Environment Protection Engineering

Vol. 34 2008 No. 3

STANISŁAW KRZANOWSKI*, ANDRZEJ WAŁĘGA*

EFFECTIVENESS OF ORGANIC SUBSTANCE REMOVAL IN HOUSEHOLD CONVENTIONAL ACTIVATED SLUDGE AND HYBRID TREATMENT PLANTS

The efficiency of BOD_5 removal in a bioreactor using conventional activated sludge technology was compared to BOD_5 removal in a hybrid reactor. The comparison was based on mathematical models of both bioreactors considering substrate diffusion into the biofilm and growth kinetics of microorganisms in the activated sludge. The results from the simulation show that a greater reduction of organic substances occurs in the hybrid bioreactor compared to the reactor using conventional activated sludge. Moreover, it was demonstrated that a greater number of packets per filter bed and an increase in sewage recirculation from the secondary settlement tank lead to an improved efficiency of BOD_5 removal from wastewater.

1. INTRODUCTION

There is a common belief that aerobic biological treatment systems achieve an efficient reduction of organic compounds in wastewater, but remove biogens only to a certain degree. In the case of household treatment plants using conventional activated sludge, fluctuations in pollutant loading, in the volume of wastewater, and also variable environmental conditions negatively affect the operation of these systems [5], [7]. Systems with biofilm-forming microorganisms are considered more advantageous compared with conventional solutions, i.e. suspended-biomass bioreactors [3]. These systems are characterized by the steady-state conditions of sewage treatment processes, a long biomass residence time, and a better resistance to toxic substances and sudden changes in ambient conditions. Moreover, bioreactors with biomass attached to the filling material have smaller dimensions compared to the conventional systems with suspended microorganisms. In this respect, they have a greater potential in small, household sewage treatment plants.

* Department of Sanitary Engineering and Water Management, Agriculture University of Cracow, al. Mickiewicza 24/28, 30-059 Cracow, Poland, e-mail: rmkrzano@cyf-kr.edu.pl

Particular interest in hybrid reactor systems combining activated sludge technology with biofilters [10] has been observed since the mid-twentieth century. Research conducted by HAMOD and AL-GHUSAIN [3] on a pilot Aerated Submerged Fixed Film (ASFF) reactor composed of a submerged biofilter filled with vertically mounted ceramic panel packs revealed a high efficiency of organic substance removal. The hydraulic loading of the filter bed ranging from 0.04 to 0.68 $m^3 \cdot m^{-2} \cdot d^{-1}$ achieved BOD_5 removal of between 90 and 99.7% with COD_{Cr} removal being between 79 and 97.9%. RODGERS [10] conducted his research on a filter bed filled with PVC modules, obtaining over a 92% COD reduction at the level of 43 g COD $\cdot m^{-2} \cdot d^{-1}$. In their investigations of sewage treatment in filter beds, YAMAGIWA et al. [11] used a modern solution involving the application of a hydrophobic, porous membrane made of Teflon which additionally distributed oxygen in the bed. With organic matter loading of the bed at the level of 6 g $\cdot m^{-2} \cdot d^{-1}$, the authors obtained a 95% reduction in total organic carbon. NAKIJAMA et al. [9] demonstrated the usefulness of anaerobic–aerobic systems filled with plastic filter packs for treatment of small volumes of wastewater. Specifically, these systems are for an equivalent number of inhabitants less than 10, with discharges from single houses. In 70% of the samples analysed, BOD_5 values in treated wastewater did not exceed 20 mg $O_2 \cdot dm^{-3}$. Moreover, it was demonstrated that introducing an additional sewage recirculation loop from the aerobic to the anaerobic chamber favoured a greater reduction of organic matter and nitrogen compounds.

The article focused on comparing the effectiveness of organic carbon removal from wastewater in conventional activated sludge and hybrid systems. The assessment was made on the basis of model computations considering substrate diffusion into the biofilm and growth kinetics of organisms in the suspension.

2. MATERIALS AND METHODS

Model computations of conventional activated sludge and hybrid reactors were conducted on the basis of wastewater mass balance and growth kinetics of microorganisms according to the assumptions presented in figure 1.

The structure and description of the mathematical model of the conventional activated sludge bioreactor were quoted after GEBARA [2]. The substrate concentrations in the bioreactor were determined from the following equation:

$$S_e^2[(1+\alpha)^2 D - (1+\alpha)\mu_{\max} + (1+\alpha)k_d] + S_e\left[\mu_{\max} S_i + \left(\frac{\mu_{\max}\alpha X_r}{Y}\right) + K_s(1+\alpha)^2 D + K_s k_d(1+\alpha) - (1+\alpha)DS_i - k_d S_i\right] - K_s(1+\alpha)DS_i - K_s k_d S_i = 0, \quad (1)$$

where: Y is the cell yield (mg), $\mu_{\max}$ is the maximum specific growth rate (d^{-1}), k_d is the decay rate (d^{-1}), D is the dilution factor ($mg \cdot dm^{-3}$), K_s is the substrate concentration when the growth rate is half of maximum ($mg \cdot dm^{-3}$). The descriptions of remaining variables were put in figure 1.

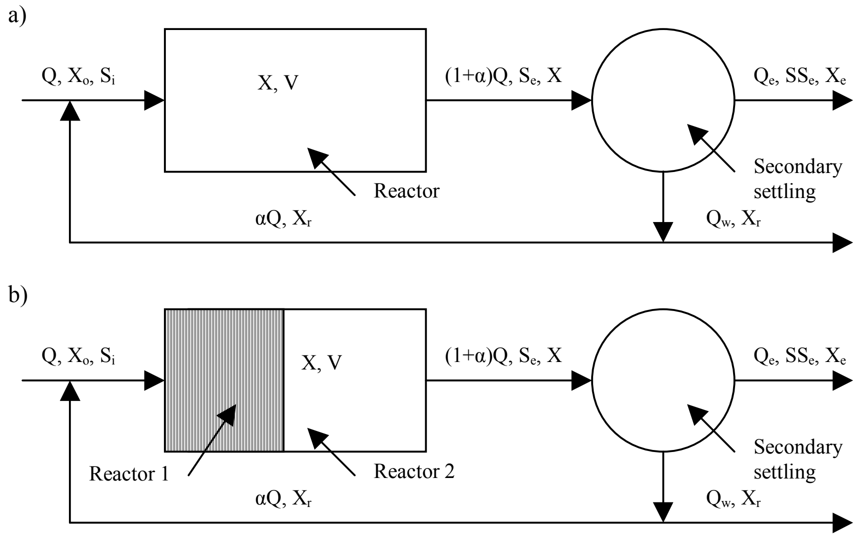

Fig. 1. The scheme for calculation: a) conventional activated sludge reactor, b) hybrid reactor: Q is the quantity of sewage ($cm^3 \cdot min^{-1}$), X_0 is the influent biomass concentration ($mg \cdot dm^{-3}$), S_i is the influent substrate concentration ($mg \cdot dm^{-3}$), X is the biomass concentration in reactor ($mg \cdot dm^{-3}$), V is the aeration tank volume (cm^3), α is the recycling ratio, S_e is the substrate concentration in effluent of reactor ($mg \cdot dm^{-3}$), SS_e is the substrate concentration in effluent from secondary settling ($mg \cdot dm^{-3}$), Q_e is the quantity of sewages in effluent from secondary settling ($cm^3 \cdot min^{-1}$), X_e is the effluent biomass concentration ($mg \cdot dm^{-3}$), Q_w is the quantity of excess sludge ($cm^3 \cdot min^{-1}$), X_r is the recycled biomass concentration ($mg \cdot dm^{-3}$)

The mathematical model of substrate transformation in the biofilm is based on the following assumptions [2]:

- substrate depletion inside the biofilm occurs according to the Michaelis–Menten kinetics equation,
- the rate of substrate depletion inside the biofilm equals the rate at which the substrate from the surrounding liquid diffuses into the film,
- the substrate diffusion from the liquid volume into the biofilm occurs according to Frick's law.

Frick described the substrate flux into the biofilm using the following equation [6]:

$$J = \frac{D_f (S_i - S_f)}{L_f}, \tag{2}$$

where: J is the flux of substrate inside the biofilm ($cm^3 \cdot cm^{-2} \cdot s^{-1}$), D_f is the diffusion coefficient ($cm^2 \cdot s^{-1}$), S_f is the biofilm substrate concentration ($mg \cdot dm^{-3}$), L_f is the active biofilm thickness (cm).

The Michaelis–Menten kinetics equation is as follows:

$$\frac{dS}{dt} = \frac{kS_f X}{(K_s + S_f)} \cdot L_f , \tag{3}$$

where: k is the maximum substrate degradation rate (d^{-1}), X_f is the biofilm bacterial concentration ($mg \cdot dm^{-3}$).

By solving equation (3) and making the appropriate transformations, one obtains the following relationship for substrate concentration in the biofilm:

$$S_f^2 + S_f \left[K_s - S_i + \frac{k X_f L_f^2}{D_f} \right] - K_s S_i = 0 . \tag{4}$$

According to the scheme shown in figure 1b, the hybrid bioreactor container was divided into two parts. The first part consists of several plastic filter packets acting as a submerged biofilter, whereas the second part is a conventional activated sludge reactor. Substrate with the concentration S_i feeds reactor 1. The outflow of the first S_1 bioreactor is simultaneously the inflow for bioreactor 2. As a result of mineralization processes, the substrate will be partially removed with the remaining substrate flowing through the outflow as S_2. The reactor 1 outflow has been described by the following equation:

$$S_1 = S_i - \frac{JA_c N}{Q} , \tag{5}$$

where: A_c is the surface area of a cell inside a net ($m^2 \cdot m^{-3}$), N is the number of packets placed in aeration tank.

The bioreactor 2 outflow has been computed on the basis of relationship (1). The BOD_5 value in the outflow of the secondary settling tank is a total of the BOD_5 in the outflow of the aerobic reactor and biochemical oxygen demand of the suspension solids. Theoretically, the total oxygen demand for oxygenation of organic substances in the suspension is 1.42 mg O_2 ·mg smo^{-1} and BOD_5 constitutes 0.68 of the total oxygen demand [8]. Finally, the value of BOD_5 (mg O_2 ·dm^{-3}) in the outflow of the secondary settling tank will be equal to

$$S_2 = S_e + 0.68 \cdot 1.42 \cdot SS_e , \tag{6}$$

where: S_e is the effluent substrate concentration, SS_e is the effluent suspended solids.

The wastewater characteristics of the bioreactor inflow and outflow were based on actual measurement data from household treatment plants using conventional activated sludge technology and hybrid systems [1], [7]. Mean sewage flow into the system was assumed to be 69.4 $cm^3 \cdot min^{-1}$, the average BOD_5 value after the septic tank equalled 178.0 mg $O_2 \cdot dm^{-3}$, and the mean concentration of total suspended solids in the outflow of the conventional activated sludge bioreactor was assumed to be 51.6 mg $\cdot dm^{-3}$. For the hybrid system with one packet this was 18.3 mg $\cdot dm^{-3}$ and for the other number of packets this was 5.0 mg$\cdot dm^{-3}$. The kinetic reaction constants were from GEBARA [2] and HENZE et al. [4]: $D_f = 4.37 \cdot 10^{-6}$ $cm^2 \cdot s^{-1}$ (for sewage temperature of 21 °C), K_s = 87 mg $\cdot dm^{-3}$, $k = 2.08$ d^{-1}, X_f = 50 mg $\cdot cm^{-3}$, L_f = 0.01 cm, D = 8.84 mg$\cdot dm^{-3}$, $\mu_{max} = 1.5$ d^{-1}, $k_d = 0.08$ d^{-1}, X_r = 3200 mg $\cdot dm^{-3}$, Y = 0.72 mg.

The simulation computations were conducted for several variants considering a variable number of filter bed packets (N = 1, 2, 4, 8, 12, and 24) and recirculation degrees α = 0, 0.2, 0.4, 0.5, 0.7, 0.75 and 1.0. The assumed specific surface of the filling was A_c =150 $m^2 \cdot m^{-3}$. The simulation was made for mean daily sewage inflow, mean BOD_5 value, sewage flowing from the septic tank, and average concentration of total suspended solids in the outflow from the monitored objects.

3. RESULTS

The results of model computations of BOD_5 removal effectiveness in conventional activated sludge and hybrid bioreactors were presented in figure 2. The simulation showed that the number of packets and the degree of sewage recirculation significantly influenced wastewater treatment results. The poorest results of organic sub-

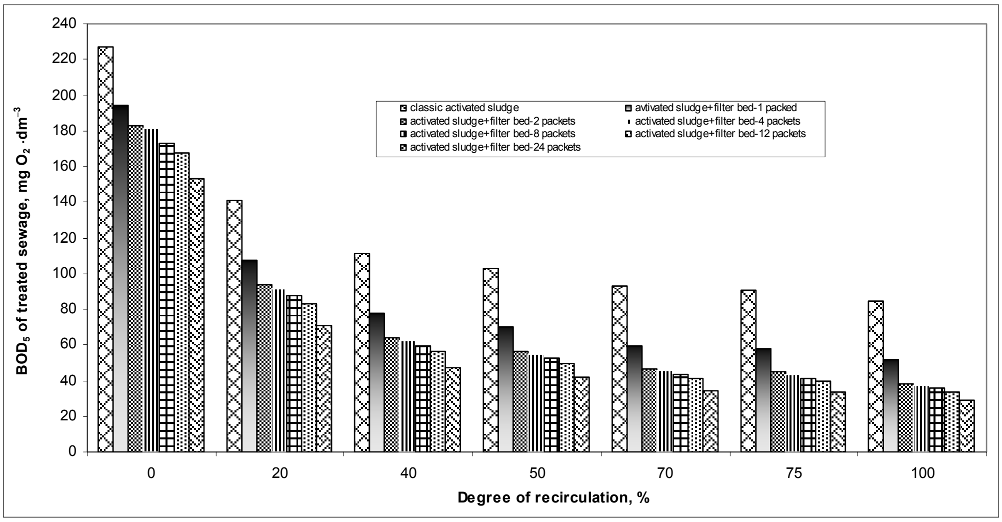

Fig. 2. The values of BOD_5 in treated sewage obtained from the calculated model

stance removal in the hybrid reactor were obtained when just one filter packet was used; however BOD_5 removal improved when a larger number of packets were used (table 1). For instance, with 100% recirculation, BOD_5 reduction ranged from 71% for $N = 1$ to 83.7% for $N = 24$. When the number of packets was increased to 2, the reduction grew by 7.4%. Additional packets did not contribute to any substantial improvement of organic substance removal. Finally, at the packet number $N = 24$, the BOD_5 reduction was 12.7% higher in relation to $N = 1$. In the comparable, conventional bioreactor, BOD_5 reduction was only 52.6%. The difference in the results for BOD_5 reduction in the systems analyzed ranged from 26 to 37%, with the hybrid system achieving a higher efficiency.

Table 1

The effectiveness of BOD_5 removal with a recirculation degree of $\alpha = 1.0$

Conditions	Removal of BOD_5 (%)	Increase in BOD removal (%)
1 packet	71.0	–
2 packets	78.4	7.4
4 packets	78.9	7.9
8 packets	79.9	8.9
12 packets	80.9	9.9
24 packets	83.7	12.7

A complete lack of recirculation resulted in a very poor treatment efficiency. In this case, the contact time of sewage with biomass is likely too short and the microorganisms are unable to take up a sufficient quantity of substrate. A notable improvement in the efficiency of organic substance removal is noted when the recirculation degree is increased to 20% of mean daily sewage inflow. At this recirculation degree, the BOD_5 values in the outflow of the hybrid bioreactor fluctuate from 107.7 mg $O_2 \cdot dm^{-3}$ at one packet filling to 70.6 mg $O_2 \cdot dm^{-3}$ at 24 packets. BOD_5 removal stabilizes when the recirculation degree is increased to over 20% $Q_{d\mathrm{mean}}$. This is the case for both the hybrid and conventional bioreactors. Increasing the recirculation degree allows a reduction in the number of packets. This results in a smaller bioreactor, which is particularly important for small household sewage treatment plants. The differences in the effectiveness of organic substance removal in both systems result from the positive role of the biofilter in substrate transformations. With conventional activated sludge, the substrate is taken up by the microorganisms suspended in the bioreactor. The introduction of an additional element, i.e. submerged bed, to the system leads to the development of an additional microorganism population adhering to the filling material. These microorganisms mainly absorb easily biodegradable substances through diffusion, whereas the other organic matter fractions are removed by the suspended microorganisms. The degree of recirculation plays an important role in organic pollutant reduction by suspended microorganisms. The example of computations conducted for a bioreactor variant filled with 24 packets revealed an apparent increase in BOD_5 reduction with an increasing degree of recirculation. A change in the recirculation degree did not affect BOD_5 reduction in the biofilm. Sludge returned from the secondary settlement tank causes an increase in the suspended biomass concentration, leading to an apparently greater reduction of this index in the activated sludge. When there is no recirculation, the retention time for the suspended biomass in the system is too short. This reduces microorganism reproduction causing a slight increase in BOD_5 values in the outflow. The growth of microorganisms in the biofilm increases when more packets are used, leading to a greater reduction of organic pollutants in the filter bed. For example, the computed value of substrate reduction in the filter bed at the recirculation degree $\alpha = 1.0$ ranged from 0.7% for $N = 1$ to 16.8% for $N = 24$ (table 2). On the other hand, substrate reduction by suspended biomass revealed only slight changes, oscillating between 71 and 80.3%. However, it should be noticed that the main process of organic substance removal occurs in the biomass suspended in the bioreactor.

Table 2

BOD_5 removal effectiveness using a biofilm and activated sludge for a varying number of nets, for $\alpha = 1.0$

Conditions	Removal of BOD_5 inside the biofilm (%)	Removal of BOD_5 in activated sludge (%)
1 packet	0.7	71.0
2 packets	1.4	78.1
4 packets	2.8	78.3
8 packets	5.6	78.7
12 packets	8.4	79.2
24 packets	16.8	80.3

4. CONCLUSIONS

The following conclusions may be drawn as a result of the simulation conducted:

1. The hybrid reactor model presented in the paper, based on substrate diffusion into the biofilm and the growth kinetics of microorganisms, provides a useful tool for designing and simulating BOD_5 removal.

2. The simulation conducted revealed that hybrid bioreactors have a higher organic substance removal efficiency compared to conventional activated sludge treatment plants.

3. Microorganisms suspended in the form of activated sludge play the crucial role in organic substance removal in the hybrid bioreactor.

4. BOD_5 removal increases with an increasing degree of sewage recirculation from the secondary settling tank and with a higher number of bed packets.

5. The use of plastic packets in a conventional activated sludge bioreactor may contribute to an improved organic substance removal without the necessary extension of the treatment plant. Such a measure is justifiable not only for ecological, but also for operational reasons. Moreover, it is much cheaper than adding new facilities to an existing system.

REFERENCES

[1] BUGAJSKI P., *Wpływ czynników eksploatacyjnych na efekty oczyszczania ścieków w przydomowych oczyszczalniach z osadem czynnym*, PhD thesis, AR, Kraków, 2005.

[2] GEBARA F., *Activated sludge biofilm wastewater treatment system*, Wat. Res., 1999, 33 (1), 230–238.

[3] HAMODA M.F., AL-GHUSAIN A., *Analysis of organic removal rates in the aerated submerged fixed film process*, Wat. Sci. Tech., 1998, 38, 8–9, 213–221.

[4] HENZE M., HARREMOËS P., JANSEN J., ARVIN E., *Oczyszczanie ścieków. Procesy biologiczne i chemiczne*, Wyd. Politechniki Świętokrzyskiej, Kielce, 2002.

[5] JÓŹWIAKOWSKI K., MARZEC M., *Problemy funkcjonowania przydomowych oczyszczalni ścieków z osadem czynnym – badania wstępne*, Przegląd Naukowy, Inżynieria i Kształtowanie Środowiska, 2006, 2 (34), 163–171.

[6] KEMBŁOWSKI Z., MICHAŁOWSKI S., STRUMIŁŁO C., ZARZYCKI R., *Podstawy teoretyczne inżynierii chemicznej i procesowej*, Wyd. Naukowo-Techniczne, 1985, 373.

[7] KRZANOWSKI S., WAŁĘGA A., *New technologies of small domestic sewage volume treatment applied in Poland*, Infrastruktura i Ekologia Terenów Wiejskich, Komisja Technicznej Infrastruktury Wsi, PAN, Oddział w Krakowie, 2007, 3, 69–78.

[8] METCALF E., *Wastewater Engineering*, McGraw-Hill, New York, 1991.

[9] NAKAJIMA J., FUJIMURA Y., INAMORI Y., *Performance evaluation of on-site treatment facilities for wastewater from households, hotels and restaurants*, Wat. Sci. Tech., 1999, 39 (8), 85–92.

[10] RODGERS M., *Organic carbon removal using a new biofilm reactor*, Wat. Res., 1999, 33, 6, 1495–1499.

[11] YAMAGIWA K., YOSHIDA M., ITO A., OHKAWA A., *A new oxygen supply metod for simultaneous organic carbon removal and nitrification by a one-stage biofilm process*, Wat. Sci. Tech., 1998, 37, 4–5, 117–124.

EFEKTYWNOŚĆ USUWANIA SUBSTANCJI ORGANICZNEJ W OCZYSZCZALNIACH PRZYDOMOWYCH Z KLASYCZNYM OSADEM CZYNNYM I W OCZYSZCZALNIACH HYBRYDOWYCH

Porównano efektywność redukcji BZT_5 w bioreaktorze pracującym w klasycznej technologii osadu czynnego i w bioreaktorze hybrydowym, opierając się na modelach matematycznych obu bioreaktorów. W modelach tych uwzględniono dyfuzję substratu do wnętrza błony biologicznej i kinetykę wzrostu mikroorganizmów w osadzie czynnym. Wyniki otrzymane dzięki symulacji pozwalają stwierdzić, że bioreaktor hybrydowy zapewnia większą redukcję substancji organicznej niż klasyczna metoda osadu czynnego. Wykazano ponadto, że zwiększenie zarówno liczby pakietów w złożu, jak i stopnia recyrkulacji osadu z osadnika wtórnego sprzyja lepszej efektywności usuwania BZT_5 ze ścieków.