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BASIC TECHNOLOGICAL PARAMETERS OF THE ACTIVATION PROCESS FOR TWO BIOREACTOR CONFIGURATIONS

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Abstract: Technological parameters of the activation process in wastewater treatment plant activation systems are analyzed for basic bioreactor configurations, for the chemostat and for the plug flow, both with the recirculation of concentrated activated sludge. The first type of bioreactors represents conventional aerated tanks, but also loop bioreactors. The second type of bioreactors includes, for example, oxidation ditches. The paper presents an evaluation of the basic technological parameters of the activation process for the two mentioned configurations of bioreactor systems with recirculation of concentrated activated sludge. In addition, a new relation for sludge age evaluation is proposed for an activation system with a plug flow bioreactor. The article also provides examples of connections between the values of the technological parameters of the activation process for the two analyzed types of bioreactor systems.

KEYWORDS: chemostat with recirculation, plug flow bioreactor, activation process, retention time, sludge age, recirculation factor, thickening factor

1 Introduction

The last decades of the previous century are characterized by an enormous development of biotechnological processes and their equipment. This trend was visible in both biotechnological branches, in the production and also in the degradation. New types of aerobic and anaerobic bioreactors started to operate also in wastewater treatment (WWT) plants. In particular, loop bioreactors have demonstrated high progressiveness and effectiveness [5, 8, 10, 11]. Moreover, they save a ground-plane area.

The basic types of the loop bioreactors used in aerobic wastewater treatment, in the activation process, are shown schematically in Fig. 1 [4]. Types a), b), c) in Fig. 1 are common in the WWT plants. Excellent results have been reached in a deep shaft bioreactor [11] developed by ICI Co., Great Britain. In the deep shaft, the airlift principle of operation is utilized. The shafts are up to 100 m deep and in some special cases even more. These bioreactors are characterized by a very high oxygen utilization, which is over 80 %, while the *E*-parameter ranges from 3 to 5 kg O_2 per 1 kWh of energy consumption. They can also operate in WWT plants processing very polluted wastewater, because they are able to reduce the pollution from BOD_5 = 15 000 mg/l to BOD_5 = 120 mg/l. Deep shaft bioreactors are more effective than conventional aeration basins for agglomerations of over 15 000 inhabitants.

The tower bioreactors of the German companies Hoechst and Bayer utilize the principle of a jet loop type bioreactor [1]. The *E*-parameter is in the range of 3 to 4 kg O_2 per 1 kWh. A compact loop type bioreactor also seems to be very convenient, but it has not yet found industrial greater utilization. Despite of the incontestable advantages of the loop bioreactors mentioned above, conventional aerated basins are still often used in WWT plants. They are demanding on ground-plan area and the oxygen utilization is not more than 25 %.

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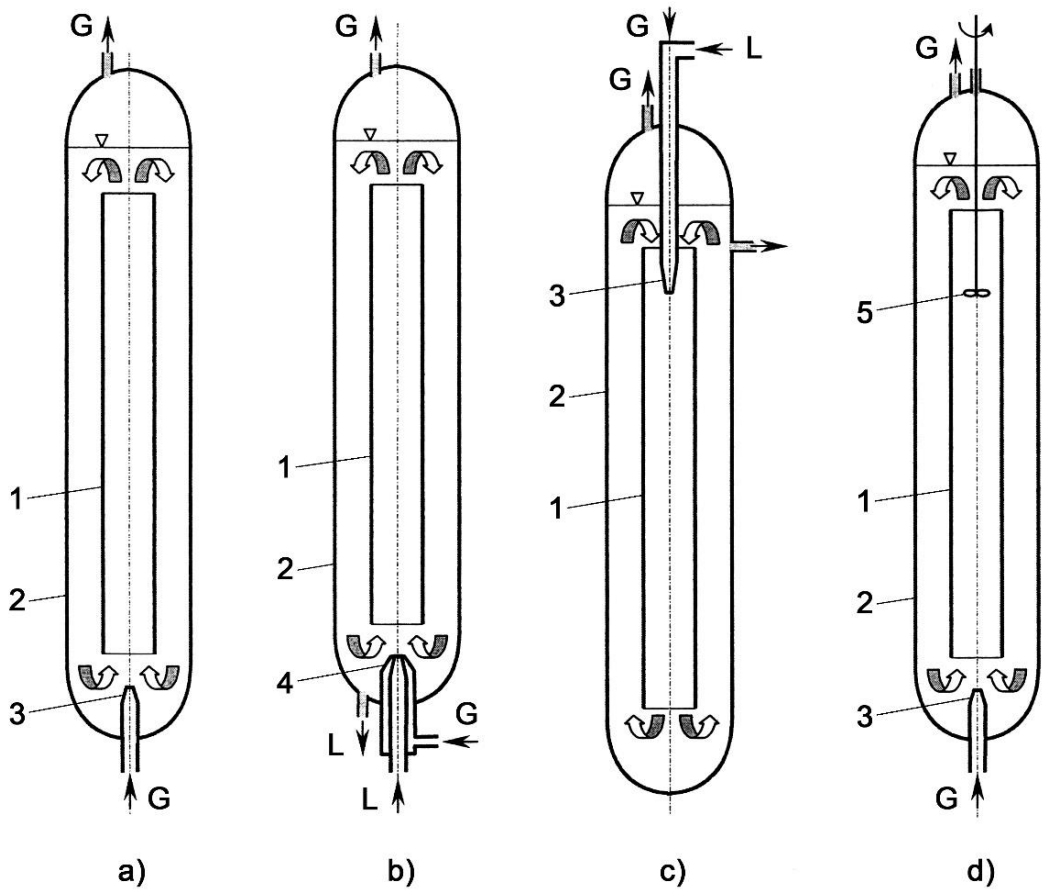


Fig. 1 Basic types of loop bioreactors.
a) airlift loop, b) jet loop, c) compact loop (down flow jet loop), d) propeller loop
1 – inner tube, 2 – outer tube, 3 – jet, 4 – air liquid distributor, 5 – propeller
G – gas (air), L – liquid

2 Basic technological parameters of the activation process

In order to characterize the technological properties of individual types of bioreactors with recirculation of concentrated activated sludge, special parameters of the activation process were proposed. Chudoba and Dohányos [6, 7] published the following basic parameters of the activation process:

- hydraulic retention time t_h

$$t_h = \frac{V}{F}, \tag{1}$$

- retention time with recirculation t_r

$$t_r = \frac{V}{F\ (1+\tau)} = \frac{t_h}{1+\tau}, \tag{2}$$

- sludge age t_x

$$t_x = \frac{V\ x}{F(1-\omega)\ \delta\ x + \omega\ F\ \gamma\ x} = \frac{t_h}{(1-\omega)\ \delta + \omega\ \gamma}, \tag{3}$$

- loading of activation vessel B_v

$$B_v = \frac{F\ s_0}{V} = \frac{s_0}{t_h}, \tag{4}$$

- productivity of activation vessel ΔB_v

$$\Delta B_v = \frac{F\left(s_0 - s\right)}{V} = \frac{s_0 - s}{t_h}, \tag{5}$$

- sludge loading B_x

$$B_x = \frac{F\ s_0}{V\ x} = \frac{s_0}{x\ t_h} = \frac{B_v}{x}, \tag{6}$$

- sludge productivity ΔB_x

$$\Delta B_x = \frac{F\ \left(s_0 - s\right)}{V\ x} = \frac{s_0 - s}{x\ t_h} = \frac{\Delta B_v}{x}, \tag{7}$$

- effectiveness of activation process η

$$\eta = \frac{s_0 - s}{s_0}\ 100\ \%. \tag{8}$$

The dimensionless factors in the previous equations usually have the following values:
- the recirculation factor τ is up to 0.3,
- the thickening factor γ is up to 5,
- the sludge concentration reduction factor δ in the clean water is up to 0.005,
- the superfluous sludge outflow factor ω, which expresses how much of the wastewater entering the activation system flows out of it in the form of the superfluous concentrated activated sludge for further processing, is approximately 0.005.

The following relations can be written to express the interconnection among these dimensionless factors [2, 3]:

$$\tau \leq \frac{1-\omega\,\gamma}{\gamma-1}, \tag{9}$$

$$\delta = \frac{1-\gamma\,\omega-\tau\,\left(\gamma-1\right)}{1-\omega}. \tag{10}$$

3 Characteristics of the two analyzed types of bioreactors

The two analyzed types of bioreactors can be defined based on ideal cases of mixing their contents. The first type corresponds to a bioreactor with perfect mixing called a chemostat. The second type represents a bioreactor with a plug flow. Aerated tanks and loop bioreactors, used in aerobic wastewater treatment, approach the first ideal type of bioreactors in terms of mixing their contents. Oxidation ditches, which can also be used in aerobic wastewater treatment, are operationally close to the second ideal type of bioreactors in terms of mixing

their contents. Both types of bioreactors work with the recirculation of concentrated activated sludge.

The first bioreactor system, schematically shown in Fig. 2, is the chemostat with recirculation of concentrated activated sludge. It consists of the aerobic bioreactor (activation vessel) where a degradation of pollutants occurs, and sedimentation vessel serving for separation of clean water and concentrated activated sludge. Concentration of the activated sludge in the activation vessel, which is characterized by a uniform content composition throughout the entire volume, is 3000 to 3500 mg/l, and the concentration of the activated sludge outflowing from the sedimentation vessel bottom is within the range of 15000 to 17500 mg/l. The outflowing sludge is distributed into the recirculating part, which returns as activated sludge to the activation vessel entrance, and into the superfluous part, which is thickened and then anaerobically digested in order to obtain methane gas.

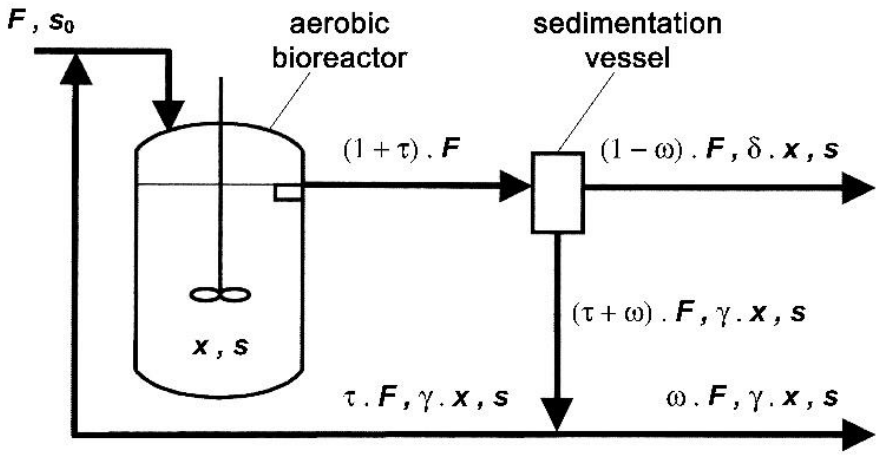


Fig. 2 Scheme of the chemostat with concentrated biomass recirculation.

The second analyzed bioreactor system is the plug flow bioreactor with recirculation of concentrated activated sludge. It is shown schematically in Fig. 3. Plug flow within the bioreactor content means that sufficient mixing occurs in the lateral direction (transversely), but none in the longitudinal direction. A plug flow bioreactor is characterized by concentration gradients of some components in the flow direction of its content from inlet to outlet. Concentration gradients can be positive (biomass or activated sludge concentration) or negative (substrate and dissolved oxygen concentrations). The sedimentation vessel serves the same purpose as in the case of the chemostat.

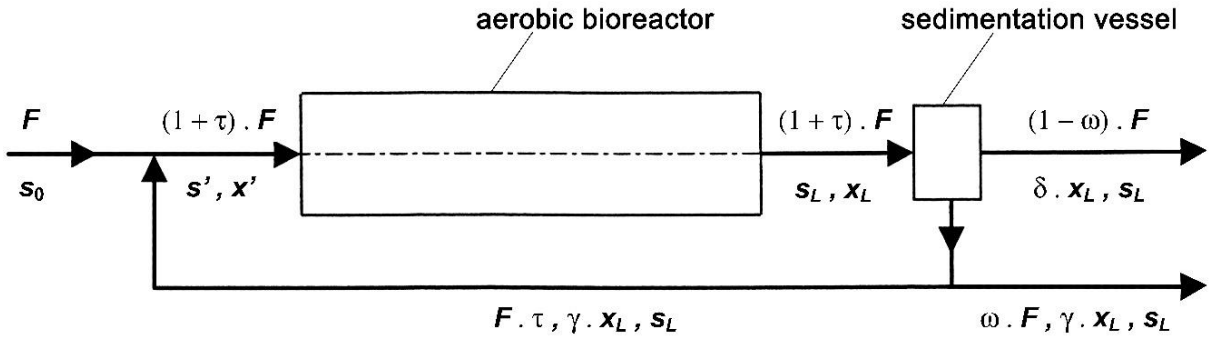


Fig. 3 Scheme of plug flow bioreactor with concentrated biomass recirculation.

The sludge age parameter t_x, defined by equation (3), is the ratio of the amount of sludge dry matter in the bioreactor and the amount of sludge dry matter removed from the activation system per unit of time. Some literature [9] presents equations for calculating the sludge age parameter t_x, which result from the mass balance of the biomass (dry matter of activated sludge) and the substrate in the activation system with the recirculation of the concentrated biomass (activated sludge). The equation

$$t_x = \frac{t_h\ x}{Y_{xs}\left(s_0 - s\right) - k_e\ t_h\ x} \tag{11}$$

is valid for a bioreactor of the chemostat type, if it is assumed in the mass balance that $\delta = 0$ (the outflowing clean wastewater does not contain any biomass). For a plug flow bioreactor, the relationship of Lawrence and Mc Carty for sludge age is published in the literature [9], which is as follows

$$t_x = \frac{s_0 - s + \left(1-\tau\right)\ K_s \ln\dfrac{s'}{s}}{\mu_{\max}\left(s_0 - s\right)}. \tag{12}$$

The maximum value of the specific growth rate of biomass μ_{max} in equation (12) can be expressed by the equation

$$\mu_{\max} = \frac{Y_{xs}\left(s_0 - s\right)\left(K_s + s\right)}{t_h\ x\ s}, \tag{13}$$

which results from the mass balance of the substrate in the activation system. In equations (12) and (13), constant concentrations of biomass and substrate along the bioreactor were assumed. However, such an assumption is not quite correct.

According to the definition of sludge age by equation (3), it is possible to write the equation

$$t_x = \frac{V\dfrac{1}{2}\left(x' + x_L\right)}{F\ \left[\left(1-\omega\right)\delta\ x_L + \omega\ \gamma\ x_L\right]}, \tag{14}$$

in which the arithmetic mean of the input biomass concentration x' and the output biomass concentration x_L was assumed. These parameters were derived in the literature [3] and are expressed by the following equations:

$$x' = \frac{\gamma\ \tau\ x_L}{1+\tau}, \tag{15}$$

$$x_L = x' + Y_{xs}\left(s' - s_L\right), \tag{16}$$

where

$$s' = \frac{s_0 + \tau\ s_L}{1+\tau}. \tag{17}$$

By substituting equation (15) into equation (14) and rearranging, the sludge age will be expressed by the following equation:

$$t_x = \frac{t_h\left(1+\tau+\gamma\ \tau\right)}{2\ (1+\tau)\ \left[\left(1-\omega\right)\delta+\omega\ \gamma\right]}. \tag{18}$$

Based on equations (15), (16), and (17), it is possible to write the following equation for the recirculation factor τ:

$$\tau = \frac{x_L - Y_{xs}(s_0 - s_L)}{x_L\left(\gamma - 1\right)}. \tag{19}$$

4 Results

A comparison of the operation of activation systems with individual analyzed types of bioreactors (chemostat and plug flow bioreactor) can be performed on the basis of specific values of the basic technological parameters of the activation process and the relationships between them. The assumed usual values of the parameters [6, 9], which are necessary for the calculation of the basic technological parameters of the activation process, are listed in Tab. 1 for the activation system with a chemostat bioreactor and in Tab. 2 for the activation system with a plug flow bioreactor.

Tab. 1 Parameters necessary for the calculation of the basic technological parameters of the activation process in a system with a chemostat bioreactor.

Parameter	Symbol	Value
hydraulic retention time	t_h (h)	4 to 14
thickening factor	γ (–)	4.3
factor of superfluous sludge effluent	ω (–)	0.005
factor of sludge concentration reduction	δ (–)	0.005
maximum of the recirculation factor	τ_{max} (–)	0.2965
initial substrate concentration expressed by BOD_5	s_0 ($mg.l^{-1}$)	300
substrate concentration expressed by BOD_5	s ($mg.l^{-1}$)	10
biomass concentration	x ($mg.l^{-1}$)	3000
yield coefficient of biomass from substrate	Y_{xs} (–)	0.6
endogenous metabolism coefficient	k_e (h^{-1})	0.0025

Tab. 3 and Tab. 4 contain the calculated ranges of values of the basic technological parameters of the activation process, corresponding to the values of the parameters listed in Tab. 1 and Tab. 2. The values of the sludge age parameter t_x, listed in Tab. 3 and Tab. 4, are calculated using the basic definition equation (3).

Tab. 2 Parameters necessary for the calculation of the basic technological parameters of the activation process in a system with a plug flow bioreactor.

Parameter	Symbol	Value
hydraulic retention time	t_h (h)	15 to 48
thickening factor	γ (–)	4.3
factor of superfluous sludge effluent	ω (–)	0.005
factor of sludge concentration reduction	δ (–)	0.005
maximum of the recirculation factor	τ_{max} (–)	0.2965
initial substrate concentration expressed by BOD_5	s_0 (mg.l^{-1})	300
substrate concentration at bioreactor inlet expressed by BOD_5	s' (mg.l^{-1})	234.6
substrate concentration at bioreactor outlet expressed by BOD_5	s_L (mg.l^{-1})	10
biomass concentration at bioreactor inlet	x' (mg.l^{-1})	2910
biomass concentration at bioreactor outlet	x_L (mg.l^{-1})	3000
yield coefficient of biomass from substrate	Y_{xs} (–)	0.4
saturation constant	K_s (mg.l^{-1})	12

Tab. 3 Calculated values of the basic technological parameters of the activation process in a system with a chemostat bioreactor.

Parameter	Symbol	Value
hydraulic retention time	t_h (h)	4 to 14
retention time with recirculation	t_r (h)	3.09 to 10.81
sludge age	t_x (d)	6.29 to 22.01
loading of activation vessel	B_v (kg.m^{-3}.d^{-1})	1.80 to 0.51
productivity of activation vessel	ΔB_v (kg.m^{-3}.d^{-1})	1.74 to 0.50
sludge loading	B_x (kg.kg^{-1}.d^{-1})	0.600 to 0.171
sludge productivity	ΔB_x (kg.kg^{-1}.d^{-1})	0.580 to 0.166
effectiveness of activation process	η (%)	96.67

The relationships between the values of the basic technological parameters of the activation process for the two considered activation systems are also shown in the form of graphs in Figs. 4 to 8. The dependences of the loading of activation vessel parameter B_v and the productivity of activation vessel parameter ΔB_v on the hydraulic retention time parameter t_h are shown for the activation system with chemostat bioreactor in Fig. 4a) and for the activation system with plug flow bioreactor in Fig. 4b). Similarly, Fig. 5a) shows the dependences of sludge loading parameter B_x and sludge productivity parameter ΔB_x on the hydraulic retention time parameter t_h for the activation system with chemostat bioreactor and Fig. 5b) for the activation system with plug flow bioreactor.

Tab. 4 Calculated values of the basic technological parameters of the activation process in a system with a plug flow bioreactor.

Parameter	Symbol	Value
hydraulic retention time	t_h (h)	15 to 48
retention time with recirculation	t_r (h)	11.58 to 37.07
sludge age	t_x (d)	23.58 to 75.47
loading of activation vessel	B_v (kg.m^{-3}.d^{-1})	0.480 to 0.150
productivity of activation vessel	ΔB_v (kg.m^{-3}.d^{-1})	0.464 to 0.145
sludge loading	B_x (kg.kg^{-1}.d^{-1})	0.162 to 0.051
sludge productivity	ΔB_x (kg.kg^{-1}.d^{-1})	0.157 to 0.049
effectiveness of activation process	η (%)	96.67

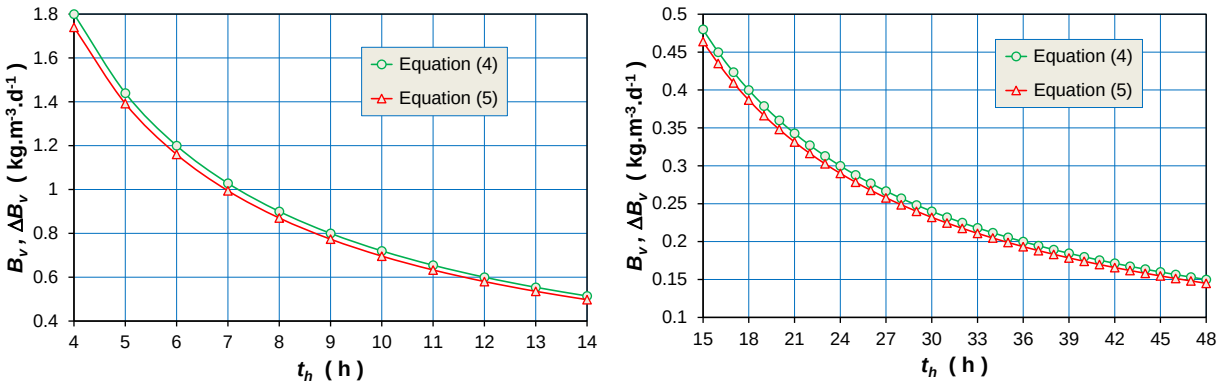
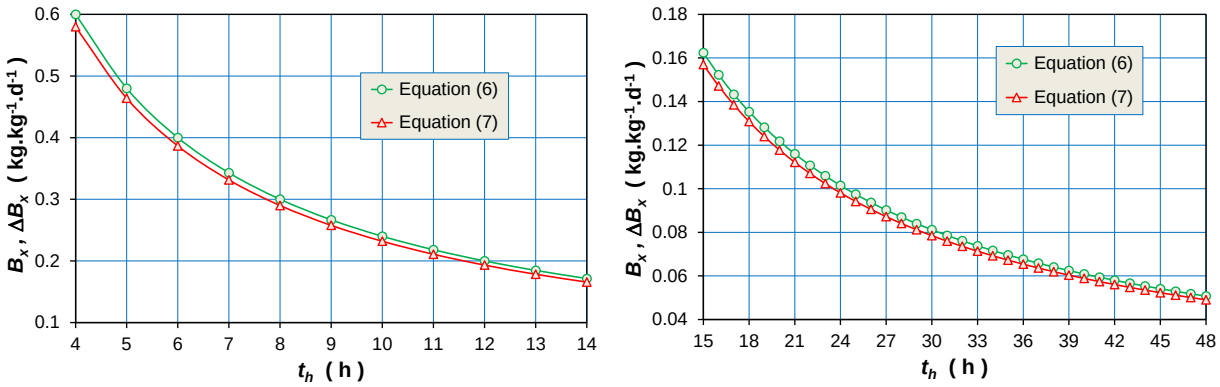


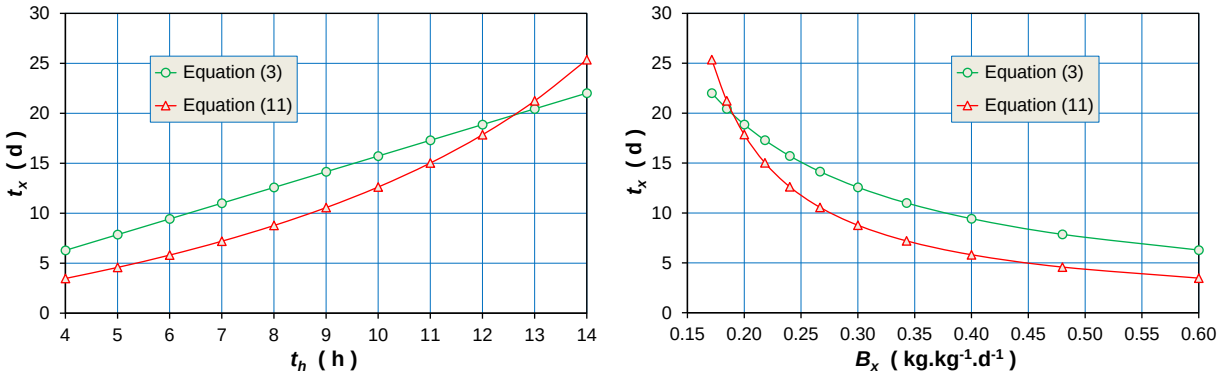
Fig. 4 The dependences of the activation vessel loading B_v and the activation vessel productivity ΔB_v on the hydraulic retention time t_h for the activation system: a) with a chemostat bioreactor, b) with a plug flow bioreactor.

The technological parameter sludge age t_x is specially evaluated, based on its definition by equation (3) and also on the basis of equations (11) and (12), which result from the mass balance of the biomass (dry matter of activated sludge) and the substrate in both analyzed activation systems. Moreover, for the activation system with plug flow bioreactor, the sludge age parameter t_x is also calculated using the new proposed equation (18), which was created by refining the basic definition equation (3) for the operating conditions of the activation system with plug flow bioreactor. The dependences of the values of the sludge age parameter t_x, which were calculated by several mentioned methods, on the values of the hydraulic retention time parameter t_h and the sludge loading parameter B_x are shown for the activation system with a chemostat bioreactor in Fig. 6a) and Fig. 6b) and for the activation system with a plug flow bioreactor in Fig. 7 and Fig. 8.



a) b)

Fig. 5 The dependences of the sludge loading B_x and the sludge productivity ΔB_x on the hydraulic retention time t_h for the activation system:
a) with a chemostat bioreactor, b) with a plug flow bioreactor.



a) b)

Fig. 6 The influence of the hydraulic retention time t_h (graph a)) and the sludge loading B_x (graph b)) on the sludge age t_x for the activation system with a chemostat bioreactor.

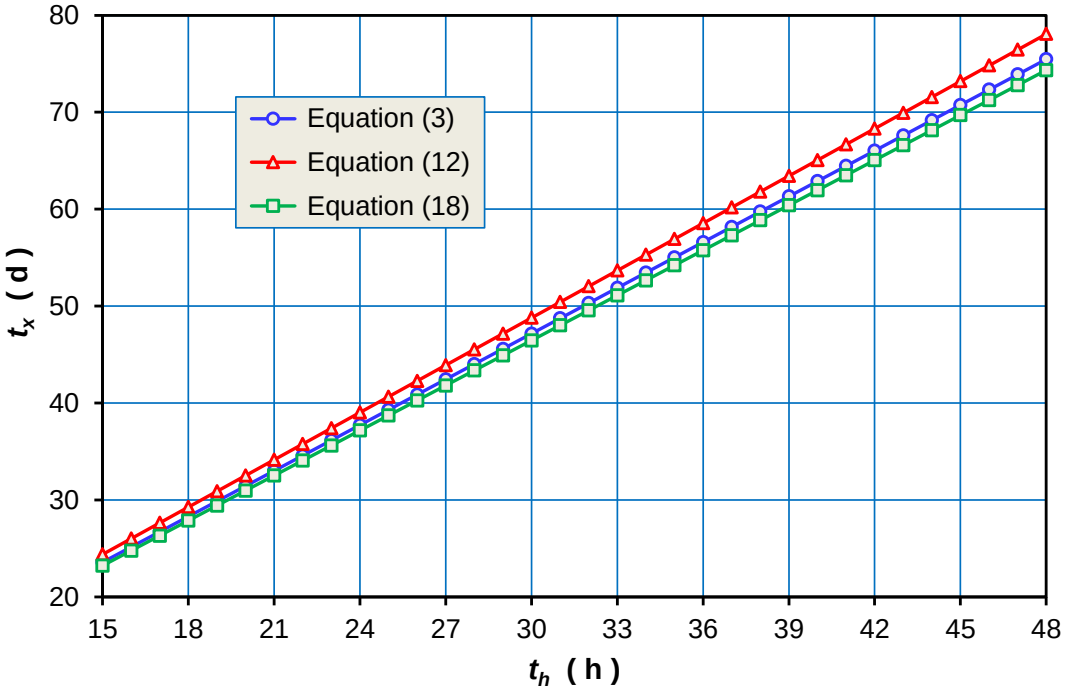


Fig. 7 The influence of the hydraulic retention time t_h on the sludge age t_x for the activation system with a plug flow bioreactor.

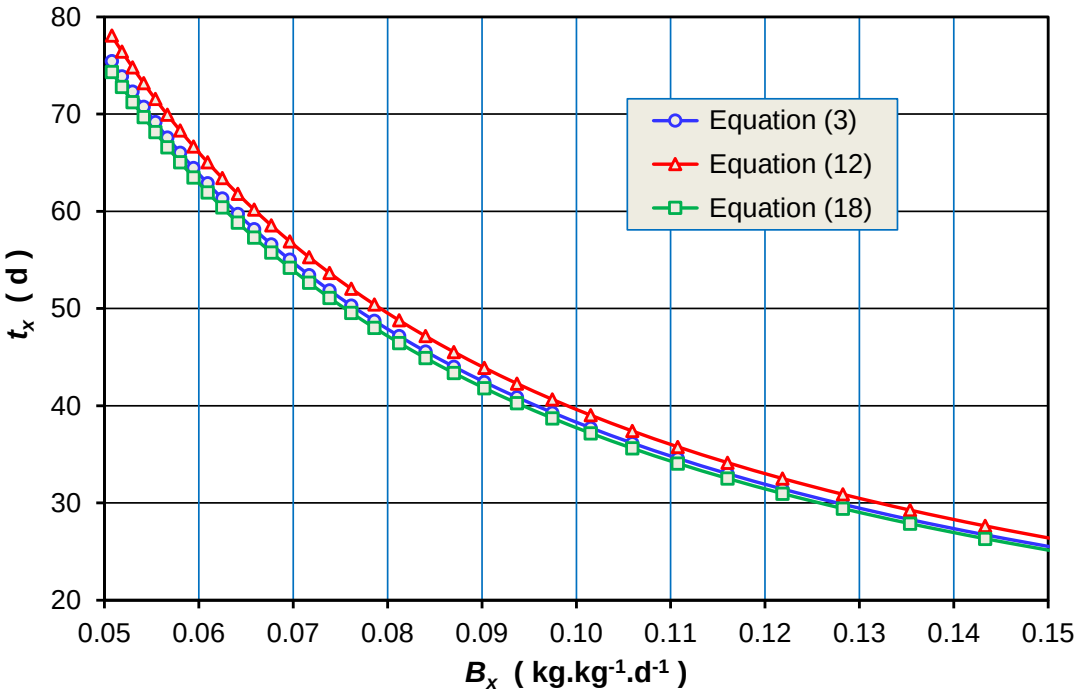


Fig. 8 The influence of the sludge loading B_x on the sludge age t_x for the activation system with a plug flow bioreactor.

Conclusion

The technological properties of two types of activation systems (activation system with a chemostat bioreactor and activation system with a plug flow bioreactor), which are used in the technologies of WWT plants, are characterized by means of the basic technological parameters of the activation process. The specific values of the technological parameters of the analyzed activation systems are presented, as well as the relations between them. The main advantages and disadvantages of some bioreactors, which are most often used in the activation systems of WWT plants, are also briefly described.

For a more exact evaluation of the sludge age parameter t_x in the activation system with a plug flow bioreactor, a new relationship (equation (18)) was proposed. Equation (18) considers hydraulic retention time t_h and other important process parameters, similar to the basic definition equation (3) of the sludge age parameter valid for the activation system with a chemostat bioreactor. The mutual deviations between the values of the sludge age parameter calculated according to equations (3), (12), and (18) are evident from the graphs in Fig. 7 and Fig. 8, which show the dependences of the sludge age t_x on the hydraulic retention time t_h and the sludge age t_x on the sludge loading B_x, respectively. It should be noted that the values of the sludge age parameter t_x calculated according to equation (12) are influenced by the accuracy of determining the basic biochemical parameters μ_{max} and K_s.

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NOMENCLATURE

BOD	- biochemical oxygen demand	($kg.m^{-3}$)
B_v	- loading of activation vessel	($kg.m^{-3}.s^{-1}$)
B_x	- sludge loading	(s^{-1})
ΔB_v	- productivity of activation vessel	($kg.m^{-3}.s^{-1}$)
ΔB_x	- sludge productivity	(s^{-1})
E	- parameter expressing amount of transferred oxygen per energy unit	($kg_{O2}.kWh^{-1}$)
F	- influent flow rate	($m^3.s^{-1}$)
K_s	- saturation constant	($kg.m^{-3}$)
k_e	- endogenous metabolism coefficient	(s^{-1})
s	- substrate concentration	($kg.m^{-3}$)
s'	- substrate concentration at reactor inlet	($kg.m^{-3}$)
s_0	- initial substrate concentration	($kg.m^{-3}$)
s_L	- substrate concentration at reactor outlet	($kg.m^{-3}$)
t_h	- hydraulic retention time	(s)
t_r	- retention time with recirculation	(s)
t_x	- sludge age	(s)
V	- volume of unaerated wastewater content	(m^3)
WWT	- wastewater treatment	
x	- biomass concentration	($kg.m^{-3}$)
x'	- biomass concentration at reactor inlet	($kg.m^{-3}$)
x_L	- biomass concentration at reactor outlet	($kg.m^{-3}$)
Y_{xs}	- yield coefficient of biomass from substrate	(–)
γ	- thickening factor	(–)

δ	- factor of sludge concentration reduction	(–)
η	- effectiveness of activation process	(%)
μ_{max}	- maximum of biomass specific growth rate	(s^{-1})
τ	- recirculation factor	(–)
τ_{max}	- maximum of recirculation factor	(–)
ω	- factor of superfluous sludge effluent	(–)

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