

Wastewater treatment in a microbial membrane bioreactor — a model of the process

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Abstract

A model of microbial membrane bioreactor with convective flow through the membrane is presented in the paper. Permeability coefficients η_i in reference to microbial cells, substrates and possible reaction products as well as intensification coefficient Ψ which is a hydrodynamic parameter very significant for this bioreactor type, were introduced. The latter coefficient is used to control the bioreactor operation. Advantages of the membrane bioreactor over the classical flow bioreactor are presented. A reduction of residence time, with other parameters kept constant, or an increase of the conversion degree which enables the growth of feed stream, is reached in the range of coefficient $1 < \Psi < 3$. A further increase of parameter Ψ does not cause such a significant intensification any longer.

Due to high efficiency of the membrane bioreactor operating in a broad range of inlet concentrations and at low outlet concentration, this type of a microbial bioreactor is particularly recommended in industrial wastewater biodegradation.

Keywords: Microbial membrane bioreactor; Process intensification; Permeability coefficient; Substrate conversion degree; Residence time

1. Introduction

Microbial cells are the most important of the available catalysts for degradation of the compounds present in water and sewage. This is so because this catalyst type has high specificity of enzymes, but at the same time is not inactivated and from the point of view of process economy is

similar to a chemical catalyst. The only condition to make this degradation process efficient, is to set up conditions suitable for microbial cell growth (pH, temperature, the range of carbon source concentration, the effect of other substances present in the medium) and a proper substrate stream. The process is effective when the concentration

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of active biomass is high. Hence the use of a microfiltration membrane which holds up cells in the biodegradation zone is highly recommended.

A high concentration of a biocatalyst allows us to carry out the process at an increased feed stream [1], while the high reaction degree obtained causes that the sewage undergoes an advanced treatment.

The membrane bioreactor was applied to biodegradation of many types of organic [2–4] and inorganic pollutants [5,6]. If a difference between particle sizes of the substrate and product is big, it is desirable that beside microbial cells held up on the membrane, also high-molecular substrate is caught and the product is removed. This is a special case of the microbial membrane bioreactor.

Despite numerous applications of the membrane bioreactor, its characteristic has not been fully presented in the literature. The present paper refers to a model characteristic prepared on the basis of a mathematical model of the membrane bioreactor. The characteristic serves to make a proper selection of a parameter which intensifies the bioreactor operation (Ψ).

2. A model of the membrane bioreactor

The proposed model of the membrane bioreactor operating in a unsteady state is shown schematically in Fig. 1.

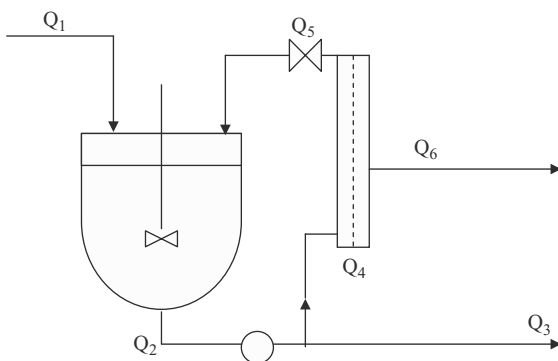


Fig. 1. Bioreactor with membrane separation mode.

The following assumptions were made when developing the model:

- (1) Diluted solutions are considered in which contraction of volume related to the change of their composition is negligible. This enables balancing of the system basing on volume fractions which usually occur in biotechnology and on volumetric streams.
- (2) Reaction conditions in the pipes of a circulation loop are identical as in the reactor tank, which means that volume of the reaction zone is enlarged by the pipe volume. In practice, the pipe volume is negligible.

In the unsteady state, the balance of volumetric stream in the reaction zone is given by the equations:

$$Q_1 + Q_5 - Q_2 - \frac{dV_R}{dt} = 0 \quad (1)$$

$$Q_1 - Q_6 - Q_3 - \frac{dV_R}{dt} = 0 \quad (2)$$

$$Q_2 - Q_4 - Q_3 = 0 \quad (3)$$

and the balance of streams of components is given by the below relations, which in order to make future transformations easier, were separated into the equations for reaction substrates, reaction products and microbial cells.

$$Q_1 \cdot c_{sk,1} + Q_5 \cdot c_{sk,5} - Q_2 \cdot c_{sk,2} - V_R \cdot r_{s1} - \frac{d(V_R \cdot c_{sk,2})}{dt} = 0 \quad \text{for } k = 1, \dots, n \quad (4)$$

$$Q_1 \cdot c_{pj,1} + Q_5 \cdot c_{pj,5} - Q_2 \cdot c_{pj,2} + V_R \cdot Y_{pj/s} \cdot r_{s1} - \frac{d(V_R \cdot c_{pj,2})}{dt} = 0 \quad \text{for } j = 1, \dots, m \quad (5)$$

$$Q_1 \cdot X_1 + Q_5 \cdot X_5 - Q_2 \cdot X_2 + V_R \cdot Y_{x/s} \cdot r_{s1} - \frac{d(V_R \cdot X_2)}{dt} = 0 \quad (6)$$

On the other hand, the balance of streams in the separation zone is given by the equations:

$$Q_4 - Q_5 - Q_6 = 0 \quad (7)$$

$$Q_4 \cdot c_{sk,4} - Q_5 \cdot c_{sk,5} - n_{sk,6} = 0 \quad (8)$$

$$Q_4 \cdot c_{pj,4} - Q_5 \cdot c_{pj,5} - n_{pj,6} = 0 \quad (9)$$

$$Q_4 \cdot X_4 - Q_5 \cdot X_5 - n_{x,6} = 0 \quad (10)$$

The relation for a transmembrane stream of subsequent components of the system depends on the type of transport through the membrane (convection or diffusion). When cell biomass is involved in the process, ultrafiltration or microfiltration is usually applied [7].

A stream of solution (solvent) in convective mass transport through the membrane is described by the equation:

$$Q_6 = W \cdot A \cdot \Delta P \quad (11)$$

The value of parameter W for pure solvent is given by a membrane producer. In the case of multicomponent systems with non-typical composition (which is often the case in biotechnology), this value is smaller and depends on solution concentration and turbulence over the membrane surface ($W = W \cdot f(c, Re)$), hence it is usually determined experimentally. As follows from Eq. (11) stream Q_6 can be arbitrarily big, due to the application of a membrane with relatively large surface.

Separation properties in this type of mass transport are used to be determined by the hold-up coefficient R_i :

$$R_i = 1 - \frac{c_{i,perm}}{c_{i,ret}} = 1 - \eta_i \quad (12)$$

The value of $\eta_i = 0$ corresponds to total hold-up which leads to the biggest change of concentration, while $\eta_i = 1$ is related to total permeability. In practice, to obtain high turbulence of flow

over the membrane, high values of circulation (stream Q_4) are applied, hence stream Q_6 does not exceed several percent of stream Q_4 . Since these changes are small, in the membrane practice the hold-up coefficient is usually related to inlet concentration [8], which corresponds to

$$R_i = 1 - \frac{c_{i,6}}{c_{i,4}} = \text{const} = 1 - \eta_i \quad (13)$$

The transmembrane stream of component “ i ” will be in this case:

$$n_{i,6} = Q_6 \cdot c_{i,4} \cdot \eta_i \quad (14)$$

An important feature of the convective mass transport is that

$$c_{i,5} \geq c_{i,4} \quad (15)$$

$$0 \leq c_{i,6} \leq c_{i,4} \quad (16)$$

Most processes carried out in the presence of microorganisms (an exception are the systems with substrate or product inhibition) are described by Monod equation [9–11], hence r_s in Eqs. (4)–(6) assumes the form:

$$r_{s1} = \frac{1}{Y_{x/s}} \cdot X_2 \cdot \mu = \frac{1}{Y_{x/s}} \cdot X_2 \cdot \frac{\mu_{\max} \cdot c_{s1,2}}{K_S + c_{s1,2}} \quad (17)$$

3. Model analysis of the microbial membrane bioreactor

The above analysis refers to the most frequent type of a microbial membrane bioreactor, in which biocatalyst (microbial cells) is completely held up on the membrane, while all other components, including limiting substrates, pass freely through the membrane. Hence it can be stated that

$$\eta_x = \frac{X_6}{X_4} = 0 \quad (18)$$

$$\eta_s = \frac{c_{s,6}}{c_{s,4}} = 1 \quad (19)$$

Assuming that the stream of sterilized medium does not contain microorganisms ($X_1 = 0$) the balance of microbial cells leads to the relation:

$$\mu = \frac{Q_3}{V_R} \tag{20}$$

Taking

$$Q_1 = Q_3 + Q_6 \tag{21}$$

and substituting:

$$\tau = \frac{V_R}{Q_1} \tag{22}$$

one gets

$$\tau = \frac{1}{\mu \cdot \Psi} \tag{23}$$

where parameter

$$\Psi = \frac{1}{1 - \frac{Q_6}{Q_1}} \tag{24}$$

is called the intensification coefficient of a microbial membrane bioreactor. This is a hydrodynamic parameter which controls operation of the membrane bioreactor. The domain of the parameter is $\Psi (< 1, \infty)$, and for the classical agitated flow bioreactor $\Psi = 1$.

The balance of substrate limiting the growth (under the assumption that there is no separation) and using Eqs. (4), (17), (22) and (23) we have

$$c_{s,1} - c_{s,2} = \frac{1}{Y_{x/s}} \cdot \frac{1}{\Psi} \cdot X_2 \tag{25}$$

On the other hand, using kinetic Eq. (17) one gets

$$c_{s,2} = \frac{K_S}{\frac{\mu_{\max}}{\mu} - 1} = \frac{K_S}{\mu_{\max} \cdot \tau \cdot \Psi - 1} \tag{26}$$

$$\begin{aligned} X_2 &= Y_{x/s} \cdot \Psi \cdot (c_{s,1} - c_{s,2}) \\ &= Y_{x/s} \cdot \Psi \cdot \left(c_{s,1} - \frac{K_S}{\mu_{\max} \cdot \tau \cdot \Psi - 1} \right) \end{aligned} \tag{27}$$

It is obvious that the above relations have sense for the bioreactor in which substrate is used ($c_{s,1} > c_{s,2}$), hence a condition:

$$c_{s,1} > \frac{K_S}{\mu_{\max} \cdot \tau \cdot \Psi - 1} \tag{28}$$

As follows from Eq. (26), substrate concentration in the stream leaving the membrane bioreactor does not depend on its concentration in the inlet stream as is the case in the classical agitated flow bioreactor. Therefore, even highly concentrated wastewater can be supplied to the bioreactor.

A supremacy of the membrane bioreactor over the classical agitated bioreactor was considered basing on the above proposed model and analyzing the two cases.

3.1. Constant level of $c_{s,2}$

Keeping a constant level of $c_{s,2}$ is equivalent to the constant value of μ . In this case, from Eqs. (25) and (26) the relations follow:

$$\frac{\tau_{bm}}{\tau_{clas}} = \frac{1}{\Psi} \tag{29}$$

$$\frac{X_{2,bm}}{X_{2,clas}} = \Psi \tag{30}$$

It is characteristic of the bioreactor in which a microbiological transformation takes place, that there is some minimum residence time below which no steady state can be achieved because the so-called “microbial cell elution” from the reaction zone takes place [12].

$$\tau_{\min} = \frac{1}{\mu_{\max} \cdot \Psi} \tag{31}$$

Hence, the range of residence times in the membrane bioreactor is

$$\tau \in \left(\frac{1}{\mu_{\max} \cdot \Psi}, \infty \right) \tag{32}$$

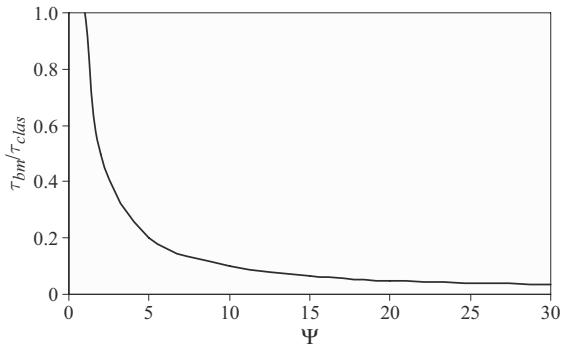


Fig. 2. Relation of the residence times in the membrane microbial bioreactor and in the classical agitated bioreactor in dependence on the value of intensification coefficient Ψ ($c_{s,2}$ in both cases is kept on the same value).

As can be seen in Fig. 2 which illustrates the relation described by Eq. (29), the residence time is shortened appreciably already at $\Psi = 3$. A further growth of the intensification parameter does not cause such a significant reduction of the residence time.

It is important that this relation is universal, irrespective of strain type, carbon source, the origin of feeding stream or process rate constants. It is obvious that shortening of the residence time makes it possible to reduce the bioreactor size or increase the feeding stream, which in the case of wastewater generated in big quantities is very significant from the economic point of view.

3.2. Preservation of constant τ

An identical residence time in the agitated reactor and in the one with a separation module (at other parameters being constant) due to cell concentration in the membrane bioreactor causes that the concentration ($c_{s,2}$) is lower and this in turn induces a change in the value of μ , according to Eq. (23):

$$\mu_{bm} = \frac{\mu_{clas}}{\Psi} \quad (33)$$

Using Eqs. (26) and (27) one can prove that

$$\frac{c_{s,2,bm}}{c_{s,2,clas}} = \frac{\mu_{max} \cdot \tau - 1}{\mu_{max} \cdot \tau \cdot \Psi - 1} \quad (34)$$

$$\frac{X_{2,bm}}{X_{2,clas}} = \Psi \cdot \frac{c_{s,1} - c_{s,2,bm}}{c_{s,1} - c_{s,2,clas}} = \Psi \cdot \frac{\frac{c_{s,1}}{K_M} - \frac{1}{\mu_{max} \cdot \tau \cdot \Psi - 1}}{\frac{c_{s,1}}{K_M} - \frac{1}{\mu_{max} \cdot \tau - 1}} \quad (35)$$

As follows from Eq. (35), very big changes in microbial cell concentration appear for small values of $\tau \cdot \mu_{max}$.

Upon substitution of the reduced concentration (c_s^*) which is a multiplicity of Monod constant:

$$c_s^* = \frac{c_s}{K_M} \quad (36)$$

the conversion degree for the discussed membrane reactor ($\eta_s = 1$) is given by the equation

$$\alpha_{bm} = \frac{c_{s,1}^* - c_{s,2}^*}{c_{s,1}^*} = 1 - \frac{1}{c_{s,1}^*} \cdot \frac{1}{\mu_{max} \cdot \tau \cdot \Psi - 1} \quad (37)$$

hence

$$\frac{\alpha_{bm}}{\alpha_{clas}} = \frac{1 - \frac{1}{c_{s,1}^*} \cdot \frac{1}{\mu_{max} \cdot \tau \cdot \Psi - 1}}{1 - \frac{1}{c_{s,1}^*} \cdot \frac{1}{\mu_{max} \cdot \tau - 1}} \quad (38)$$

Figs. 3 and 4 show an example of the effect of Ψ on a change in the conversion degree in the membrane bioreactor as compared to the classical one, at two different values of $\mu_{max} \cdot \tau$ equal to 3.5 and 7.0, in Figs. 3 and 4, respectively. An increase of the intensification coefficient induces a substantial increase of the conversion degree ($\alpha \in (0,1)$), a special strong influence being observed for low concentrations of the raw material, exceeding slightly the minimum concentration (according to Eq. (28)). This is related to the fact

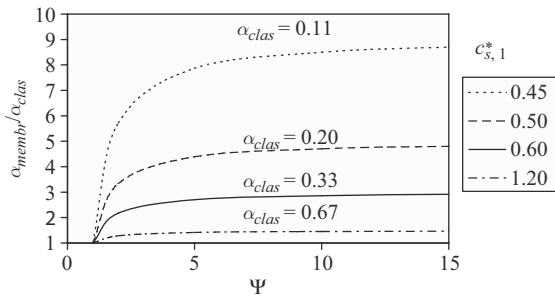


Fig. 3. The effect of Ψ on a change in the conversion degree in the membrane bioreactor as compared to the classical one, at $\mu_{\max} \cdot \tau$ equal to 3.5 and at different substrate concentration.

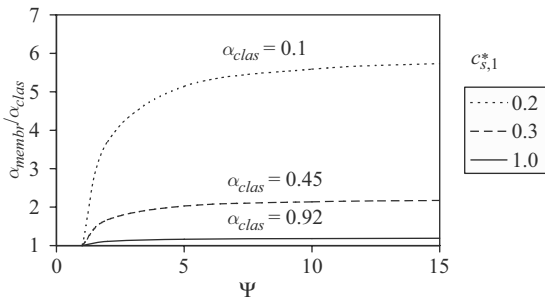


Fig. 4. The effect of Ψ on a change in the conversion degree in the membrane bioreactor as compared to the classical one, at $\mu_{\max} \cdot \tau$ equal to 7 and at different substrate concentration.

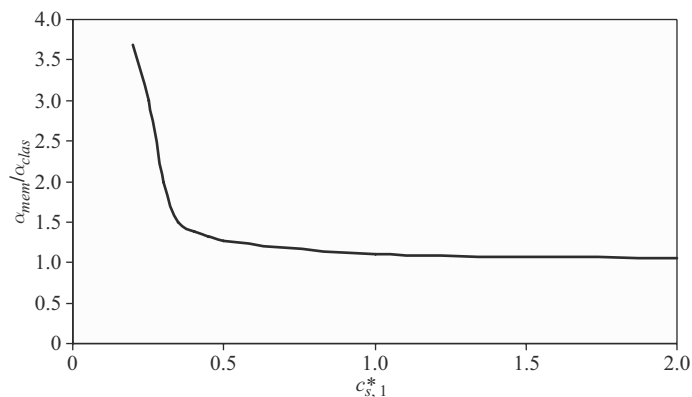


Fig. 5. Intensification in membrane bioreactor as a function of the substrate concentration in feed stream, at $\mu_{\max} \cdot \tau = 7$ and $\Psi = 2$.

that to these concentrations correspond low conversion degrees in the classical bioreactor and the range of intensification in this case is broad. Also for this reason more evident is the intensification at a lower value of $\mu_{\max} \cdot \tau$. In all cases the effect of the intensification coefficient is significant in the range of Ψ from 1 to 3. A further biomass concentration has no significant meaning.

4. Conclusions

Analysis of the efficiency of the microbial membrane bioreactor based on the proposed model shows that this bioreactor has a prevalence over the classical agitated bioreactor. Due to the use of a membrane which arrests cells, an increase of biomass concentration in the system causes a reduction of the residence time, i.e. a decrease of the reactor size and/or an increase of the feeding stream, or when the residence time is kept constant the conversion degree can be increased. Such intensification is particularly significant when concentration in the feeding stream is low. This case is typical of the microbiological industrial wastewater treatment and in this process the use of the membrane bioreactor may be extremely efficient which is illustrated by the relation for some operation parameters of the membrane bioreactor (Fig. 5).

It has been shown that irrespective of the system (strain, carbon source, kinetic equation constants) a significant intensification in the membrane bioreactor is observed at the parameter $1 < \Psi < 3$. This is the range for which technological processes should be carried out.

Nomenclature

A	surface, m^2
c	concentration, $kg\ m^{-3}$
c^*	reduced concentration, $kg\ m^{-3}$
K_S	constant in Monod equation, $kg\ m^{-3}$
n	density of mass stream, $kg\ m^{-2}\ s^{-1}$
ΔP	pressure difference, Pa
R	hold-up coefficient
r_s	reaction rate, $kg\ m^{-3}\ s^{-1}$
Q	volume stream, $m^3\ s^{-1}$
t	time, s
V_R	reactor volume, m^3
W	membrane permeability, $m^3\ m^{-2}\ Pa^{-1}\ s^{-1}$
X	cell concentration, $kg\ m^{-3}$
$Y_{x/s}$	coefficient of biomass efficiency
$Y_{p/s}$	coefficient of product synthesis

Greek symbols

α	conversion degree
η	permeability coefficient
τ	residence time, h
Ψ	intensification coefficient
μ	specific growth rate, h^{-1}
μ_{max}	maximal growth rate, h^{-1}

Subscripts

bm	membrane bioreactor
$clas$	classical agitated flow-bioreactor
p	product
s	substrate
sl	limiting substrate
1,2,....	no. of streams

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