of the changes of microbial bio film on removal capacity

Figure 22 shows model sensitivity to the changes of entrance moisture on the time of unreliable conditions in Biofiltration. Following moisture increase of the entrance air, in fact, microbial bio film wastes later and as a result, more time is provided for unreliable condition of the system.

Figure 22: the effect of the changes of entrance moisture on the time of unreliable condition

4. Conclusion

According to surveys of this study, the following results were obtained:

1. Biofiltration hexane data are entered into the model steadily and unsteadily. The results of model predictions showed good agreement with experimental data. Based on these results, this model could well be used to describe the biofiltration under the same conditions.

2. The steady model, even relative to the reference with more complex equations, had less error; this is a strength point.
3. The algorithm is embedded in such a way that the program will enhance the speed of the application, and presents the results in less than half a minute.

4. Simplifying assumptions had not a significant impact on the results of model predictions, and the models could well give an estimate of the level of output densities.

5. The sensitivity analysis showed that the saturation constant and maximum growth rate have minimal impact on the results of model predictions, and yet the greatest impact is related to biofilm thickness and the moisture.

References


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