Biochemical Engineering Journal 121 (2017) 118–130

Contents lists available at ScienceDirect

Biochemical Engineering Journal

journal homepage: www.elsevier.com/locate/bej

Regular article

Three-phase fluidized bed bioreactor modelling and simulation

Szymon Skoneczny*, Wojciech Stryjewski, Katarzyna Bizon, Bolesław Tabiś

Department of Chemical and Process Engineering, Cracow University of Technology, Poland

ARTICLE INFO

Article history:
Received 14 March 2016
Received in revised form 19 October 2016
Accepted 28 January 2017
Available online 31 January 2017

Keywords:
Fluidized bed
Bioreactor
Mathematical modelling
Steady states
Stability
Oscillations

ABSTRACT

A mathematical model of a three-phase fluidized bed biofilm reactor for aerobic processeses is presented. The growth of attached biomass, its decay and interphase transfer were taken into consideration in the proposed quantitative description of the bioreactor. The presented model of the fluidized-bed bioreactor is the unique one which takes into account partial thickening of biomass and its recirculation. The stationary characteristics was determined with the use of a novel simplified numerical method for the assessment of stability of steady states. The effect of microbial growth kinetics on steady state multiplicity was characterized. The relationship between biofilm growth and boundaries of fluidized bed existence was shown. Conditions of the biofilm's existence on carrier particles were formulated. Some novel dynamic characteristics concerning fluidized bed bioreactors were presented.

1. Introduction

Three-phase fluidized bed biofilm reactors are commonly used in environmental protection engineering and biotechnology. Among other uses, they are used to carry out microbiological degradation processes of toxic organic compounds [1–5], microbiological nitrification process [6] and synthesis of some drugs, e.g. penicillin, oxytetracycline and other organic compounds [7–9], and in the production of yeast [10]. A review of numerous applications of three-phase fluidized bed bioreactors was presented by Schügerl [11].

The key advantages of fluidized bed bioreactors are: highly expanded interphase surface, simple construction and, above all, the possibility of the separation of the mean residence time of the liquid phase and the immobilized biomass. Moreover, immobilization of biomass on fine particles results in a many times higher concentration of biomass in comparison with stirred tank bioreactors with suspended cells. According to Tang and Fan [2], due to the immobilization of the microorganisms the concentration of biomass in a fluidized bed reactor can be up to 30–40 kg/m^3, i.e. around ten times higher than in tank bioreactors with activated sludge. As arises from unstructured kinetics, rates of microbiological processes is proportional to the concentration of active biomass in the reaction environment. The application of fluidized bed bioreactors also eliminates the phenomenon of bed clogging, which is commonly observed in biofilters with a fixed bed.

In view of the numerous applications of three-phase fluidized bed bioreactors in biotechnology, research focused on the mathematical modelling and simulation of these apparatuses has been in progress for many years. Heterogeneous models for aerobic microbiological processes were published in the 1980s. Representative works from this period are papers by Park, Davis and Wallis [7,8], Chang and Rittmann [12], Tang et al. [2,3], Worden and Donaldson [5], and Wisecarver and Fan [4].

In the early 2000 s Onysko et al. [1] applied an integral approximation method for the modelling of biofilm dynamics in a study concerning the dynamics of a fluidized bed bioreactor. The authors analysed a process with a single limiting substrate. The first works concerning the application of nonlinear analysis for the investigation of the stationary and dynamic properties of three-phase fluidized bed bioreactors were published in the first decade of the 21st century [13].

The most recent mathematical model of the three-phase fluidized bed bioreactor has been proposed by Olivieri et al. [14]. However, the model assumes a lack of mass transfer resistance between the liquid phase and the biofilm, and the decay of immobilized biomass is also omitted. Moreover, the cited authors did not take into account the distributions of diffusion coefficients and biomass density in the biofilm. Hence, a more general model has been proposed, and furthermore, an analysis of the influence of several process parameters which have not been taken into account in the literature has been conducted.

* Corresponding author at: Department of Chemical and Process Engineering, Cracow University of Technology, ul. Warszawska 24, 31-155 Cracow, Poland.
E-mail address: skoneczny@chemia.pk.edu.pl (S. Skoneczny).

http://dx.doi.org/10.1016/j.bej.2017.01.017
1369-703X/

Nomenclature

a_s	Specific external biofilm surface area (m^{-1})
ak_c	Gas-liquid volumetric mass transfer coefficient (h^{-1})
Bi $_i$	Biot number, (i = A, T)
c_A, c_B, c_T	Mass concentration of carbonaceous substrate, biomass and oxygen, respectively ($kg\,m^{-3}$)
d_0	Diameter of a solid carrier (m)
D_e	Effective diffusion coefficient in biofilm ($m^2\,h^{-1}$)
F_V	Volumetric flow rate ($m^3\,h^{-1}$)
h	Height coordinate in the apparatus (m)
H	Total height of the fluidized bed (m)
k	Maximum specific growth rate (h^{-1})
k_o	Decay rate coefficient(h^{-1})
k_{det}	Biofilm detachment rate coefficient (h^{-1})
k_s	Liquid-biofilm mass transfer coefficient ($m\,h{-}1$)
K_A, K_T	Saturation constants for carbonaceous substrate and oxygen in kinetic equations ($kg\,m^{-3}$)
K	Gas-liquid interphase equilibrium constant
K_{in}	Inhibition constant ($kg\,m^{-3}$)
L_b	Thickness of the biofilm (m)
m_B	Total mass of biomass (kg)
n_s	Number of carrier particles
N	Number of internal collocation points
r_A, r_T	Uptake rate of carbonaceous substrate and oxygen, respectively ($kg\,m^{-3}\,h^{-1}$)
r_B	Growth rate of biomass ($kg\,m{-}^3\,h{-}^1$)
r_b	Radius of the bioparticle (m)
r_{det}	Detachment rate of biomass ($kg\,m^{-3}\,h^{-1}$)
r_0	Radius of the carrier particle (m)
S	Cross-sectional area of the apparatus (m^2)
t	Time (h)
u	Superficial velocity ($m\,s{-}1$)
u_b	Bubble rise velocity ($m\,s{-}^1$)
u_{0g}	Superficial air velocity ($m\,s{-}^1$)
V	Volume (m^3)
w_{BA}, w_{BT}	Yield coefficients (kg B·kg A^{-1}), (kg B·kg T^{-1})
x	Current coordinate in the biofilm (m)
x_a	Fraction of active biomass in the biofilm
z	Dimensionless coordinate in the biofilm
Z	Dimensionless coordinate in the fluidized bed
α	Degree of conversion of the carbonaceous substrate
β	Dimensionless concentration of biomass in liquid phase
γ	Dimensionless concentration of oxygen in liquid phase
δ	Dimensionless concentration of oxygen in the biofilm
ε_g	Gas hold-up in the multi-phase system
ζ	Fraction of carrier particles in the liquid
η	Dimensionless concentration of carbonaceous substrate in the biofilm
ϑ	Biomass thickening coefficient
ξ	Recirculation ratio of the liquid
ρ_a	Concentration of active biomass in the biofilm ($kg\,m^{-3}$)
ρ_b	Concentration of biomass in the biofilm ($kg\,m^{-3}$)
$\bar{\rho}_b$	Average concentration of biomass in the biofilm ($kg\,m^{-3}$)
ρ_0	Density of solid carrier ($kg\,m^{-3}$)
τ_0^c	Mean residence time of the liquid in the installation (h)
Φ	Thiele modulus

Nomenclature

Superscripts

b	Biofilm phase
c	Liquid (continuous) phase
g	Gas phase

Subscripts

A, B, T	Refer to carbonaceous substrate, biomass and oxygen, respectively
s	Refers to surface of the biofilm
f	Refers to feed stream
r	Refers to recirculated stream

A comparison of the proposed mathematical model with other models of a three-phase fluidized bed bioreactor for aerobic processes is presented in Table 1. It can be seen from Table 1 that the presented model is the unique one which takes into account the partial thickening of biomass and its recirculation. Apart from this, a novel simplified numerical method for the assessment of stability of steady states was proposed, which is based on hypothesis concerning concentration distributions in the biofilm and its surroundings. The proposed model was used for the nonlinear analysis of the steady states, and for the analysis of the dynamic behaviour of the three-phase fluidized bed bioreactor with double-substrate limited processes.

2. Mathematical model of the bioreactor

The mathematical model of the fluidized bed bioreactor consists of: a quantitative description of fluidized bed hydrodynamics, interphase mass transfer, kinetics of the microbiological process, and dynamics of biofilm growth on fine carrier particles (Fig. 1).

A schematic diagram of the analysed bioreactor is presented in Fig. 2. Symbols used in the mathematical model of the installation have been marked in this figure.

2.1. Model of a microbiological process in biofilm

Beyenal and Tanyolac [16] proved experimentally that the standard deviation of the mean biofilm thickness is sufficiently small to use a mean value in calculations. This assumption is applied in this work. A representative volume in the biofilm is a sphere with a differential thickness. In mass balance equations formulated for the representative volume, the following terms are taken into account:

a) diffusional mass inflow and outflow,
b) utilization of substrates due to the microbiological process,
c) accumulation of substrates.

The application of the mass conservation principle for the carbonaceous substrate A and oxygen T gives the following equations

$$4\pi x^2 \frac{\partial c_A^b}{\partial t} dx = 4\pi x^2 D_{eA} \frac{\partial c_A^b}{\partial x} - 4\pi(x-dx)^2 \cdot \left(D_{eA} \cdot \frac{\partial c_A^b}{\partial x} - \frac{\partial}{\partial x} D_{eA} \frac{\partial c_A^b}{\partial x} dx \right) - 4\pi x^2 \cdot r_A^b(c_A^b, c_T^b, x)\,dx \quad (1a)$$

$$4\pi x^2 \frac{\partial c_T^b}{\partial t} dx = 4\pi x^2 D_{eT} \frac{\partial c_T^b}{\partial x} - -4\pi(x-dx)^2 \cdot \left(D_{eT} \cdot \frac{\partial c_T^b}{\partial x} - \frac{\partial}{\partial x} D_{eT} \frac{\partial c_T^b}{\partial x} dx \right) - 4\pi x^2 \cdot r_T^b(c_A^b, c_T^b, x)\,dx \quad (1b)$$