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Comparison of the Monod and Kincannon-Stover Models for Kinetic Evaluation in an Anaerobic Baffled Reactor (ABR)

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Abstract
A pilot scale anaerobic baffled reactor (ABR), for treating low-strength industrial wastewater (671.5±49.9 mg COD/L, 350.1±36.8 mg BOD_5/L) was studied. The reactor was started with a hydraulic retention time (HRT) of 25 h and this was gradually reduced to 3.33 h. The best reactor performance was observed with an organic loading rate (OLR) of 4.45 g COD/L.d which was at HRT of 4 h and the COD removal efficiency was obtained up to 78.27% and majority of COD removal was occurred in the first compartment. Under these conditions, for prediction of the effluent substrate concentration (S_e) and optimum volume of the ABR (V), the Monod and Kincannon-Stover models were investigated. With using the Kincannon-Stover model, parameters of U_{max} and K_B were obtained 2 and 2.14 g COD/L.d, respectively since, for the Monod model, the parameters of K and K_S resulted as 1.54 g COD/g VSS.d and 0.21g COD/L, respectively. The regression line for the plotted linear equation of the Kincannon-Stover model had a R^2 of 0.84 which was lower than that found for the Monod model with R^2 of 0.985. Meanwhile, in the Monod model, the parameters of Y and K_d were obtained 0.073 g VSS/g COD and -0.008 d^{-1}, respectively. The present study demonstrated that the Monod model is more suitable and applicable for formulating a kinetic model for prediction of the effluent substrate concentration and optimum volume of the ABR at the similar operation conditions.

Keywords: Degree of regression, Effluent substrate concentration, Kinetic parameters, Optimum volume, Substrate removal rate.

مقایسه مدل‌های مونود و کینکنون – استور در ارزیابی سینتیکی یک راکتور بافلدار بی‌هوازی

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چکیده
یک پایلوت راکتور بافلدار بی‌هوازی، به‌منظور تصفیه فاضلاب صنعتی ضعیف (۶۷۱/۵±۴۹/۹ mg COD/L و ۳۵۰/۱±۳۶/۸ mg BOD_5/L) مورد مطالعه قرار گرفت. کارکرد راکتور با زمان ماند هیدرولیکی ۲۵ ساعت آغاز شد که به تدریج تا ۳/۳۳ ساعت کاهش یافت. بهترین عملکرد راکتور در نرخ بارگذاری آلی ۴/۴۵ g COD/L.d، در زمان ماند هیدرولیکی ۴ ساعت مشاهده شد که راندمان حذف COD برابر با ۷۸/۲۷٪ بدست آمد و بیشتر حذف COD در اتاقک اول حادث شد. در این شرایط برای پیش بینی غلظت سوبسترای خروجی (S_e) و حجم اپتیمم راکتور (V)، مدل‌های مونود و کینکنون – استور مورد بررسی قرار گرفتند. با استفاده از مدل کینکنون – استور، پارامترهای U_{max} و K_B به ترتیب برابر با ۲ و ۲/۱۴ g COD/L.d بدست آمدند؛ در حالی که در مدل مونود، پارامترهای K و K_S به ترتیب برابر با ۱/۵۴ g COD/g VSS.d و ۰/۲۱ g COD/L بدست آمدند. خط رگرسیونی معادله خطی رسم شده مدل کینکنون – استور دارای R^2 برابر با ۰/۸۴ بود که پایین تر از مقدار بدست آمده برای مدل مونود با R^2 برابر با ۰/۹۸۵ بود. در ضمن، در مدل مونود، پارامترهای Y و K_d به ترتیب برابر با ۰/۰۷۳ g VSS/g COD و ۰/۰۰۸ d^{-1}- بدست آمدند. این مطالعه اثبات کرد که مدل مونود مدل مناسب‌تر و کاربردی تر برای فرموله کردن مدل سینتیکی به‌منظور پیش بینی غلظت سوبسترای خروجی و حجم اپتیمم راکتور بافلدار بی‌هوازی تحت شرایط عملیاتی مشابه می باشد.

کلمات کلیدی: درجه رگرسیون، غلظت سوبسترای خروجی، پارامترهای سینتیکی، حجم اپتیمم، نرخ حذف سوبسترا.

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Introduction

Anaerobic digestion is a complex process of degradation of organic compounds through a variety of intermediates into methane and carbon dioxide, by the action of a consortium of anaerobic microorganisms (Liu *et al*., 2002; Singh and Prerna, 2009). The increased utilization of anaerobic systems has been associated with the development of high-rate reactors that are able to separate hydraulic retention time (HRT) from solids retention time (SRT) for retaining the active biomass in the reactor for a long period (Lettinga *et al*., 1997; Akunna and Clark, 2000). Nowadays with use of innovative high-rate reactors such as the upflow anaerobic sludge blanket (UASB), anaerobic baffled reactor (ABR), anaerobic filter (AF), anaerobic sequencing batch reactor (ASBR) and anaerobic hybrid reactors, anaerobic treatment can now challenge the cost of aerobic treatment for many wastewater treatment applications (Rajeshwari *et al*., 2000). Among these reactors, the ABR was suggested by many researchers as a promising system for treatment of industrial and municipal wastewaters (Kuscu and Sponza, 2005; Dama *et al*., 2002). The development of ABR was undertaken which needed neither the sludge blanket nor the granular biomass by virtue of its configuration (Langenhoff *et al*., 2000; Bodkhe, 2009). The most significant advantage of the ABR is its ability for partial separation of the acidogenesis and methanogenesis phases longitudinally down the reactor without operational issues and costs related to the phased reactors (Vossoughi *et al*., 2003; Wang *et al*., 2004). Process modeling is a useful tool for describing and predicting the performance of anaerobic digestion systems (Jimenez *et al*., 2004). It seems that a combination of theoretical considerations and experimental findings can be used together in order to generate models with a more realistic fit (Noykova and Gyllenberg, 2000). Most models are not operationally useful, because of their complexity and the uncertainties in selection and measurement of input and output parameters crucial to effective simulation and prediction. Hence, modeling efforts often are based upon selected fundamental principles and then generalized in order to enhance applied facility for process and design control. (Siles *et al*., 2008). There are different models for predicting the effluent substrate concentration in anaerobic treatment systems. In the models of Grau, Contois, Chen & Hashimoto, Kincannon-Stover and First-order kinetics, the effluent substrate concentration, S_e, is a function of the influent substrate concentration, S_i. This is in contrast with the Monod model where S_e is independent of S_i. Meanwhile these models also most frequently assume completely mixed and steady-state conditions (Malina and Pohland, 1992). In order to better understand the ABR operation and to describe reactor performance, attempts have been made to model an ABR reactor (Xing *et al*., 1991). Kennedy and Barriault assumed the ABR to be a continuous stirred tank reactor (CSTR) and used first order kinetics with results that showed first order kinetics for evaluating of substrate removal didn't describe ABR behavior (Kennedy and Barriault, 2007). Bachmann and co-workers proposed a combination of a flat fixed film model with a variable order model that incorporated the concepts of liquid-layer mass transfer, Monod characteristics, and molecular diffusion to describe the ABR process. This model assumed a constant diffusion layer depth and required the specific surface area of biomass in each reactor compartment, which is difficult to determine (Bachmann *et al*., 1985). Nachaiyasit extended the model to spherical biofilms which, with requirement to surface area measurements, the obtained model is difficult to apply (Nachaiyasit, 1995; Kennedy and Barriault, 2007). Studies with purpose of substrate removal rate evaluation using Grau, Contois, Chen & Hashimoto and Kincannon-Stover models were not investigated in the pilot or full scale ABR until now.

The purposes of the present work are: a) formulation of kinetic models for prediction of effluent substrate concentration, S_e, and optimum volume of the ABR, V., for which the Kincannon-

Stover and Monod models were selected; b) evaluation of other kinetic parameters in the Monod models. In this study, the reason for selecting the Kincannon-Stover model, goes back to the history of ABR invention where McCarty and co-workers at Stanford University noticed that most of biomass present within an anaerobic rotating biological contactor (ARBC) was actually suspended and, when they removed the rotating disks, they observed the ABR (Barber and Stuckey, 1999). Furthermore, the initial Kincannon-Stover model that is described as equation (1), was first used for Rotating Biological Contactor (RBC) systems for which they assumed that the suspended solids in the RBC is negligible in comparison to the attached biomass. In this model parameters of ds/dt and A represent the substrate removal rate and disk surface area, respectively (Stover and Kincannon, 1982; Flora *et al*., 1995).

$$\frac{d_s}{d_t} = \frac{U_{max}\,(\frac{Q\,S_i}{A})}{K_B + (\frac{Q\,S_i}{A})} \qquad (1)$$

Results of other studies with aim of modification of this model showed the suspended biomass is a significant factor in organic removal in the fixed film reactors. Broch-Due and co-workers observed that the suspended biomass contributes nearly 50% of total organic removal in the moving bed biofilm reactors. Therefore they put volume of the reactor, V, instead of A in the equation (1). Hence, the modified Kincannon-Stover model is described as equation (2) (Broch-Due *et al*., 1994).

$$\frac{d_s}{d_t} = \frac{U_{max}\,(\frac{Q\,S_i}{V})}{K_B + (\frac{Q\,S_i}{V})} \qquad (2)$$

Monod models have been widely used to describe the process kinetics of anaerobic digesters for which most research has showed the S_e is independent of S_i (McCarty and Mosey, 1991; Malina and Pohland, 1992), but in some studies S_e was a function of the S_i (Hu *et al*., 2002). On this basis, in the evaluation of substrate removal rate from olive mill wastewater, Martin and co-workers observed that the Contois model is more suitable than the Monod model to predict the anaerobic digester performance (Martin *et al*., 1994). However, in this study the Monod model was selected because of its reliability and the success of this model for predicting the anaerobic reactors performance in numerous research projects. The Monod model for substrate removal rate is described as equation (3) (Tchobanoglous and Burton, 2003).

$$\frac{d_s}{d_t} = \frac{K\,X\,S_e}{K_s + S_e} \qquad (3)$$

Materials and Methods

Reactor Set-up

The plexi glass ABR in pilot scale, with rectangular shape, external dimensions of 100 cm length, 25 cm width and a depth of 40 cm, and the working volume of the reactor of 100 L was used in this study. As shown in Fig. 1, the reactor was divided into six identical 16.67 L compartments by vertical standing baffles, each compartment having downflow (down comer) and upflow (up comer) regions created by a vertical hanging baffle. The width of up comer was 2.6 times of the width of down comer (The width of up comer and down comer were 12.2 and 4.6 cm, respectively). The lower portions of the hanging baffles were bent 3 cm above the reactor`s bottom at a 45° angle to route the flow to the center of the up comer , thus achieving better contact and greater mixing of feed and biosolids at the base of each riser. Liquid sampling ports were located about 10 cm from the top of each compartment. This reactor was equipped with a temperature control chamber (water bath) for adjustment of reactor temperature. During the start-up and also the steady-state periods, the operating temperature was

maintained constant at 35 ± 0.5ºC. The influent feed was pumped from equalization tank of Amirkabir industrial park wastewater treatment plant (which is located in Isfahan Province, Iran) to ABR pilot using an adjustable diaphragm pump (Ethatron, HRS technology, Italy).

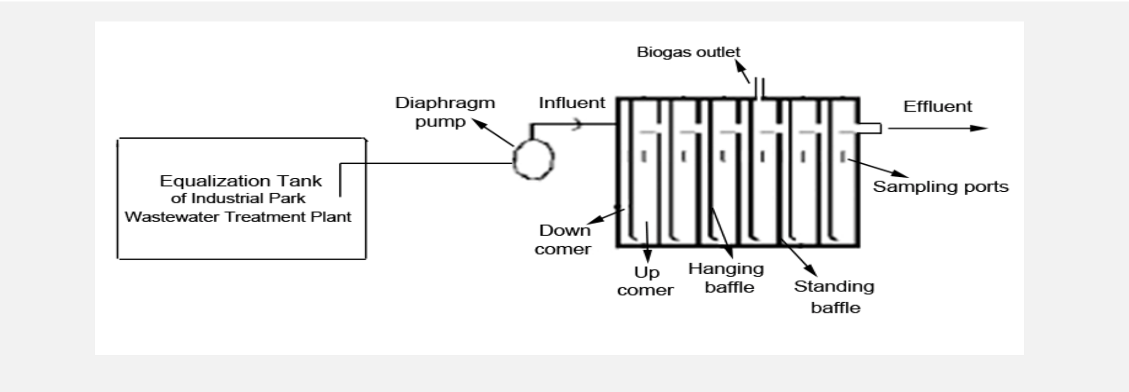

Figure 1- Schematic diagram of pilot-scale Anaerobic Baffled Reactor used in this study.

Seed Sludge

The ABR was initially seeded with anaerobic digested sludge taken from the anaerobic digester of municipal wastewater treatment plant (Isfahan Province, Iran). Before seeding the reactor, large particles and debris from the sludge were removed by passing it through a sieve (<5 mm). The neat anaerobic sludge was then introduced uniformly into all six compartments of reactor, so that each compartment was filled with 35% sludge with solids concentration of 36.7 g SS/L and 25.1 g VSS/L giving a total of 878 g VSS in the reactor. This value (8.78 g VSS/L of reactor volume) was in accordance with the initial VSS values used in other studies on ABR (Barber and Stuckey, 1999). The remaining part of each compartment was filled with industrial park wastewater taken from equalization tank. After seeding the reactor, the lids were sealed and operating temperature was maintained constant at 35± 0.5 ºC.

Wastewater Characteristics

Characteristics of wastewater from the Amirkabir Industrial Park are shown in the Table 1. Indeed, 25% of the mixture of this wastewater comprised effluents from textile, cardboard, meat processing and dairy industries, and the main part of it was sanitary effluents from different factories. Generally, during the reactor operation period, experimental results showed no need to add nitrogen and phosphorous to influent of the reactor.

Table 1 - Wastewater characteristics of industrial park fed to ABR in this study.

Parameters	Concentration
COD (mg/L)	671.5 ± 49.9
BOD_5 (mg/L)	350.1 ± 36.8
TSS (mg/L)	258.8 ± 51.6
SO_4^{-2} (mg/L)	443.8 ± 60.7
TN (mg N/L)	57.4 ± 8.03
TP (mg P/L)	5.22 ± 0.94
Ortho-P (mg/L)	17.05 ± 1.36
pH	7.57 ± 0.19

Analysis

Liquid samples were taken from the influent, six compartments, and effluent of the reactor, starting at the last compartment towards the first, to prevent air intrusion and to maintain anaerobic conditions. COD, pH and TSS were measured every two days. While influent total nitrogen (TN), total phosphorous (TP), Orthophosphate (Ortho-P) and BOD_5 were measured weekly and temperature was monitored daily. These parameters were set based on Standard Methods for the Examination of Water and Wastewater (APHA, 2005). Photometer AL-250 of Aqualytic was used for analyzing of COD, BOD-system Oxi-Direct of Aqualytic for analyzing of BOD_5 and photometer

Multi-Direct of Aqualytic for analyzing of SO_4^{-2}, TN, TP and Ortho-P were used. Meanwhile Senso-Direct pH200 of Aqualytic was used for measuring of pH (Aqualytic devices were made in Germany).

Results

Reactor Start-up and Performance

Prompt start-up is essential for a highly efficient operation of ABR, due to the slow growth rates of anaerobic microorganisms, especially MPBs; establishment of the most suitable microbial population is critical to the prompt start-up of ABR (Liu *et al*., 2010). Table 2 shows a summary of reactor operation conditions. For the ABR start-up, the system was initially run on batch for 10 days. During this time, the content of the reactor was recycled once for homogeneity. After this period, the ABR was run continuously with feeding the industrial park wastewater. During the entire length of the study, the organic loading rate (OLR) was increased by decreasing the hydraulic retention time (HRT). The reactor was started with HRT of 25 h (corresponding OLR= 0.58 ± 0.02 g COD/L.d). It was gradually decreased to 20, 10, 6.67, 5, 4 and 3.33 h in steps that corresponding OLRs are shown in Table 2. As shown in Fig. 2 and also in Table 2, the OLR was finally increased to 5.44 g COD/L.d at HRT of 3.33 h. For each HRT, steady state was marked by relatively stable effluent COD values with less than 5% variation. Therefore, the HRT was decreased after that no more fluctuation was observed in effluent COD. In this study the best ABR operation conditions was observed at HRT of 4 h. In this condition, it was assumed that a steady-state condition prevailed in the best reactor performance and the experiments were carried out in the completely mixed condition for kinetics evaluation. According to Fig. 2 and Fig. 3, the maximum of COD removal efficiency was obtained up to 78.27% with HRT of 4 h (corresponding OLR= 4.45 g COD/L.d). Meanwhile COD variation profile at different compartments of ABR system is illustrated in Fig. 4. As shown in this figure, most of the COD removal occurred in the first compartment. As COD decreased in the preceding compartment, a reduction in substrate utilization rate of the microorganisms in the subsequent compartments would result, leading to lower removal efficiency. (Krishna *et al*., 2007; Saritpongteerala and Chaiprapat, 2008).

Table 2- ABR reactor operation conditions (continuous running).

Operation Days	HRT (h)	Upflow Liquid Velocity (m/h)	OLR (g COD/L.d)	COD Removal %	pH (first-sixth compartments)	Effluent TSS (mg/L)
1-6	25	0.157	0.58 ± 0.02	4.52 ± 3.2	7.875-7.93	24 ± 0.89
7-26	20	0.196	0.79 ± 0.03	38.1 ± 12.3	6.557-6.98	27.3 ± 2.19
27-54	10	0.392	1.61 ± 0.11	53.8 ± 6.5	6.92-7.31	34.4 ± 1.85
55-71	6.67	0.588	2.44 ± 0.15	63.2 ± 4.43	6.82-7.1	39.9 ± 2.11
72-85	5	0.784	3.43 ± 0.13	65.4 ± 4.66	6.347-6.783	42.01 ± 1.5
86-96	4	0.980	4.1 ± 0.26	71.6 ± 6.67	6.253-6.74	46.4 ± 1.41
97-105	3.33	1.176	5.13 ± 0.35	44.6 ± 13.1	7.073-7.373	59.3 ± 3.27

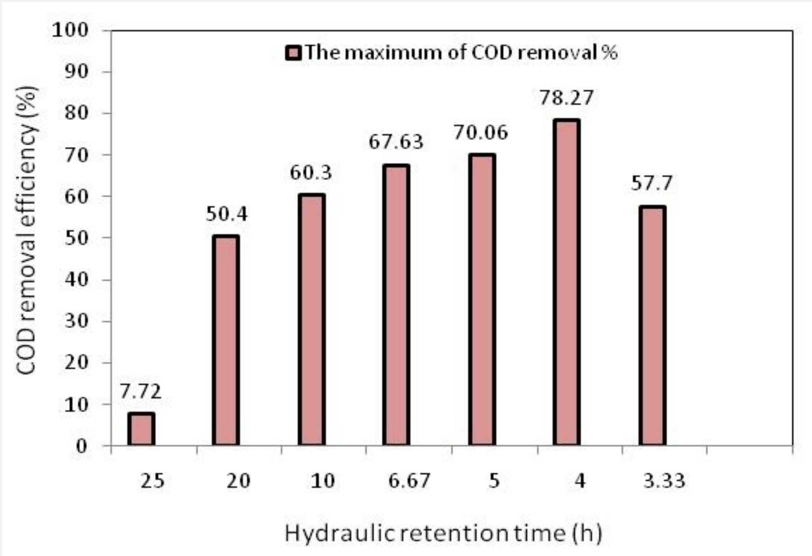

Figure 2 - COD removal efficiency based on loading rates.

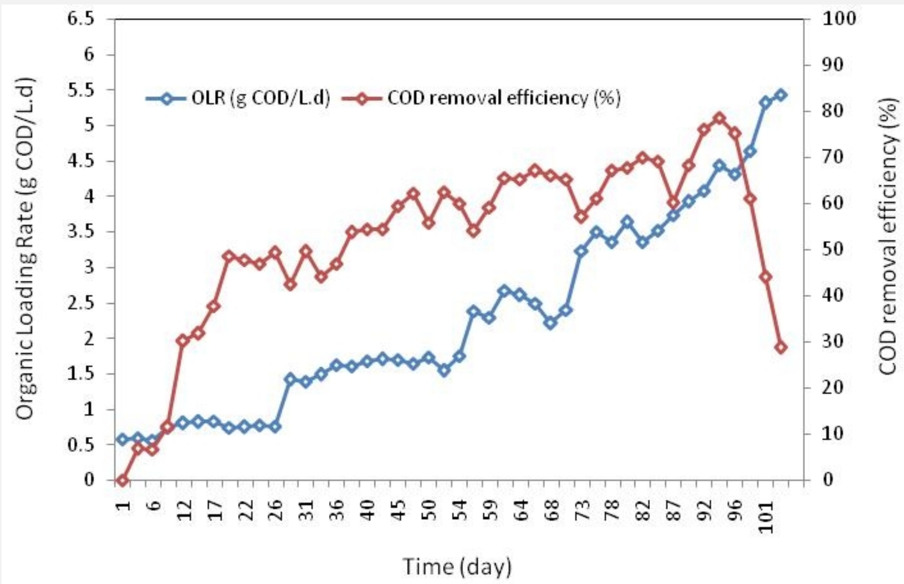

Figure 3 - The maximum of COD removal efficiency based on HRTs.

Formulating Kinetic Models using Kincannon-Stover Model

With the aim of formulating kinetic models for prediction of S_e and optimum V of the ABR using Kincannon-Stover model, the following stages were done:

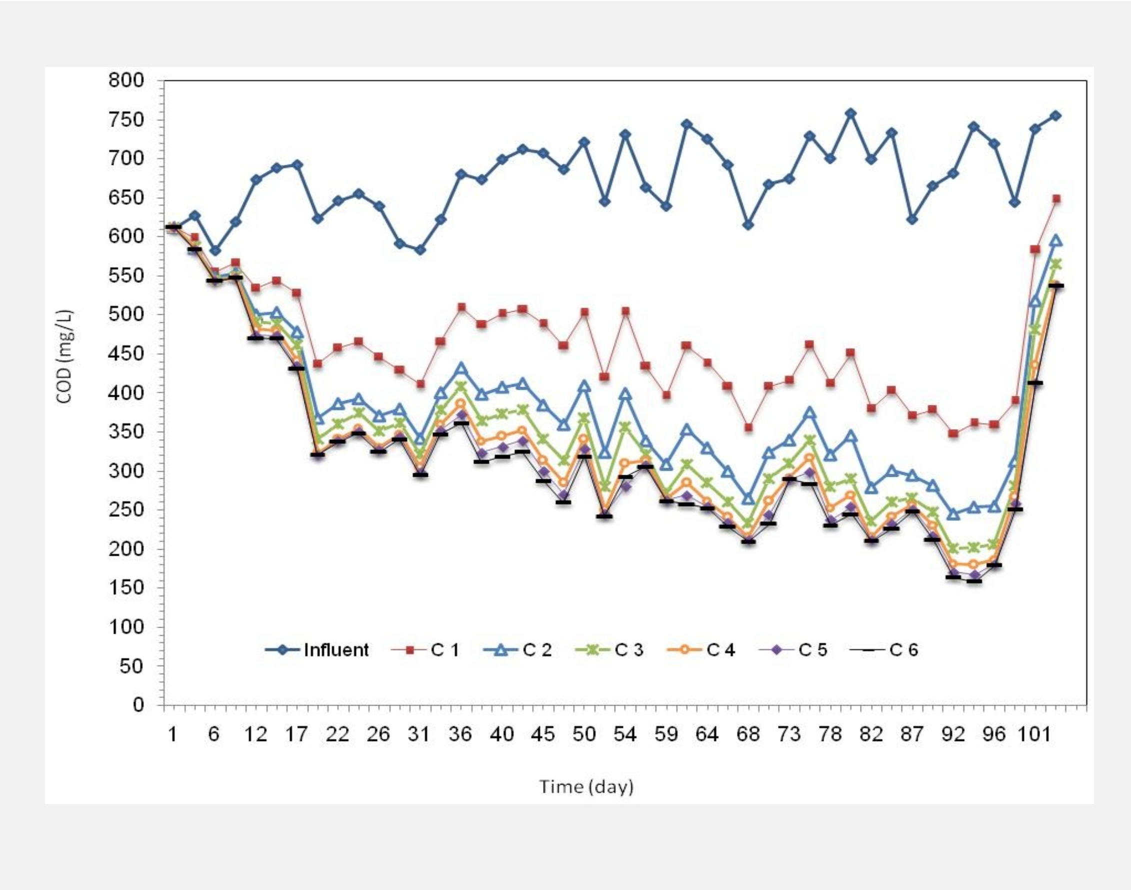

Figure 4 - COD variation profile at different compartments of ABR (C_i: Compartment).

The substrate removal rate based on the mass balance of substrate into and out of the biological reactor can be described as equation (4) (Tchobanoglous and Burton, 2003).

$$\frac{d_s}{d_t} = \frac{Q}{V}(S_i - S_e) \qquad (4)$$

From equations of (2) and (4), the equation (5) was resulted.

$$\frac{d_s}{d_t} = \frac{Q}{V}(S_i - S_e) = \frac{U_{max}\,(\frac{Q\,S_i}{V})}{K_B + (\frac{Q\,S_i}{V})} \qquad (5)$$

Then the linear equation (6) can be made from equation (5).

$$\frac{1}{\frac{d_s}{d_t}} = \frac{V}{Q(S_i - S_e)} = \frac{K_B}{U_{max}}\left(\frac{V}{QS_i}\right) + \frac{1}{U_{max}} \qquad (6)$$

Finally, the equation (7) was obtained for the effluent substrate concentration, S_e, and the equation (8) was obtained for the volume of the ABR at the similar operation conditions, V.

$$S_e = S_i - \frac{U_{max} \cdot S_i}{K_B + \frac{Q\,S_i}{V}} \qquad (7)$$

$$V = \frac{Q\,S_i}{\left(\frac{U_{max} \cdot S_i}{S_i - S_e}\right) - K_B} \qquad (8)$$

According to equation (6), by plotting $V/Q(S_i\text{-}S_e)$ against V/QS_i, a straight line was achieved that this plot is shown in the Fig. 5. Then, by measuring the intercept and slope of this line, the parameters of U_{max} and K_B were obtained 2 g COD/L.d and 2.14 g COD/L.d, respectively that the regression line had a R^2 of 0.84 where R is the degree of regression. Meanwhile by substitution of obtained U_{max} and K_B in the equations (7) and (8), equations (9) and (10) were resulted. The equation (9) describes the S_e and the equation (10) describes the V, under similar operation conditions, e.g., type of wastewater, similar ABR, temperature,
etc.

$$S_e = S_i - \frac{2\,S_i}{2.14 + \frac{Q\,S_i}{V}} \tag{9}$$

$$V = \frac{Q\,S_i}{\left(\frac{2\,S_i}{S_i - S_e}\right) - 2.14} \tag{10}$$

Formulating Kinetic Models using Monod Model

With the aim of formulating kinetic models for prediction of S_e and V of the ABR using Monod Model, the following stages were done:

From equations of (3) and (4), the equation (11) was achieved.

$$\frac{d_s}{d_t} = \frac{Q}{V}(S_i - S_e) = \frac{K\,X\,S_e}{K_s + S_e} \tag{11}$$

Then the linear equation (12) can be made from equation (11).

$$\frac{XV}{Q(S_i - S_e)} = \frac{K_s}{K}\frac{1}{S_e} + \frac{1}{K} \tag{12}$$

Eventually, equation (13) resulted for the S_e that definitions of β and Δ are described as equations (14) and (15), respectively.

$$S_e = \frac{-\beta \pm \sqrt{\Delta}}{2Q} \tag{13}$$

$$\beta = Q(K_s - S_i) + XVK \tag{14}$$

$$\Delta = \beta^2 + 4Q^2 S_i K_s \tag{15}$$

Also the equation (16) was obtained for the V of the ABR at the similar operation conditions.

$$V = \frac{Q(S_i - S_e)(S_e + K_s)}{KXS_e} \tag{16}$$

Based on equation (12), by plotting $XV/Q(S_i\text{-}S_e)$ against $1/S_e$, a straight line resulted the plot of which is shown in Fig. 6. Then, by measuring the intercept and

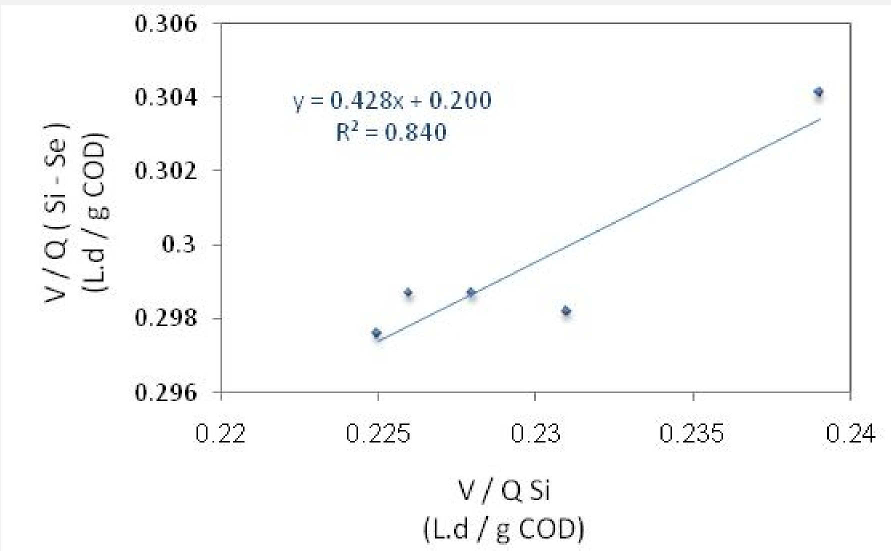

Figure 5 - The plot of the equation (6) for calculation of parameters of U_{max} and K_B in the Kincannon-Stover model.

slope of this line, the parameters of K and K_S were obtained 1.54 d^{-1}(g COD/g VSS.d) and 0.21 g COD/L, respectively the regression line of which had a R^2 of 0.985 where R is the degree of regression. Meanwhile by substitution of obtained K and K_S in the equations (14) to (16), equations (17), (18) and (19) were achieved. Hence, by substituting the obtained equations (17) and (18) into equation (13), this equation describes the S_e and the equation (19) describes the V of the ABR, under similar operation conditions, e.g., type of wastewater, similar ABR, temperature, etc.

$$\beta = Q(0.21 - S_i) + 1.54(XV) \tag{17}$$

$$\Delta = \beta^2 + 0.21(4Q^2S_i) \tag{18}$$

$$V = \frac{Q(S_i - S_e)(S_e + 0.21)}{1.54(XS_e)} \tag{19}$$

Calculation of other kinetic parameters in the Monod model

For this work the following equations (20) and (21) were used:

$$\frac{1}{\theta_c} = Y\frac{Q(S_i - S_e)}{XV} - K_d \tag{20}$$

$$K = \frac{\mu_{max}}{Y} \tag{21}$$

Applying experimental results to equation (20), by plotting $\frac{1}{\theta_c}$ against $\frac{Q(S_i-S_e)}{XV}$ a straight line was obtained whose plot is shown in Fig. 7. Then, by measuring the intercept and slope of this line, the parameters of Y and K_d were achieved at 0.073 g VSS/g COD and -0.008 d^{-1}, respectively, where the regression line had a R^2 of 0.981 where R is the degree of regression. Furthermore, by substituting obtained K and Y in the equation (21), μ_{max} was calculated 0.112 d^{-1} with following calculation:

μ_{max} = 1.54 g COD/g VSS.d × 0.073 g VSS/g COD = 0.112 d^{-1}

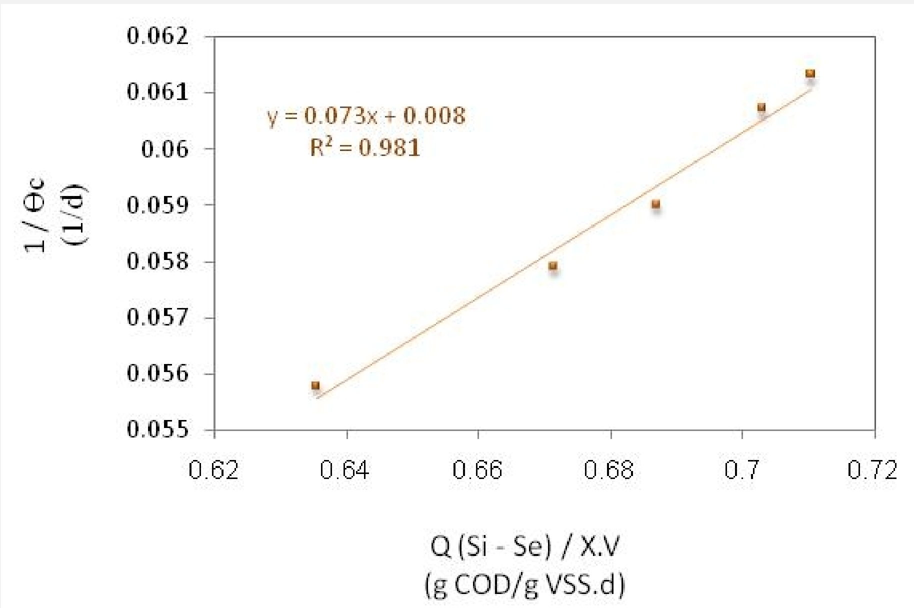

Figure 6 - The plot of equation (12) for calculation of parameters of K and K_S in the Monod model.

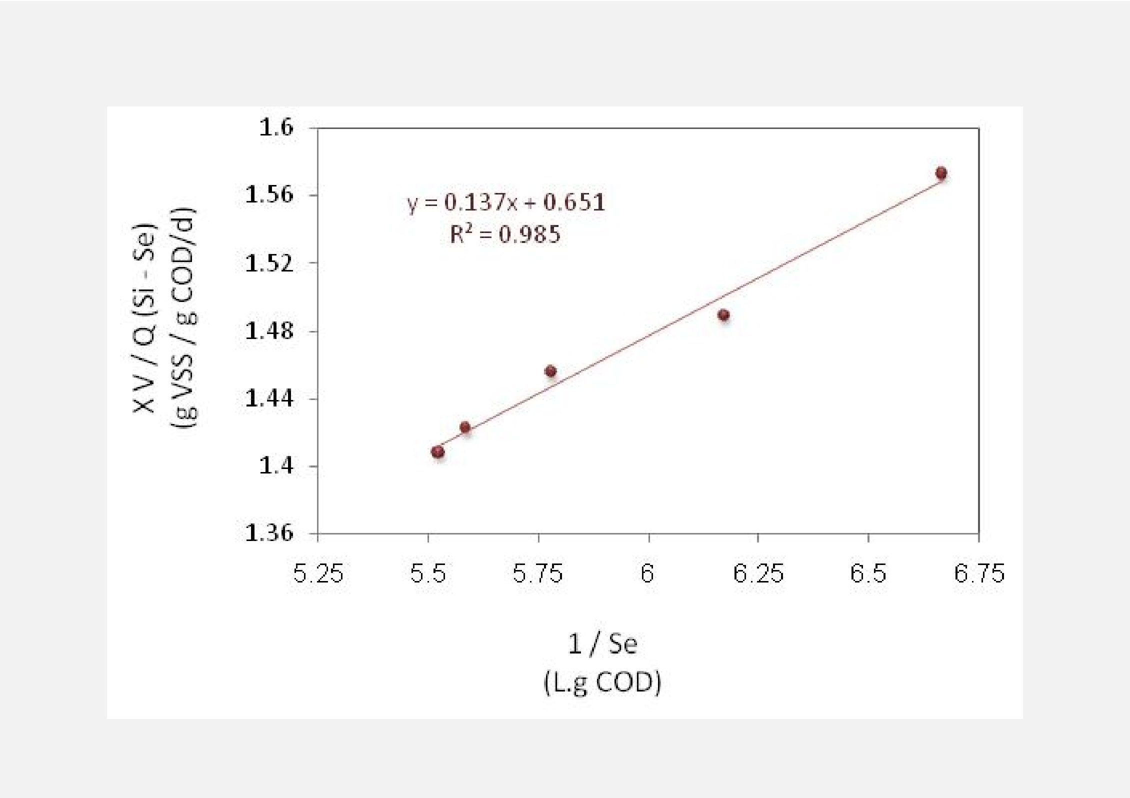

Figure 7 - The plot of the equation (20) for calculation of parameters of Y and K_d in the Monod model.

Discussion

In this study the majority of COD removal efficiency was achieved in the first compartment and low COD removal efficiencies occurred in the subsequent compartments. Indeed, as COD decreased in the earlier compartments a lower COD concentration remained for methane producing bacteria (MPBs) which lead to decrease in their biological activity in the subsequent compartments. This is because, based on bacterial kinetics, lower substrate concentration will cause lower growth rate. As a remedial solution, split feeding of ABR, i.e. entering wastewater into one of the earlier compartments (with the exception of first compartment) as well as influent of ABR, can be effective for treatment of low-strength industrial wastewaters. With this procedure, substrate concentration is increased in the subsequent compartments which causes higher MPB biological activity but it seems that there is no separation of the acidogenic and methanogenic phases with split feeding of ABR.

The regression line for the plotted linear equation of the Kincannon-Stover model had an R^2 of 0.84 which is lower than that found for the Monod model with R^2 of 0.985. Therefore dispersion of the obtained data in the Monod model was lower than the Kincannon-Stover model. Furthermore in the Monod model S_e is a function of the biomass concentration, VSS, but in the Kincannon-Stover model S_e is independent of VSS. Also in the Monod model more kinetic parameters with respect to the Kincannon-Stover model cause more accuracy of study. Hence the present study demonstrated that the Monod model is more suitable and applicable for formulating kinetic models for prediction of effluent substrate concentration and the optimum volume of the ABR at the similar operation conditions. Meanwhile in the most of kinetic studies, successfully of the Monod model has proven for evaluation of substrate removal rate.

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Nomenclature

A: Disk surface area of the RBC (cm^2).

K: The maximum of substrate utilization rate in unit mass of microorganism (g COD/g VSS.d).

K_S: Half-velocity constant (g COD/L).

K_B: Proportionality constant or substrate loading at which the rate of substrate utilization is one-half the maximum rate (g COD/L.d).

K_d: Endogenous decay coefficient (d^{-1}).

Q: Influent flow rate (L/d).

S_e: Effluent substrate concentration (g COD/L).

S_i: Influent substrate concentration (g COD/L).

U_{max}: Kincannon-Stover's maximum substrate utilization rate (g COD/L.d).

V: Volume of the reactor (L).

X: Volatile suspended solids concentration (g VSS/L).

Y: Yield coefficient (g VSS/g COD).

θ_C: Sludge age or solids retention time (d).

μ_{max} : The maximum of specific growth rate (d^{-1}).

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