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A COMPARISON OF HYDRODYNAMIC MODELS OF DIFFERENT HYBRID, FLUIDISED-BED BIOREACTORS

PORÓWNANIE MODELI HYDRODYNAMICZNYCH HYBRYDOWYCH BIOREAKTORÓW FLUIDYZACYJNYCHTY

Abstract

This is a preliminary study of hybrid fluidised-bed bioreactors considered the hydrodynamic models and their comparison. In this type of bioreactor, there are two characteristic components which determine their work mode. One part of the bioreactor works as a two-phase, gas-liquid, air-lift bioreactor. The second part is a two-phase, liquid-solid, fluidised-bed bioreactor. This type of construction provides high biomass concentration and low shear forces which influence biofilm. Two different types of construction of hybrid fluidised-bed bioreactors were proposed: with external or internal draft tube. Two different mathematical models are needed to design and analyse the operation of these devices.

Keywords: fluidised bed, air lift, hydrodynamics, mathematical modelling

Streszczenie

W artykule przeprowadzono wstępne badania fluidyzacyjnych bioreaktorów hybrydowych. Przedstawiono modele hydrodynamiki hybrydowych bioreaktorów fluidyzacyjnych i porównano je. W takich aparatach występują dwie strefy decydujące o ich warunkach pracy. Jedna z nich pracuje, jako dwufazowy bioreaktor airlift, natomiast druga to dwufazowy bioreaktor fluidyzacyjny ciało stałe - ciecz. Zastosowanie takiego bioreaktora hybrydowego umożliwia osiągnięcie większego stężenia biomasy oraz małych sił ścinających. W literaturze występują dwa typy analizowanych bioreaktorów- z zewnętrzną lub wewnętrzną recyrkulacją cieczy. Do projektowania i analizy warunków pracy obu konstrukcji niezbędne jest stworzenie dwóch oddzielnych modeli matematycznych.

Słowa kluczowe: złoże fluidalne, reaktor air lift, hydrodynamika, modelowanie matematyczne

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1. Introduction

Experimental and theoretic studies about fluidisation have been conducted for years [1-4]. Nevertheless, chemical engineering scientists around the world [5-9] are strongly engaged in the topic. Most of works focuses on the intensification of mass and heat transfer.

Fluidised beds are used also in the engineering of biochemical reactors. Tang and Fan [10], Godia and Sola [11], and Summerfelt [6] presented the advantages of fluidised beds, the main advantages being:

- significantly higher average biomass concentrations can be reached in fluidised beds than in tank reactors;
- average residence time of biomass immobilised as a biofilm, apart from slurry reactors, is not related with the average residence time of a liquid phase;
- intensification of mass transfer between the liquid phase and the biofilm.

Two types of fluidised-bed bioreactors are used: two-phase, liquid-solid and three-phase gas-liquid-solid apparatus. The optimal oxygen level is achieved by oxygen mass transfer from gas bubbles to a liquid phase inside the bioreactor. The oxidation of liquid stream can be also realized by an external oxygenate apparatus. Usage of two-phase, fluidised-bed bioreactors is limited by the amount of oxygen dissolved in the liquid phase. On the other hand, in three-phase fluidised bed bioreactors shear forces affecting the biofilm may damage microorganisms' cells. The point is to construct a piece of apparatus that provides a high level of oxidation in a two-phase, fluidised-bed bioreactor.

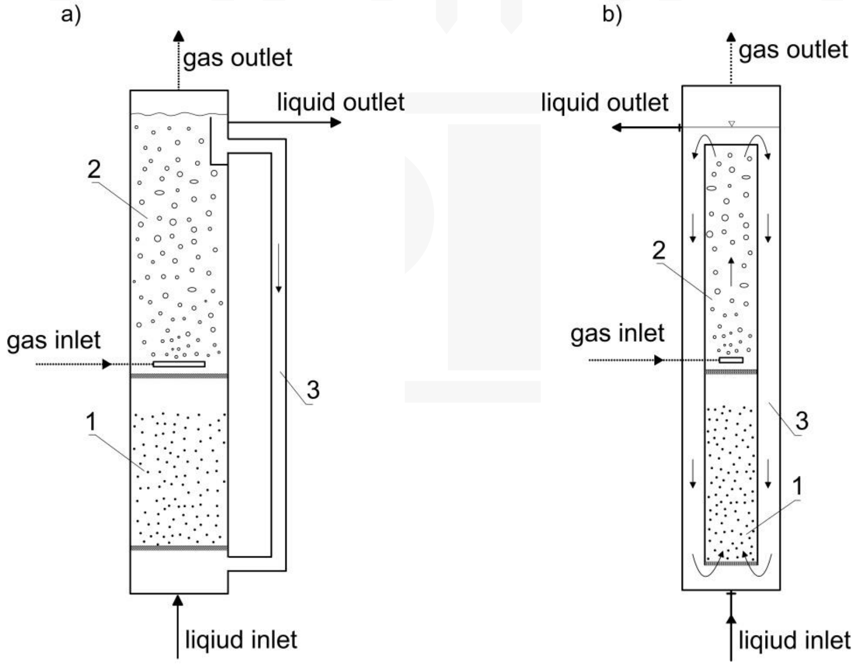

Fig. 1. Scheme of hybrid, fluidised-bed bioreactor: a) with external liquid recirculation, b) with internal liquid recirculation

2. Characteristics of hybrid, fluidised-bed bioreactors

Guo et al. [12] proposed the construction of apparatus in which a two-phase, fluidised-bed bioreactor and an air-lift bioreactor (gas-liquid apparatus) were combined. Such solution is presented in Fig. 1a and is alternatively proposed by Olivieri et al. [13] in Fig. 1b. These pieces of apparatus differ from each other by the method in which recirculation of liquid could be realized.

There are two zones in the main part of the apparatus – a zone with a two-phase, fluidised bed marked as ‘1’ and a zone of barbotage apparatus marked as ‘2’ in which the oxidation of the liquid phase is realised. Due to differences of densities between riser ‘1’ and downcomer zone ‘3’, the liquid circulates in the apparatus in the same manner as in the air-lift bioreactor.

Hybrid, fluidised-bed bioreactors provide an aerobic bioprocess in a two-phase, fluidised-bed bioreactor where drug forces affecting the biofilm are lower than shear forces in three-phase, fluidised-bed bioreactors. Another advantage of hybrid, fluidised-bed bioreactors is higher level of biomass concentration then in two-phase airlift bioreactors. Moreover, in this case energy is not consumed by liquid circulation pump.

3. Mathematical model of hydrodynamics

The mathematical modelling of innovative and not widely used reactor may qualify it to use in industry. The numerical calculations are needed to determine proper geometrical parameters of apparatus and process parameters characteristics. The comparison of mathematical model of hybrid, fluidised-bed bioreactor with internal and external circulation of liquid is important to choose the better construction, when we consider only the hydrodynamics of those bioreactors.

Optimal geometrical dimensions of apparatus may be obtained by mathematical modelling, simulating its operation. The work of the hybrid, fluidised-bed bioreactor can be characterised by the following values:

- velocity of liquid (u_{0ci}) and gas (u_{gi}) in each zone of the apparatus
- gas hold-up in each zone of the apparatus (ε_i)
- dynamic height of the fluidised-bed (H_f).

In order to estimate these parameters, the model of hydrodynamics has to be defined. Balancing of pressure drops during media flow through the bioreactor can be used to do it. The driving force of liquid circulation corresponds to density differences of the binary phase mixture between air-lift zone ‘2’ and downcomer zone ‘3’ and it can be obtained by:

$$\Delta p = H_r \cdot \varepsilon_2 \cdot \rho_c \cdot g \qquad (1)$$

where

H_r – height of barbotage zone in meters;
ε_2 – gas hold-up in barbotage zone ‘2’;
ρ_c – liquid density, kg·m^{-3};
g – gravitational acceleration, m·s^{-2}.

3.1. The mathematical model of hybrid, fluidised-bed bioreactor hydrodynamics with an internal pipe

Formation of the mathematical model for such device (Fig. 1b) may be realised by balancing the driving force with following pressure drops:

a) hydrodynamic resistances in zones ‘1’, ‘2’ and ‘3’

$$\Delta p_1 = 0{,}5 \cdot \lambda_1 \cdot \frac{H - H_r}{d_1} \cdot u_{c1}^2 \cdot \rho_c \tag{2}$$

$$\Delta p_2 = 0{,}5 \cdot \lambda_2 \cdot \frac{H_r}{d_2} \cdot u_{c2}^2 \cdot \rho_c \tag{3}$$

$$\Delta p_3 = 0{,}5 \cdot \lambda_3 \cdot \frac{H}{d_h} \cdot u_{c3}^2 \cdot \rho_c \qquad d_h = d_3 - d_2 \tag{4}$$

where

λ_i – coefficient of axial hydrodynamic resistances for zone *i*, $i = 1, 2, 3$;
H – overall bioreactor height in meters;
d_i – the zone *i* diameter, $i = 1, 2, 3$ in meters;
u_{ci} – liquid velocity in zone *i*, $i = 1, 2, 3$ $\text{m}\cdot\text{s}^{-1}$.

b) pressure drop on a fluidised bed:

$$\Delta p_f = H_{mf} \cdot (\rho_s - \rho_c) \cdot (1 - \varepsilon_{mf}) \cdot g \tag{5}$$

where

H_{mf} – height of fluidised bed refers to minimum fluidisation conditions in meters;
ε_{mf} – fluidised-bed porosity refers to minimum fluidisation conditions;
ρ_s – density of fluidised material, $\text{kg}\cdot\text{m}^{-3}$.

c) pressure drop in the surroundings of the lower edge of the draft tube:

$$\Delta p_b = 0{,}5 \cdot \zeta_b \cdot u_{c3}^2 \cdot \rho_c \tag{6}$$

where

ζ_b – hydrodynamic resistance coefficient in the surroundings of the lower edge of the draft tube.

d) pressure drop onto two supporting nets,

$$\Delta p_s = \zeta_s \cdot u_{c1}^2 \cdot \rho_c \tag{7}$$

where

ζ_s – hydraulic resistance coefficient of the net.

The pressure-drop balance from equations (1-7) may be presented as:

$$\Delta p = \sum_{i=1}^{3} \Delta p_i + \Delta p_f + \Delta p_b + \Delta p_s \tag{8}$$

Obtaining these quantities is possible when to equation (8) mass balances of gas and liquid will be added:

$$S_2 \cdot \varepsilon_2 \cdot (u_{c2} + \upsilon) = S_2 \cdot u_{0g} \tag{9}$$

$$S_2 \cdot (1 - \varepsilon_2) \cdot u_{c2} = S_3 \cdot u_{c3} + S_2 \cdot u_{0c} \tag{10}$$

where

S_i – vertical superficial of zone i, $i = 1, 2, 3$ m^2;

υ – slip velocity of gas bubbles, $m \cdot s^{-1}$;

u_{0g} – velocity of gas referring to the cross-sectional area of zone ‘1’, $m \cdot s^{-1}$.

In a steady state, velocities of liquid in zones ‘1’ and ‘2’ are tied up by continuity equation:

$$S_1 \cdot u_{0c1} = S_2 \cdot u_{c2} \cdot (1 - \varepsilon_2) \tag{11}$$

where

u_{0ci} – liquid velocity referring to cross sectional area of zone i, $i = 1, 2, 3$ $m \cdot s^{-1}$.

After fusion of equations (8-11) a model is stated as a function of two variables: gas hold-up in zone ‘2’ and liquid velocity in zone ‘2’:

$$\varepsilon_2 \cdot u_{g2} - u_{0g} = f_1(\varepsilon_2, u_{c2}) = 0 \tag{12a}$$

$$\Delta p - \sum_{i=1}^{3} \Delta p_i + \Delta p_f + \Delta p_b + \Delta p_s = f_2(\varepsilon_2, u_{c2}) = 0 \tag{12b}$$

To solve the system of equations (12a and 12b), the Newton method may be applied. In the literature exists the other approach to calculation of pressure drop balance [13]; the same results from presented here mathematical models in a different way were obtained by Olivieri et al. [13].

3.2. Mathematical model of hydrodynamics of hybrid, fluidised-bed bioreactor with external recirculation pipe

In the case shown in Fig. 1a, the driving force is defined in the same way as in hybrid, fluidised-bed bioreactors with an internal draft tube (1). The model in such an example is obtained by balancing the following pressure drops:

a) hydrodynamic resistances in all zones of bioreactor:

$$\Delta p_1 = 0.5 \cdot \lambda_1 \cdot \frac{H - H_r}{d_1} \cdot u_{c1}^2 \cdot \rho_c \tag{13}$$

$$\Delta p_2 = 0.5 \cdot \lambda_2 \cdot \frac{H_r}{d_2} \cdot u_{c2}^2 \cdot \rho_c \tag{14}$$

$$\Delta p_3 = 0.5 \cdot \lambda_3 \cdot \frac{H}{d_3} \cdot u_{c3}^2 \cdot \rho_c \tag{15}$$

b) the pressure drop on the fluidised bed:

$$\Delta p_f = H_{mf} \cdot (\rho_s - \rho_c) \cdot (1 - \varepsilon_{mf}) \cdot g \tag{16}$$

c) the pressure drop on the bottom and upper nets in the fluidisation zone:

$$\Delta p_s = \zeta_s \cdot u_{c1}^2 \cdot \rho_c \tag{17}$$

d) the pressure drop in the inlet of the external draft tube:

$$\Delta p_{m1} = 0{,}5 \cdot \xi_1 \cdot u_{c3}^2 \cdot \rho_c \tag{18}$$

where

ξ_1 – local friction coefficient in the inlet of the external draft tube.

e) the pressure drop in the outlet of the external pipe:

$$\Delta p_{m2} = 0.5 \cdot \xi_2 \cdot u_{c3}^2 \cdot \rho_c \tag{19}$$

where

ξ_2 – local friction coefficient in the outlet of the external draft tube.

f) the pressure drops on two nodes of the external draft tube

$$\Delta p_{m3} = \xi_3 \cdot u_{c3}^2 \cdot \rho_c \tag{20}$$

where

ξ_3 – local friction coefficient on the node of the external pipe.

The balance of the pressure drops is given by:

$$\Delta p = \sum_{i=1}^{3} \Delta p_i + \Delta p_f + \Delta p_s + \sum_{i=1}^{3} \Delta p_{mi} \tag{21}$$

Equation (21) differs with equation (8) because of different friction coefficients and the pressure drop in zone ‘3’. Equations (9-11), which are also valid for this case were matched with the model (21). Obtained in that way model is presented in eq. (22).

$$\varepsilon_2 \cdot u_{g2} - u_{0g} = f_1(\varepsilon_2, u_{c2}) = 0 \tag{22a}$$

$$\Delta p - \sum_{i=1}^{3} \Delta p_i + \Delta p_f + \Delta p_b + \Delta p_s + \sum_{i=1}^{3} \Delta p_{mi} = f_2(\varepsilon_2, u_{c2}) = 0 \tag{22b}$$

To solve model (22), Newton's method may be applied.

4. Hydrodynamic restrictions

The operation characterization of hybrid bioreactors is schematically presented in Fig.1. depends on behavior of granular biomass medium in zone "1". There are three kinds of fluidised bed behaviour depending upon the liquid velocity in the given zone – a stationary bed lies on the bottom site (if the velocity of liquid is lower than minimum fluidization velocity u_{mf}) ; immobilised on the top of the zone bed (if the velocity of the liquid is at least equal to terminal velocity u_t), and a fluidised bed (if the velocity is between the presented values). When fluidisation occurs, the dynamic height of the fluidised bed increases with increases in velocity and it corresponds to the functioning of the bioreactor. It can be noted that in both cases, two boundary velocities have to be obtained and that the work area of apparatus could be described.

The porosity of the fluidised bed also changes when the velocity of liquid increases and of course, the dynamic height of the fluidised bed in zone '1' is limited by the geometric height of the zone so that additionally, the velocity of fluidisation can comply with the following relationship:

$$u_{0c1} : H_f < H - H_r \tag{23}$$

The above relationship means that the fluidised bed may only expand at the moment when all of zone '1' is completely filled by the fluidised grains. After crossing presented in equation (23) limitation, the fluidised material will be assembling under the top site of fluidization zone. In that case the liquid flow through the porosity stationary bed and it can lead to overgrowth the bed by biomass.

Inequality (24) prevents the chance of gas bubbles being present in the fluidization zone. Limitation (24) may prevent it.

$$u_{c3} = u_{0c3} < \upsilon \tag{24}$$

When the bioreactor is equipped with the external recirculating pipe, this situation cannot occur, so restriction (24) is not needed.

Characterisation of operation regimes of hybrid fluidised bed bioreactors indicate, that liquid and gas flow in the apparatus have to be limited for both gas and liquid to provide its correct operation. These restrictions are related with specificity of fluidisation process.

5. Hydrodynamic characterisation of hybrid, fluidised-bed bioreactors

In this part of the paper, solutions of model will be presented. Calculations were performed for both hybrid, fluidised bed bioreactors with internal and external draft tubes. Technical specifications of the apparatus is presented in Table 1. The values of the other parameters were the same in all analyzed cases. The grain diameters are equal to $7\cdot10^{-4}$ m, the density of solid $\rho_s = 1800\ \mathrm{kg\cdot m^{-3}}$, the fluidised-bed porosity refers to minimum fluidisation conditions $\varepsilon_{mf} = 0.5$, the density of liquid $\rho_c = 1000\ \mathrm{kg\cdot m^{-3}}$ and the viscosity of liquid $\eta_c = 0.001\ \mathrm{kg\cdot m^{-1}\cdot s^{-1}}$.

Table 1

Technical specifications of hybrid, fluidised-bed bioreactors with external and internal draft tubes (all measurements are in meters)

	Bioreactor with external draft tube	Bioreactor with internal draft tube
Overall height of apparatus	3	3
Height of barbotage zone ‘2’	1.5	1.5
Zone ‘1’ diameter	0.3	0.3
Zone ‘2’ diameter	0.3	0.3
Zone ‘3’ diameter	0.4	0.05
Diameter of grains of fluidised material	$1.5\cdot10^{-3}$	$1.5\cdot10^{-3}$
Height of stationary bed of grains	0.03	0.03

Aerobic microbiological processes may occur in these items of apparatus. As has been noticed before, it is important to provide optimal oxygen concentration in the reacting medium. The change of gas velocity has an influence upon the hydrodynamic parameters in all bioreactor zones – for that reason, this value should be studied.

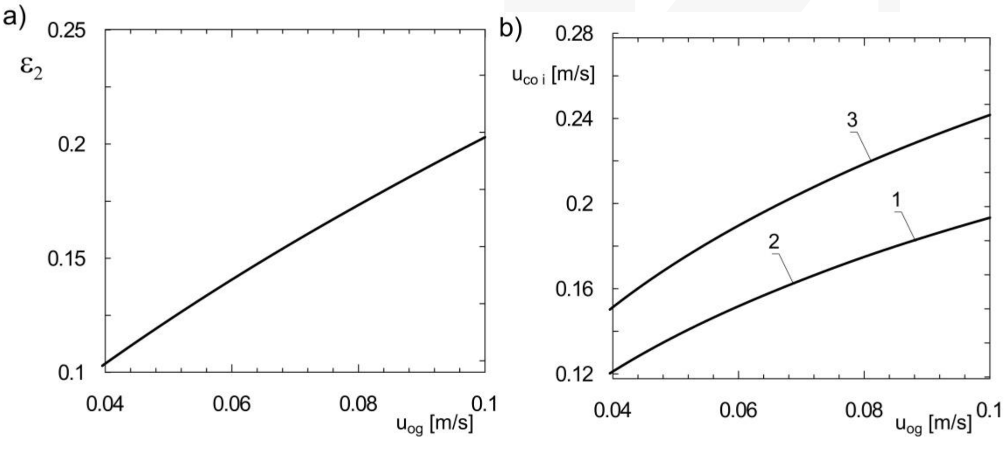

Fig. 2. Relationships of a) gas hold-up in zone ‘2’ and b) apparent liquid velocities in all zones of bioreactor from the velocity of gas delivered to hybrid, fluidised-bed bioreactor with internal draft tube

In Fig. 2, the relationship between gas hold-up in barbotage zone ‘2’ and the apparent liquid velocity in all zones was presented. These results let to account operation parameters for hybrid fluidised-bed bioreactor with internal draft tube instead of velocity of delivered gas. From Fig. 2a, it could be interpreted that increases of gas velocity cause gas hold-up increase in zone ‘2’. Due to a larger gas phase, oxygen transfer from gas to liquid phase is intensified and, as a consequence, the oxygenation of the microbiological environment increases. Moreover, increasing the gas hold-up causes a change of driving force, as is signified in Equation (1). Increased velocities of the liquid phase in all zones of the bioreactor can be observed (Fig. 2b). Due to the diameters of zones ‘1’ and ‘2’ being the apparent velocities of liquid in these zones also have the same values. Change of liquid velocity in the fluidisation zone increases the expansion of the fluidised bed. In case of significant gas distribution increase in the hybrid fluidized bed bioreactor, may it causes fluidized material assemblage under the upper site and additionally bubbles can flow to that zone. For that reason, hydrodynamic parameters should still be under control, using conditions (23, 24).

The simulation results for the hybrid, fluidised-bed bioreactor with external recirculation pipe are presented in Fig. 3. Due to the analyses, it can be observed that there is a strong similarity of hydrodynamic process parameters in both devices. In this case, a higher rate of gas flow can be achieved due to no possibility of gas bubbles flowing to zone ‘3’. It effects in increasing the oxidation level without significant change of work conditions.

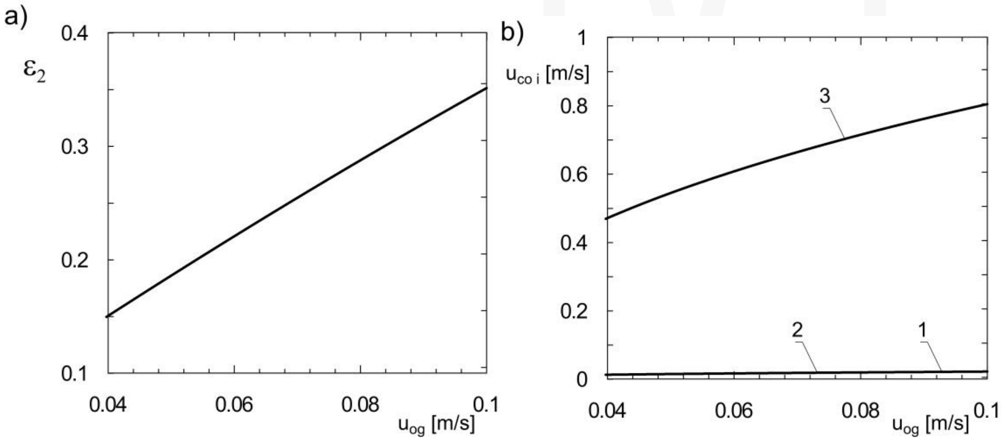

Fig. 3. Relation a) gas hold-up in zone “2” and b) apparent liquid velocities in all zones of apparatus with velocity of delivered gas for hybrid fluidized bed bioreactor with external draft tube

6. Summary

In this paper, mathematical models of two cases of hydrodynamic, hybrid, fluidised-bed bioreactors were presented. The rules of modelling such devices are similar. For each device, the mathematical model is stated by a system of two nonlinear equations. These two equations have to be completed by correspond system of hydrodynamic conditions. The difference between models is realised within condition, presented in equation (23). In the bioreactor with an external recirculation pipe, there is no risk of bubbles transferring into the fluidisation zone and that is the main advantage of such a solution.

Obtained models can be used to numerical simulation of hydrodynamics of analysed reactors. As is shown, hydrodynamics parameters of different items of apparatus are qualitatively the same – differences between results are caused by the geometric dimensions of devices.

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