Calibration and verification of models of organic carbon removal kinetics in Aerated Submerged Fixed-Bed Biofilm Reactors (ASFBBR): a case study of wastewater from an oil-refinery

Karol Trojanowicz and Włodzimierz Wójcik

ABSTRACT

The article presents a case-study on the calibration and verification of mathematical models of organic carbon removal kinetics in biofilm. The chosen Harremoës and Wanner & Reichert models were calibrated with a set of model parameters obtained both during dedicated studies conducted at pilot- and lab-scales for petrochemical wastewater conditions and from the literature. Next, the models were successfully verified through studies carried out utilizing a pilot ASFBBR type bioreactor installed in an oil-refinery wastewater treatment plant. During verification the pilot biofilm reactor worked under varying surface organic loading rates (SOL), dissolved oxygen concentrations and temperatures. The verification proved that the models can be applied in practice to petrochemical wastewater treatment engineering for e.g. biofilm bioreactor dimensioning.

Key words | biofilm modelling, biofilm reactors, petrochemical wastewater

INTRODUCTION

The development of mathematical models to provide mechanistic representation for processes that take place in biofilms first occurred in the nineteen-seventies (1970s) and continues successfully to this day. There has been progress on a wide range of models within this field. From analytical and pseudo-analytical, one-dimensional models describing the process of the utilization of a single substrate by heterotrophic microorganisms; through much more complex, numerically solved models of biofilm describing the simultaneous removal of organic carbon and nutrients by multi-species, auto-and heterotrophic biota; to the complex two- and three-dimensional models developed in recent years, detailing the processes in biofilm in the micro-scale, like the spatial structure of biofilm, mass transport and hydrodynamics within biofilm and the spatial distribution of different types of organisms and their interactions within biofilm (Mann & Stevenson 1997; Henze et al. 2000; Morgenroth et al. 2000; Vanhooren 2002; Wanner et al. 2006; Takacs et al. 2007). Authors such as P. Wilderer, P. Harremöes, and B. E. Rittmann, emphasize the need to link theory with practice, for the transition from the design and operation of fixed bed biofilm reactors based on engineering pragmatism to the application in these areas of well-developed scientific theories. These authors indicate that this is a condition for the further development of biofilm technology and meeting the future challenges of emerging contaminants removal from wastewater (oxidized inorganics: bromate, selenate, chromate and perchlorate, oxidized organics: chlorinated aliphatics, chlorinated aromatics, nitro-aromatics and fluorinated aliphatics, metals: cadmium, zinc and nickel, endocrine disruptors: pharmaceuticals, plasticizers) (Wuertz et al. 2005; Wanner et al. 2006; Rittmann 2007).

The paper is novel because of a previous lack of information on the calibration and verification of mathematical models of organic carbon removal kinetics in attached-growth bioreactors treating petrochemical (oil-refineries) wastewater. Also a set of model parameters utilized during the calibration and verification – such as kinetic and stoichiometric coefficients, biomass parameters, and COD fractions...
of pretreated petrochemical wastewater – were determined in the course of separate dedicated experiments conducted using actual petrochemical wastewater and biofilm grown under exposure to such wastewater. Calibrated models can be applied to dimensioning of Aerated Submerged Fixed-Bed Biofilm Reactors (ASFBBR) used for the treatment of wastewater from the petrochemical industry.

Objectives

The aim of the presented research was the practical demonstration of the calibration and verification of two mathematical models of organic carbon removal kinetics in biofilms (Harremoës 1978 model and Wanner & Reichert 1996 model) (Harremoës 1978; Wanner & Reichert 1996). The mathematical models were calibrated using the conditions of oil-refinery wastewater treatment with an Aerated Submerged Fixed-Bed Biofilm Reactor (ASFBBR). This objective was achieved through the following steps:

- choice of kinetic models,
- model calibration based on the influent and biofilm characterization, determined kinetic parameters (in separate studies) and literature data,
- analysis of model uncertainty,
- verification of models through the analysis of operation of a pilot bioreactor under changing reactor technological parameters, such as surface organic loading rate (SOL), dissolved oxygen concentration and temperature and then comparison of the measured and simulated data (specifically the effluent concentration of COD).

If either or both of these models prove to be useful, they can be used to supplement or replace physical experiments and pilot scale tests thereby resulting in savings to plant designers and operators.

METHODS

Kinetic models

Two models of organic carbon removal kinetics in a biofilm reactor were chosen to carry out the calibration, simulation and verification, bearing in mind the following issues:

- modeling objectives - goal for which they would be used after calibration,
- modeling capability of the user of the model - ease of finding solutions to the model (depending on the model assumptions, simplifications and the resulting structure of the model), so that the possibility of their use was not limited by the future users’ (practitioners) knowledge and their resources (availability of references),
- practicality and ease of use.

Therefore, we selected two one-dimensional (1D) biofilm reactor models, which enable users to easily simulate the substrate removal rate in relation to the unit area of biological film. The first of the selected models was developed by Paul Harremoës in 1978 and is one of the earliest analytical one-dimensional models of biofilms describing the kinetics of organic carbon conversion processes in biofilm. The second model was developed by Wanner & Gujer (1986) and further extended and verified by Wanner & Reichert (1996). It is undergoing continued research and is widely considered to be the state-of-the-art in 1D biofilm modeling. The detailed description of both models are readily available in the literature (Harremoës 1978; Wanner & Gujer 1986; Wanner & Reichert 1996; Reichert 1998a, b; Henze et al. 2000; Vanhoooren 2002; Wanner et al. 2006).

The software used for simulation

Simulations based on the Harremoës model were conducted using a simple calculator written in Visual Basic for Excel, developed for the purpose of this project and tentatively named BiofilmSimulator (Trojanowicz 2009).

Simulations based on the Wanner-Reichert model were performed using a dedicated software application called Aquasim 2.1 f (EAWAG) (Reichert 1998a, b; Wanner & Morgenroth 2004).

Object of modeling

A pilot Aerated Submerged Fixed-Bed Biofilm Reactor (ASFBBR) was installed in the technological line of an industrial wastewater treatment plant at the Oil Refinery "Glimar" S.A. in Gorlice, (see Figure 1) in the southern part of Poland. The pilot bioreactor was set as third stage wastewater treatment, the wastewater’s pretreatment with a gravity oil-water separation (API), coalescent separation (CPI) and the coagulation-flotation units (DAF).

Oil-refinery wastewater composition

As it was mentioned in previous section, wastewater at the bioreactor inlet was mechanically and chemically treated (oil-water separators API and CPI, dissolved air flotation DAF
with coagulation and floculation processes). Therefore, the wastewater was coagulated via a full-scale process and contained mostly soluble organic compounds (soluble fraction of COD). The COD fractions in the samples taken at bioreactor inlet and outlet were determined in a dedicated experiments (Trojanowicz 2009) which is to be the subject of a separate article. Values of determined COD fractions at the bioreactor inlet are presented in Table 1. Biodegradable fraction of COD \((f_B)\) during the same experiments was equal to 0.4 in relation to soluble COD and 0.45 in relation to total COD in the wastewater at the bioreactor inlet.

Calibration

The values of most parameters of the model were compiled from additional pilot and laboratory experiments. During conducting of these experiments the respirometric methods were chosen to determine: the heterotrophic growth rate \((\mu_{\text{max},H})\), decay coefficient \((b_H)\), half saturation coefficient \((K_S)\) and fraction of active heterotrophic biomass \((f_{A,H})\). The method for heterotrophic yield \((Y_H)\) determination based directly on COD and the total suspended solids measurements during batch tests. Details concerning methods of kinetic and stoichiometric parameters determination for heterotrophic microorganisms under petrochemical wastewater condition were described in a separate article (Trojanowicz et al. 2009). The values of biofilm parameters: concentration of total suspended solids in biofilm \((X_{T_{PB}})\), concentration of active heterotrophic bacteria in biofilm \((X_{A_{PB}})\) and biofilm thickness \((L)\) were determined utilizing samples of biofilm taken from pilot ASFBBR bioreactor (Trojanowicz 2009). The values of some parameters such as the half saturation coefficient for dissolved oxygen \((K_O)\), and the oxygen and organic matter diffusion coefficients in water \((D_O, D_S)\) were taken from the literature (Wanner et al. 2006).

A set of model parameters used in their calibration are presented in Table 2.

Verification

Verification of the model was carried out on an independent sample of input data (not used for calibration) collected during the operation of the pilot plant. The concentration of organic compounds measured as COD was a control parameter. During the pilot tests the reactor worked under conditions of variable loading rates of COD, dissolved oxygen concentration and temperature. Wastewater flow rate, volume of the bed of the fixed bed biofilm reactor, and the efficiency of aeration system were modified to obtain the following effects:

- low organic loading rate / high concentration of oxygen,
- low organic loading rate / low concentration of oxygen,
- high organic loading rate / high concentration of oxygen,
- high organic loading rate / low concentration of oxygen.

Simulations were conducted for steady state conditions allowing a comparison of both models. In addition to the two sets of data obtained during the pilot research, a study with the dynamic simulations from Aquasim 2.1 f. was carried out. The results of real data (measured COD) from the operation of the pilot plant were compared with data from the simulation.

The program of measurements at the stage of model verification. Table 3 shows the input data required to conduct the simulation. The scope of this program affected the measurements and the physical and chemical analysis of wastewater at the inlet and outlet of the bioreactor, which were necessary to verify the models. The control parameter (COD value in the wastewater) was measured daily along with wastewater pH, flow rate, temperature and dissolved oxygen concentration. COD was measured as total COD and soluble COD (after wastewater filtration through 0.45 μm membrane filters) in the inlet of the bioreactor and as soluble COD in the outlet of the bioreactor. Besides the parameters described above, the concentration of total suspended solids,

### Table 1

<table>
<thead>
<tr>
<th>COD</th>
<th>Inlet [gCOD/m³]</th>
<th>Fraction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>95.5 (34.8–170.9)</td>
<td>–</td>
</tr>
<tr>
<td>Particulates</td>
<td>30.3 (3.5–85.7)</td>
<td>31.8</td>
</tr>
<tr>
<td>Coloids</td>
<td>10.2 (1.3–38.8)</td>
<td>10.6</td>
</tr>
<tr>
<td>Soluble</td>
<td>55.0 (26.8–121.5)</td>
<td>57.6</td>
</tr>
</tbody>
</table>
nutrients and phenol index were monitored once every seven days. The Polish Standards methods (PN) were used during the tests.

**Simulation of organic carbon removal with Biofilm-Simulator 1.0 - Simulation for the steady-state.** In “Biofilm-Simulator 1.0” the properties of the simulated system are specified in the dialog box “Model Calibration and Simulation” (Figure 2). The user enters the input values in accordance with the terms set out in Table 3, and starts the simulation.

### Table 2 | A set of model parameters used for calibration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value (standard deviation)</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_{\text{max},H}$</td>
<td>d$^{-1}$</td>
<td>6.1 (0.58)</td>
<td>Maximum specific growth rate for heterotrophic biomass (Trojanowicz et al. 2009)</td>
</tr>
<tr>
<td>$Y_H$</td>
<td>GCOD/gCOD</td>
<td>0.58 (0.015)</td>
<td>Yield of heterotrophic biomass produced on substrate utilized (Trojanowicz et al. 2009)</td>
</tr>
<tr>
<td>$K_S$</td>
<td>GCOD/m$^3$</td>
<td>9.4 (2.09)</td>
<td>Half saturation coefficient for organic substrate (Trojanowicz et al. 2009)</td>
</tr>
<tr>
<td>$K_O$</td>
<td>gO$_2$/m$^3$</td>
<td>0.2 (--)</td>
<td>Half saturation coefficient for oxygen (Trojanowicz et al. 2009)</td>
</tr>
<tr>
<td>$b_H$</td>
<td>d$^{-1}$</td>
<td>0.18 (0.008)</td>
<td>Decay coefficient for heterotrophic biomass (endogenous respiration rate) (Trojanowicz et al. 2009)</td>
</tr>
<tr>
<td>$f_A,H$</td>
<td>–</td>
<td>0.46 (0.015)</td>
<td>Fraction of active heterotrophic biomass (Trojanowicz et al. 2009)</td>
</tr>
<tr>
<td>$f_B$</td>
<td>–</td>
<td>0.4 (0.15)</td>
<td>Fraction of biodegradable substrate in total soluble substrate (Trojanowicz et al. 2009)</td>
</tr>
<tr>
<td>$X_{\text{TF}}$</td>
<td>gCOD/m$^3$.biofilm</td>
<td>74300 (22000)</td>
<td>Concentration of total suspended solids in biofilm (Trojanowicz et al. 2009)</td>
</tr>
<tr>
<td>$X_{\text{HF}}$</td>
<td>gCOD/m$^3$ biofilm</td>
<td>34200 (10100)</td>
<td>Concentration of active heterotrophic bacteria in biofilm (Trojanowicz et al. 2009)</td>
</tr>
<tr>
<td>$L$</td>
<td>M</td>
<td>2.867 $10^{-4}$ (1.823 $10^{-4}$)</td>
<td>Biofilm thickness (Trojanowicz et al. 2009)</td>
</tr>
<tr>
<td>$D_O$</td>
<td>m$^2$/d</td>
<td>2 $10^{-4}$ (--)</td>
<td>Diffusion coefficient of oxygen in water (Wanner et al. 2006)</td>
</tr>
<tr>
<td>$D_S$</td>
<td>m$^2$/d</td>
<td>1 $10^{-4}$ (--)</td>
<td>Diffusion coefficient of soluble organic matter in water (Wanner et al. 2006)</td>
</tr>
</tbody>
</table>

### Table 3 | Input data required for simulation

<table>
<thead>
<tr>
<th>Model parameters</th>
<th>Reactor parameters</th>
<th>Biomass parameters</th>
<th>Indicators of water quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic coefficients</td>
<td>Volume of biofilm bed</td>
<td>Biofilm thickness</td>
<td>COD (soluble fraction)</td>
</tr>
<tr>
<td>Stoichiometric coefficients</td>
<td>Volume of bioreactor</td>
<td>Concentration of active heterotrophic biomass in biofilm</td>
<td></td>
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<td></td>
<td>Specific surface area of biofilm carrier material</td>
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<td></td>
<td>Temperature of wastewater in the bioreactor</td>
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<tr>
<td></td>
<td>Wastewater flow rate</td>
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<tr>
<td></td>
<td>Dissolved oxygen concentration</td>
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</table>
The equations defining the rate of organic carbon removal in biofilm, transport of substrate into the biofilm, and organic substrate concentration (calculated from the mass balance at the bioreactor outlet) are permanently set in the program and the user cannot change these relationships. The option initialized by the button "AutoSim" results in the automatic importing of "Reactor parameters" data from a "Data" spreadsheet, the running of the program, and the saving of simulation results.

Processes and reactor configuration in the Aquasim 2.1f program - simulation for steady state and dynamic conditions. The equations describing the kinetics of growth and decay of the heterotrophs in biofilm were specified in compliance with the formulas of Wanner and Reichert model’s Petersen matrix (Wanner & Reichert 1996; Reichert 1998a, b; Vanhooren 2002), whereas equations of transport processes and mass balance are an uneditable part of the program. In the case of steady-state simulations the active processes only included the process of heterotrophs growth which affects only one component of the system - the concentration of organic substrate in the bulk liquid. In the case of dynamic simulations the active processes were: growth and endogenous respiration of heterotrophs, which affect the concentration of organic substrate, heterotrophic biomass concentration in the biofilm and the biofilm thickness.

ANALYSIS OF MODEL UNCERTAINTY

Aquasim 2.1f. The Aquasim 2.1f program contains algorithms for the estimation of the uncertainty of simulation results (Reichert 1998a, b). The uncertainty of simulation results are calculated on the basis of the propagation of uncertainty (errors) of all model parameters (expressed as their standard deviations). Thus, for selected control parameters (the parameters of state) the software provides their average, calculated values in addition to a statistical distribution representing the uncertainty in the results. The Aquasim program can automatically estimate the standard deviation of each result of the simulation. The condition for using this capability is an a-priori knowledge of the standard deviations of the individual parameters used for model calibration.

Biofilm Simulator 1.0. An estimation of the uncertainty of the simulation results in the Biofilm Simulator 1.0 was carried out using a Monte Carlo method. This method consists of multiple repeating simulations for the same set of input data with random selection of model parameters values: kinetic parameters ($\mu_{\text{max},H}, Y_H, K_S, b_H$), the biomass parameters ($X_{\text{HF}, L}$) and the fractions coefficients ($f_{A,H}, f_B$), according to their a-priori estimated statistical distributions (standard deviations - Table 2).

RESULTS

Figures 3 to 8 present the selected, exemplary plots of measured values of COD concentration at the outlet of the bioreactor, the simulated values of the same control parameter for the two models under study, and the correlations between the measured and simulated values. Simulation results are presented separately for different dissolved oxygen concentrations and organic carbon loading rates of the bioreactor. The results obtained during dynamic and steady-state simulations are shown separately.

DISCUSSION

For all operational conditions of wastewater treatment with a pilot ASFBBR bioreactor, good compliance was observed between the simulation results and the measured data of the control parameter (COD concentration) (Figures 3–8). This confirmed that the models were selected and calibrated correctly.

Models were calibrated using a set of twelve parameters (Table 2). Nine of them were determined in complementary studies conducted in the laboratory and at pilot scales. Results of the determination of the fundamental kinetic parameters of growth and decay of heterotrophs in a biofilm under petrochemical wastewater condition (specifically: $\mu_{\text{max},H}, K_S, Y_H, X_{\text{HF}, b_H}$) show that they do not differ significantly from the values recommended for the same parameters in the litera-
ture (see Table 4). This is true despite the fact that their values were obtained during dedicated experiments, in which bio-

mass grew under exposure to petrochemical wastewater. It is quite an interesting finding because variables characteristic of industrial wastewater may cause changes in the biocenosis of heterotrophic bacteria in the treatment plant, the metabolic pathways of organic contaminants degradation, and, as a consequence, the values of kinetic parameters may change. It is of great importance when it comes to the use of biofilm models in practice, because it allows the supposition that the
values of these parameters have some level of universal character, which significantly decreases the costs and time of implementation of the models by practitioners (consultants, designers, plant operators).

The parameters discussed above are components of kinetic equations describing transformation processes in biofilm at the cellular level (Henze et al. 2000). Equally important in biofilm models are parameters that describe mass transport of substrates and products from the bulk liquid into biofilm and in the opposite direction. The values of the diffusion coefficients of the dissolved fraction of COD and oxygen, derived from the literature, are the values recommended for use in the modeling of biofilms (Wanner et al. 2006).

Figure 5 | Comparison of measured and simulated values of COD concentration in the effluent at the outlet of the bioreactor. Conditions of high organic loading rate and low dissolved oxygen concentration.

Figure 6 | Correlation between measured and simulated values of organic substrate concentration ($S_0$) at the bioreactor outlet (as COD) and between the values obtained during the simulation with the Harremoës model (BiofilmSimulator) and the Wanner and Reichert model (Aquasim). Conditions of high organic loading rate and low dissolved oxygen concentration.
Model verification was performed by comparing the values of the control parameter (dissolved fraction of COD at the bioreactor outlet) with the values measured during the process of wastewater treatment at the ASFBR pilot plant. Choosing COD as the control parameter was justified on the grounds that the role of the bioreactor was polishing the petrochemical wastewater of residual dissolved organic contaminants after pretreatment with the use of physical and chemical processes. It should be mentioned here that, as described earlier, technological parameters of the treatment
process such as bioreactor surface organic loading rate (SOL), the dissolved oxygen concentration (SO) and water temperature in the reactor varied within a wide range over the course of the study.

The results of simulations carried out for conditions of a low COD loading rate and high dissolved oxygen concentration in the reactor (SOL_{av.} = 6.5 \text{ gCOD/m}^2 \text{d}, S_O = 7.8 \text{ gO}_2/\text{m}^3), and a low COD loading rate and a relatively low dissolved oxygen concentration in the reactor (SOL_{av.} = 8.2 \text{ gCOD/m}^2 \text{d}, S_O = 2.0 \text{ gO}_2/\text{m}^3) indicate the almost complete removal of the dissolved fraction of biologically degradable COD from the wastewater. Calculated values of the biological degradable COD at the outlet of the reactor were for these conditions, on average: 3.3% and 2.1% of total COD for the Aquasim and BiofilmSimulator programs respectively. Therefore, it was necessary to confirm the accuracy of the simulation under conditions of a high organic loading rate and a high dissolved oxygen concentration in the reactor (SOL_{av.} = 25.1 \text{ gCOD/m}^2 \text{d}, S_O = 10.6 \text{ gO}_2/\text{m}^3), and a high organic loading rate and a relatively low dissolved oxygen concentration in the reactor (SOL_{av.} = 88.8 \text{ gCOD/m}^2 \text{d}, S_O = 2.8 \text{ gO}_2/\text{m}^3).

Simulated values of biodegradable COD for the conditions described above were respectively: 20.4% (BiofilmSimulator) and 21.9% (Aquasim), and 15.4% (BiofilmSimulator) and 20.9% (Aquasim) of calculated total COD in the effluent at the reactor outlet. Dissolved oxygen concentrations during reactor operation under a decreased aeration intensity were in the range from 0.3 to 6.8 \text{ gO}_2/\text{m}^3. It should be mentioned that maintaining very low oxygen concentrations (below 1 \text{ gO}_2/\text{m}^3) in the bioreactor was impossible and unreasonable due to the unfavorable anaerobic conditions which could result in fermentation of biofilm. Since the measured temperature in the reactor differed from 20\degree \text{C} (for which the kinetic parameters were determined) equations of the kinetic processes in biofilm were extended using the temperature coefficient of 1.11^{(T-20)}$, as estimated by Canziani (Canziani et al. 1999).

The simulation results for the wastewater temperatures significantly different from 20\degree \text{C} positively verified this approach. Noteworthy is the strong correlation between the results of simulations conducted on the basis of both models (Figure 4, 6 and 8). Their analysis shows that there are no significant differences between the results of simulations carried out with the Harremøes model and the Wanner and Reichert model.

Uncertainty analysis helped to evaluate the results. On the graphs comparing the real values with simulated ones (see Figure 5, 7), the uncertainty is visualized by the error bars showing the lower and upper limits within which the expected values fall.

The dynamic simulations with the Aquasim program were carried out for two periods of the pilot bioreactor's operation and they showed that the results of the COD removal from wastewater, do not differ significantly from the results obtained with the Harremøes model or the Wanner and Reichert model for the steady state.

Dynamic simulation with Aquasim allows the analysis of the second critical reactor parameter which is the biofilm thickness (L) (Reichert 1998a, b). This article also presents the capabilities offered by the Wanner and Reichert model to this issue. It should be noted that due to the limited amount of data related to biofilm thickness, such verification should not be considered as complete but rather treated as an illustration of Wanner and Reichert model potentials in this field. Nonetheless, the results of simulated biofilm thickness were close to the measured values (Figure 9).

The presented results confirmed that both biofilm models correctly reflect the processes of organic compounds removal and thus may be used in practice, including design, optimization of operation, and strategy choice for the aerated submerged fixed-bed biofilm reactor. The advantage of simulation with a simple program running in MS Excel such as BiofilmSimulator based on the Harremøes model is its simplicity of use and speed of calculation which take up to a few seconds. The BiofilmSimulator program also allows the

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**Table 4** Comparison of the values from different sources for the kinetic parameters recommended for use in models of biofilms (Rittmann & McCarty 1988; Horn & Hempel 1997; Wanner et al. 2006; Alpkvist et al. 2009; Trojanowicz et al. 2009)

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<tbody>
<tr>
<td>$u_{maxH}$ (d$^{-1}$)</td>
<td>–</td>
<td>5.50</td>
<td>6.00</td>
<td>4.707</td>
<td>6.1</td>
</tr>
<tr>
<td>$K_S$ (gCOD/m$^2$)</td>
<td>3.900</td>
<td>10.00</td>
<td>4.00</td>
<td>4</td>
<td>9.4</td>
</tr>
<tr>
<td>$b_{H}$ (d$^{-1}$)</td>
<td>0.205</td>
<td>0.03</td>
<td>0.32</td>
<td>0.08</td>
<td>0.18</td>
</tr>
<tr>
<td>$Y_{H}$ (gCOD/gCOD)</td>
<td>–</td>
<td>0.90</td>
<td>0.63</td>
<td>0.206</td>
<td>0.58</td>
</tr>
</tbody>
</table>
dimensioning of ASFBBR bioreactors. However, its limitation is the lack of ability to carry out dynamic simulations. Furthermore, it does not take into account changes in the thickness of biofilm and it requires additional empirical research on biofilm thickness control.

The Wanner and Reichert model, whose solution is found through the use of the dedicated Aquasim application, is definitely more advanced and contains a high degree of sophistication in the description of transformation processes taking place in biofilm. One of the most significant advantages of the Wanner and Reichert model for practitioners is that it can carry out dynamic simulations and simulate the processes of growth and decay of microorganisms in biofilm. Furthermore, it enables the simulation of adsorption processes of suspended solids and detachment of biofilm, which affect biofilm thickness (Wanner & Reichert 1996; Reichert 1998a, b). With this increase in complexity, however, comes increases in the requirements for user capabilities and the investment of time and resources in understanding the processes described in the model and learning to work with this software. Aquasim is a powerful tool that can be used both for research purposes, educational purposes, and for professional purposes. However, a separate version designed strictly for the purpose of engineering bioreactors should be built containing a walkthrough of the process of selecting the structure of the systems and its calibration and verification. It should also allow dimensioning of bioreactor based on the calibrated and verified model. This proposed separate version would be more useful for practitioners.

In the referenced work of other authors, there are confirmations that even very simple one-dimensional models are good estimates of the removal of organic carbon and can be successfully used in practice for engineering bioreactors (Wanner et al. 2006; Rittmann 2007). There were no reports so far, however, in the literature, on the application of these models to simulate the work of an ASFBBR type of bioreactors used for petrochemical wastewater treatment. Since, as already mentioned, the values obtained for the heterotrophic kinetic parameters do not differ substantially from those reported in the literature, this suggests the conclusion that a given set of parameters is very versatile and can be successfully applied in practice to a wide range of situations. However, before model application it would be necessary to determine COD fractions in the raw wastewater, which is characteristic feature for a particular system under study and estimate the parameters of suspended solids attachment and biofilm detachment, which are of empirical nature in the Wanner and Reichert model.

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