

Modeling of the fermentation in an internal loop airlift reactor

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Abstract

The airlift reactors have potential application in biotechnology industries due to their simple construction and less shear stress imposed on shear sensitive cells compared with the mechanically stirred tanks.

This work was focused on mathematical modeling of the fermentation process in an internal loop airlift reactor (IALR). Simulation results were verified on the fermentation of the gluconic acid by the strain *Aspergillus niger* which has been chosen as a model system. The fermentation was carried out in three laboratory IALRs (each one with different scale: 12, 40 and 200 dm³, respectively) and performed in growth or non-growth conditions. Model of the ILALR incorporated the material balance of each compound taking part in reaction. In the reactor there are recognized four main parts: bottom, riser, separator and downcomer. Each zone of that reactor was modeled separately due to the different flow pattern and the mixing behavior.

Parameters of the model, such as mass transfer coefficient of oxygen, gas hold-ups, and circulation velocities, were predicted using experimentally determined correlations.

The results of the simulations and experiments are in sufficient agreement.

Keywords

Airlift bioreactor, gluconic acid fermentation, mathematical modeling, scale-up

1. Introduction

In bioprocesses there is still preferable most common stirred tank reactor (STR). A choice of the proper type of reactor depends on the character of the biosystem. Airlift reactors (ALR) could be more convenient than STRs in processes where the low shear stress is involved using a shear sensitive strains. Mixing in ALRs is provided by expansion of the gas entering the reactor, hence there is no need to use an additional stirrer and consequently extra energy source. This could be more advantageous for production of high volume products with relatively low added value. Nevertheless, the utilization of ALRs is still limited for the sake of insufficient information about proper scale-up procedure.

2. Problem Statement, background

Mixing in ALRs is usually imperfect. From the mixing point of view, four main sections in ALRs are recognized: the bottom where the gas distributor is placed and the medium is recycled from the downcomer, the riser (in the internal loop ALR (ILALR) a concentric tube), where the medium flows upward, the gas separator and the downcomer. Each section is usually modeled separately. There are two major approaches for modeling these sections: the axial dispersion model (ADM) and the tanks in series model (TSM) [1, 2]. In our case we chose TSM.

3. Approach on modeling of ILALR

3.1. Mathematical model of ILALR

The mathematical model of an ILALR was developed by dividing the whole reactor into a system of ideal tanks in series (see Figure 1). In each tank of the ALR, material balances were written for the liquid and the gas phase. Generally, a simple scheme of the balance for a compound in a tank can be written by Eq.(1). Mathematically it presents a set of ordinary differential equations with corresponding initial conditions.

$$\begin{aligned} & \left[\begin{array}{l} \text{rate of accumulation of} \\ \text{a compound in the tank} \end{array} \right] = \left[\begin{array}{l} \text{inlet of a compound} \\ \text{to the tank} \end{array} \right] - \left[\begin{array}{l} \text{outlet of a compound} \\ \text{from the tank} \end{array} \right] + \\ & + \left[\begin{array}{l} \text{interphase transfer of} \\ \text{a compound to the tank} \end{array} \right] + \left[\begin{array}{l} \text{production (consumption)} \\ \text{rate of a compound in the tank} \end{array} \right] \quad (1) \end{aligned}$$

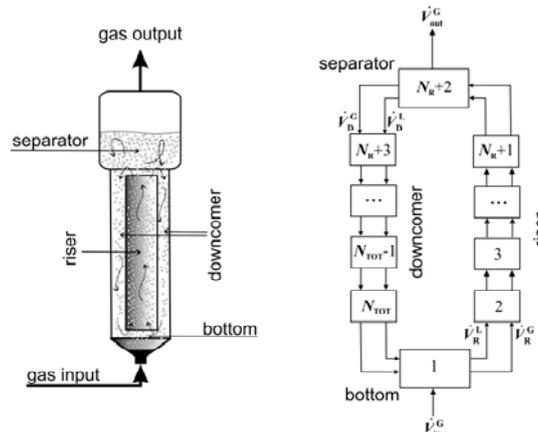


Figure 1 Schematic diagram of the tanks in series model for an ALR.

3.2. Model parameters estimation

Solution of the model equations requires a proper estimation of their parameters. These parameters that are related with hydrodynamics of the reactor (gas hold-ups in all sections, volumetric oxygen mass transfer coefficients, circulation velocities), were determined on our devices using model media. The solubility of oxygen is function of the pressure along the ALR and media composition [3, 4], what was taken into account.

3.3. Model reaction and kinetics

As a model system, gluconic acid production by the strain *Aspergillus niger* was chosen. The liquid phase with the pellets of the microorganism was treated as pseudo-homogeneous. Biotransformation of glucose (Glc) to gluconic acid (Glu) by the filamentous fungi *Aspergillus niger* represents a simple dehydrogenation reaction without involvement of complex metabolic cell pathways [5]. The overall reaction of biotransformation can be written as follows:



The expressions for the growth rates of the biomass r_X , the production rate of the product r_P , the substrate consumption rate r_S and the oxygen uptake rate r_O are referred to equations given in Table 1.

Table 1 Kinetic equations

	Growth conditions	Non-growth conditions
microbial growth rate	$r_X = \mu_m \frac{c_S}{K_S c_X + c_S} \frac{c_O^L}{K_O c_X + c_O^L} c_X$	$r_X = 0$
production rate of the product	$r_P = \frac{V_m c_X}{\left(1 + \frac{K_{PS}}{c_S} + \frac{K_{PO}}{c_O^L}\right)}$	$r_P = \frac{V_m c_X}{\left(1 + \frac{K_{PS}}{c_S} + \frac{K_{PO}}{c_O^L}\right)}$
substrate consumption rate	$r_S = -\alpha r_X - \beta r_P$	$r_S = -\beta r_P$
oxygen consumption rate	$r_O = -\gamma r_X - \delta r_P$	$r_O = -\delta r_P$

The 12 dm³ ILALR was used for the determination of kinetic parameters. According to a relatively slow reaction and sufficient mixing [6, 7], this reactor was assumed to be a CSTR. Estimation of the kinetic parameters μ_m , K_S , K_O , V_m , K_{PS} , K_{PO} , α and γ for the gluconic acid production was done by using experimental data of the growth fermentation. Parameters β and δ were determined from the stoichiometry of reaction (A). The estimated values of kinetic parameters are presented in Table 2.

Table 2 Estimated kinetic parameters

μ_m	K_S	$K_O \times 10^4$	V_m	K_{PS}	$K_{PO} \times 10^3$	α	β	γ	δ
(h ⁻¹)	(-)	(-)	(h ⁻¹)	(g dm ⁻³)	(g dm ⁻³)	(-)	(-)	(-)	(-)
0.087	5.75	1.47	2.56	1.35	2.84	2.41	0.92	0.62	0.082

3.4. Experimental arrangement

Details about the microorganism and cultivation conditions as well as geometry and analytical methods and control of the reactors during fermentation are described in our previous paper [5]. Hydrodynamic measurements (gas hold-up, circulation velocities, circulation regimes characterization and volumetric mass transfer coefficient) are in detail reported in the papers of Klein et al. [8], Blažej et al. [6, 9] and Juraščík et al. [10].

4. Results

The developed mathematical model of an ILALR was experimentally verified on 40 dm³ and 200 dm³ reactors in growth or non-growth conditions. All experiments started at the same initial concentration of glucose (equal to

150 g dm⁻³) and in case of growth fermentation with defined concentrations of other nutrients required for the microbial growth. All simulations were provided by employing the kinetic parameters estimated by using the data from the 12 dm³ ILALR (Table 2).

4.1. Scale-up simulations

The growth fermentation in 200 dm³ ILALR at constant aeration of $\dot{V}_{in}^G = 6000$ dm³ h⁻¹ is shown in Figure 2. Model data well describe the experimental courses of glucose, biomass and product. In the Figure 3 there can be seen corresponding oxygen courses along at 50th hour of the fermentation time in the same reactor. The concentration of dissolved oxygen reaches the maximum in the riser section of the ILALR. The slope of that curve is changing according to the oxygen mass transfer driving force.

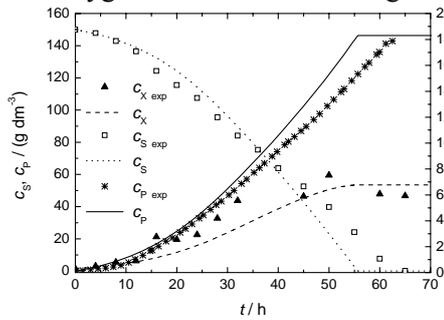


Figure 2 Model vs. experimental data of the growth fermentation in the 200 dm³ ILALR ($c_{X0} = 0.304$ g dm⁻³).

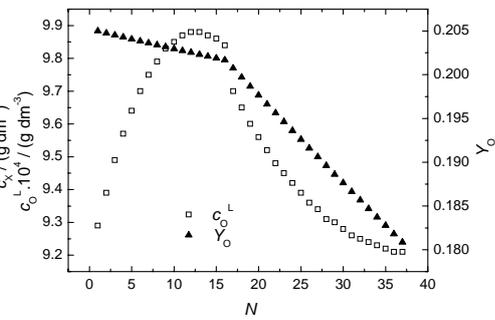


Figure 3 Oxygen profile in liquid and gas phase at 50th hour of fermentation time in the 200 dm³ ILALR.

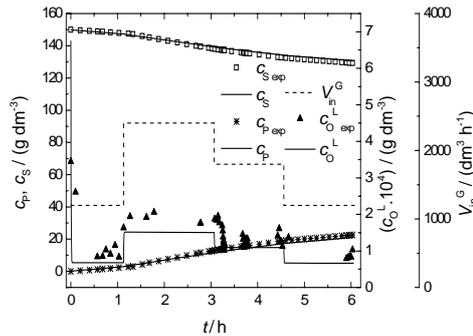


Figure 4 Non-growth fermentation in 40 dm³ ILALR at various aerations ($c_{X0} = 2.01$ g dm⁻³).

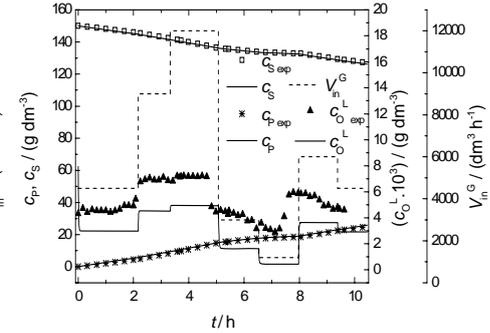


Figure 5 Non-growth fermentation in 200 dm³ ILALR at various aerations ($c_{X0} = 5.09$ g dm⁻³).

In another set of experiments in 40 dm³ and 200 dm³ ILALRs there was studied the effect of aeration on the Glu production. These experiments were provided at non-growth conditions. Results are presented in the Figure 4 and 5.

The experiments in 40 and 200 dm³ reactors were operated in range of volumetric gas flow from 1200 to 2400 dm³ h⁻¹ and from 1200 to 12000 dm³ h⁻¹ respectively. Model data for the Glc and Glu are in a good agreement with those experimental. Higher difference between the values of measured dissolved oxygen data and model results could be explained by the presence of air bubbles on the oxygen probe membrane and by the accuracy of determination of dry biomass weight concentration in the medium. It is obvious that this model is able to predict the effect of changes in aeration on rate of Glu production.

In the future this model could be a useful tool for the design and scale-up of industrial applications of IALRs.

List of symbols

- c – concentration [g dm⁻³]
 K_O, K_S – limitation constant of oxygen and substrate for the product [g dm⁻³]
 K_{PO}, K_{PS} – limitation constant of oxygen and substrate for the biomass [-]
 r – reaction rate [g dm⁻³ h⁻¹]
 V_m, μ_m – maximum specific rate for the product and growth [h⁻¹]
 \dot{V}_{in}^G – volumetric gas flow [dm³h⁻¹]
 Y – molar fraction [-]
 α, γ – growth associated glucose and oxygen consumption coefficient [-]
 β, δ – on-growth associated glucose and oxygen consumption coefficient [-]
 G, L, 0 – liquid, gas, initial
 O, P, S, X – oxygen, gluconic acid, glucose, biomass

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