Biochemical Engineering Journal 118 (2017) 70–81

Contents lists available at ScienceDirect

Biochemical Engineering Journal

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

Regular article

Hydrodynamics and mass transfer in bubble column, conventional airlift, stirred airlift and stirred tank bioreactors, using viscous fluid: A comparative study

Sérgio S. de Jesus*, João Moreira Neto, Rubens Maciel Filho

Laboratory of Optimization, Design and Advanced Control, Bioenergy Research Program, School of Chemical Engineering, University of Campinas, P.O. 6066, Zip: 13083-852 Campinas/SP, Brazil

ARTICLE INFO

Article history:
Received 8 June 2016
Received in revised form
17 November 2016
Accepted 21 November 2016
Available online 22 November 2016

Keywords:
Bioreactors
Hydrodynamics
Mass transfer
Newtonian fluids
Non-Newtonian fluids

ABSTRACT

The performance of four bioreactors (bubble column, concentric tube airlift, concentric tube stirred airlift, and mechanically stirred tank) were evaluated in this study in terms of the hydrodynamics and mass transfer, using viscous a Newtonian fluid (glycerol 65%) and a non-Newtonian fluid (xanthan 0.25%). The experimental results showed that the gas holdup and mass transfer coefficient were higher in the stirred airlift and stirred tank, on the other hand these reactors had high shear rates. In relation to power consumption, lower values were obtained in the bubble column and airlift bioreactors. In a viscous medium in which microorganisms or shear-sensitive cells are used, the use of airlift bioreactors may be the best choice for presenting a low shear environment and a reasonable oxygen transfer rate, in addition to the low power consumption. On the other hand, if the process involves microorganisms that require high oxygen rates, a stirred airlift bioreactor may be the best choice.

1. Introduction

The oxygen or other gas from a gaseous to liquid form is one of the main challenges for reactor engineering. Thousands of biological processes occur in the presence of aerobic microorganisms, and in the highly viscous medium, which implies a great challenge for the aeration system, stirring and mixing, with the purpose of supplying oxygen gas in liquid form for cell growth and maintenance in order to achieve a given product. Studies with different mediums and microorganisms reported that several factors must be taken into account for choosing the correct bioreactor. These factors include their geometry, their stirring and aeration system and the ease of operation and control, their ability to separate the product from the medium or from the by-products, energy consumption, and finally, their relative ease of post-process cleaning [1–3]. Understanding the hydrodynamic behavior of the reactor is a very important parameter, which is necessary to understand the transport phenomena involved in their operation; some parameters such as liquid circulation velocity, mixing time, gas holdup, bubble diameter, mass transfer (k_La) and shear rate should be taken into consideration [4]. For proper oxygen transfer from the gas phase to the liquid phase, the generation of regions of high shear should be avoided, since these affect the cells and produce irreversible morphological changes to the microorganism. For this reason, the stirring effect on the morphology of submerged cultures must be carefully evaluated. On the other hand, the stirrer velocity and the mixing intensity have an important role in the rupture of bubbles. To create greater turbulence in the medium and break the bubbles, many bioreactors use a set of baffles, which can also lead to an increased shear rate [5].

In submerged cultures involving aerobic organisms, the stirred tank bioreactor is the most used. This equipment has impellers for mechanical stirring of the broth [6,7]. This stirring is intended to enhance mixing, to break bubbles and to increase the turbulence of the liquid medium. The main advantage of these bioreactors is the good uniformity of the medium around the tank, avoiding the formation of aggregates, being widely used for cultures with formation of broths with complex rheological characteristics, generally mediums with non-Newtonian behavior, which require high speeds of heat and mass transfer, and in these cultures, achieving a perfect mixture is difficult, causing aeration problems [6]. Furthermore, these reactors have some disadvantages, particularly in

* Corresponding author.
E-mail address: ssjesus@gmail.com (S.S. de Jesus).

http://dx.doi.org/10.1016/j.bej.2016.11.019
1369-703X/

Nomenclature

a, b, c, d	Parameters of eq. (14) and (15) [-]
e, f, h, i,j	Parameters of eq. (20) and (21) [-]
w, x, y, z	Parameters of eq. (22) and (23) [-]
A_D	Cross-sectional area of downcomer [m^2]
A_R	Cross-sectional area of riser [m^2]
C	Instantaneous concentration of dissolved [$kmol\,m^{-3}$]
C_0	Initial concentration of dissolved oxygen [$kmol\,m^{-3}$]
C^*	Saturation concentration of dissolved oxygen [$kmol\,m^{-3}$]
D_T	Tank diameter [m]
d_i	Diameter of the impeller [m]
E	Fractional approach to equilibrium defined by eq. (4) [-]
g	Gravitational acceleration [$m\,s^{-2}$]
h_D	Height of gas-liquid dispersion [m]
h_L	Height of gas free liquid [m]
k	Consistency index [$Pa.s^n$]
k_La	Overall volumetric gas–liquid mass transfer coefficient [s^{-1}]
M	Torque [N m]
M_0	Torque due to gearbox, bearings and seals [N m]
n	Flow behavior index
N	Rotational speed of the impeller [s^{-1}]
N_p	Impeller power number [-]
P	Power consumption [$W\,m^{-3}$]
P_G	Power input due to gassing [W]
P_0	Power drawn under ungassed conditions [W]
Q	Specific air flow rate [vvm]
Re	Reynolds number [-]
t	Time [s]
t_0	Initial or start time [s]
U_G	Superficial gas velocity based on the total [$m.s^{-1}$]
V_L	Volume of liquid [m^3]
εG	Overall fractional gas holdup [-]
$\dot{\gamma}$	Shear rate [s^{-1}]
γAV	Average shear rate [s^{-1}]
μ	Dynamic viscosity [Pa s]
μap	Apparent viscosity [Pa s]
ρL	Density of the liquid [$kg\,m^{-3}$]
τ	Shear stress [Pa]

cultures with shear-sensitive cells, such as plant and animal cells that may be damaged due to their reduced viability with an increase in the stirring velocity [5]; the use of highly viscous mediums which exhibit non-Newtonian behavior can also be a disadvantage of this type of reactor, since the impeller presents flooding, and cannot be aerated at high gas velocities, resulting in poorer mixing patterns in comparison with the airlift-type reactor [7].

There are also other types of bioreactors which are very important and industrially used, called pneumatic bioreactors, in which medium stirring is performed by air bubbling. Bubble columns and airlift bioreactors can be included in this group [8]. These reactors are generally cylindrical in shape, where homogenization of the medium and aeration are carried out by air injection or the injection of other gases through a sparger located in the base to maintain a proper level of stirring and oxygen transfer, it is operated with high air flow [8,9]. The main advantages are low operating costs and maintenance due to the absence of moving parts, and ease of operation. However, the use of non-Newtonian viscous fluids is considered a limiting factor in choosing this equipment, since high viscosity decreases gas holdup and prevents the formation and stability of a bed of homogeneous bubbles, this also has a negative impact in gas-liquid mass transfer [10–14].

In order to overcome some airlift bioreactor and some stirred tank bioreactor limitation, mechanically agitated airlift bioreactors were proposed [7,15,16]. Although this type of bioreactor has not yet been used industrially, it has demonstrated a high standard of mixing of fluid-gas in the laboratory, which results in an oxygen transfer increase to the reaction system, the performance increase of the bioreactor is mainly due to mechanical stirring, which can achieve high fluid circulation due to the highly directional flow pattern [7]. These bioreactors still require more detailed studies, at both experimental and computational levels.

Comparative studies, listing the main advantages and disadvantages of these reactors, even at laboratory level, have not yet been described. Studies in the literature are limited in their comparisons between pneumatic and conventional bioreactors, with a lack of comparative studies also with hybrid bioreactors. The objective of this study was to compare, in order to list, the advantages and disadvantages of conventional, pneumatic and hybrid bioreactors. In this work the performances of four bioreactors (bubble column, airlift, stirred airlift and stirred tank) were analyzed with regards to hydrodynamics and mass transfer. In order to analyze the performance of these reactors, viscous fluids with Newtonian behavior (glycerol 65%) and non-Newtonian behavior (xanthan 0.25%) were used. For comparison purposes, the experiments were performed with the same volume of fluid and gas sparger. In experiments with mechanical stirring, a Rushton turbine impeller was used due to its wide use in laboratories and industry [17], with the same geometric similarity given by the relation $(D_T/d_i) = 3$. The results of the advantages and disadvantages of each bioreactor were enumerated.

2. Materials and methods

2.1. Bioreactors

2.1.1. Stirred tank bioreactor

A 5.0 L benchtop bioreactor was used (Bioflo III fermentor, New Brunswick Scientific, USA) with a maximum working volume of up 4.0 L. The gas sparger was adapted and built for this study and consisted of a circular perforated plate with 0.05 m diameter, with 90 holes of 0.001 m in diameter. A dissolved oxygen electrode (O2-sensor InPro6800/12/220 Mettler Toledo, Switzerland) and pH probe (405-DPAS-SC-K8S/225 Mettler Toledo, Switzerland) were used. The stirring was promoted by a Rushton turbine impeller with six blades, 0.06 m in diameter. The impeller clearance was 0.01 m. The relationship between the diameter of the impeller and the diameter of the tank $(D_T/d_i) = 3$. The dimensions of the equipment are described in Fig. 1.

2.1.2. Stirred airlift bioreactor

A concentric draft tube stirred airlift bioreactor with a working volume up to 4.0 L, described in de Jesus et al. [16] was used for the experiments. The stirring in the bioreactor was promoted by a Rushton turbine impeller with six blades, 0.06 m in diameter. The impeller clearance was 0.01 m, and $(D_T/d_i) = 3$. The air was sparged into the internal zone through a circular perforated plate with 0.05 m diameter, with 90 equidistant holes with 0.001 m diameter, located on the bottom of the bioreactor, concentric in relation to the area comprised by the riser. A dissolved oxygen electrode (O2-sensor InPro6800/12/220 Mettler Toledo, Switzerland) and two identical pH probes (405-DPAS-SC-K8S/225 Mettler Toledo, Switzerland) were used. To avoid vortex formation, four baffles