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Gas–liquid dispersion in a fibrous fixed bed biofilm reactor at growth and non-growth conditions

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ABSTRACT

There is limited data on gas dispersion characteristics of fixed bed biofilm reactors under growth and non-growth conditions. In this paper, the gas–liquid dispersion of a bubble bed packed with a fibrous structured packing for biofilm application is studied. The reactor is operated with *Pseudomonas putida* aimed at aniline degradation in wastewater. Gas hold-up and bubble size distribution are determined. Running gas–liquid reaction conditions as well as non-reactive flow gas hold-up and bubble size distribution in the presence of surface-active and viscous components were measured. The properties of the gas dispersion proved to be stabilized by the fibrous bed presence and showed improvement of the dispersion parameter by the packing. Gas hold-up was found to increase monotonously with the rise of gas superficial velocity and viscosity and with surface tension fall. Liquid superficial velocity showed marginal effect. Apart from showing high gas hold-up and low bubble size due to surface-active and viscous dissolved elements, the biochemical reaction did not pose any significant additional effect. In agreement with the expected lack of bubble coalescence and break-up in the highly ionic solution practiced, the population size distribution and average bubble size were found to vary with the major operation factors opposite to their gas hold-up contribution. Gas hold-up was correlated with the specific bubble-to-channel size ratio and further with the variables considered. An empirical equation is proposed that relates gas hold-up with all studied variables. Assuming geometric similarity of the prototype and the real vessels, the equation as well as its corresponding range of fluid velocities can be used for bioreactor design and scale-up. The results concerning the gas hold-up are shown to be comparable with previous studies of mesh wire packing.

1. Introduction

Referring to the last decennial, biological fixed bed bioreactors are increasingly used for wastewater treatment processes because of their flexibility and compactness [1–3]. Recent practical examples are: treatment of β-galactosidase entrapped in Ca-alginate-K-carrageenan gels for lactose hydrolysis [4], biodegradation and methane production from glycerol-containing synthetic wastes [5], and azo-dye decolorization in continuous mode by *Pseudomonas luteola* [6]. In parallel to these, aerobic (thus, gas–liquid) degradation has been experienced recently in some fixed bed gas–liquid systems, e.g. phenol degradation [7] and degradation of organics [8]. Such treatments involve gas–liquid equipment including various structured and unstructured packings.

A packing itself is attractive for biomass immobilization forming biofilms for large-scale biological treatment. Focusing on structured packing known to enhance transversal flow in viscous batches, it was indicated as prospective for complex non-Newtonian bio-fluid flow stabilization [9]. At high fluid velocity, it could serve as replacement of highly energy consuming mechanical mixers in mixing bioreactors. Its applications are multi-functional and require additional studies to uncover the character of functional variation in the case of the particular internal body. In the case of this study, the use of a fibrous plastic matter has been considered for gas–liquid dispersion analysis. Compared to conventional granular packing, such as clay balls, ceramic pieces, volcanic rocks, the fibrous packing presents a novelty due to its extended specific surface and plastic material (PEVA) reported to enhance the adhesion of biofilm cells [10].

Alternatively, gas–liquid bubble columns with structured packing have large potential of applications in biochemical processing. An overview of the literature [11] shows just several studies to have been devoted to low velocity bubble column operation, the

Abbreviations: PEVA, polyethylenevinylacetate; BSD, bubble size distribution.

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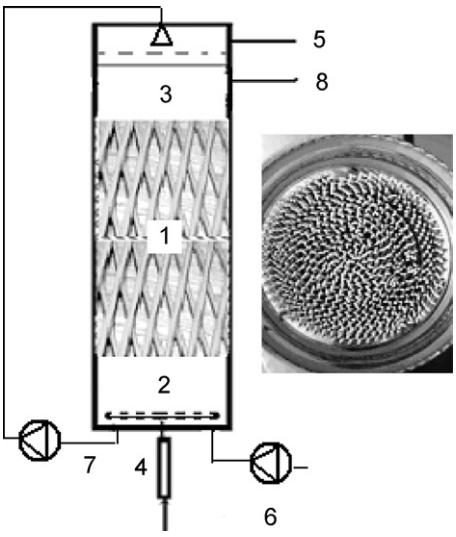

Fig. 1. Schematics of experimental vessel and PEVA packing: (1) packing section with fiber modules, (2) fluid distribution section, (3) gas disengagement section, (4) gas flow controller, (5) gas outlet, (6) liquid feed pump, (7) liquid circulation pump, and (8) liquid outlet.

hydrodynamic performance analysis of reactors with structured packing being revealed by just a few recent papers. Birrer and Böhm [9] have reported an overview analysis on the matter. Before them, structured packing parameters have been studied by Urseanu et al. [12]. Recently, packing hydrodynamics has been studied also by Moustiri et al. [13], Bhatia et al. [14], Nikakhtari and Hill [15], Maldonado et al. [16], and Monsalvo and Böhm [17]. The studies are restricted to specific designs. Most of the work concerned non-reactive model systems. Apart from column design, an important group of studies have examined the effect of liquid physical properties [18–21]. From the point of view of diversity of bioreactor objectives, the present state of knowledge points at the importance of studying the performance effects of the various classes of systems separately. These systems include both reactor geometry and fluid physical properties, e.g. pure liquids and their solutions of additives, i.e. low-viscous and highly viscous liquids and liquid phases containing surface-active matter.

In this paper, gas–liquid dispersion in bubble bed packed with fibrous structured mesh material prospective for biofilm application is studied. Gas hold-up and bubble size distribution (BSD) at both growth and non-growth conditions of batches with surface-active and viscous components are measured and analyzed.

2. Materials and methods

2.1. Bioreactor setup and packing

All experiments were carried out in a bioreactor column containing the packing. The column and packing pattern are shown schematically in Fig. 1. The packing was made of polymer fiber material 1.2–1.5 mm (*Norten Ltd., France*) produced as polyethylene (PE) and vinylacetate (VA) co-polymer, termed PEVA. The geometry comprised a pattern of thermally soldered fibers winded and folded to form a pack of concentric layers filling the circular column cross-section. The details are summarized in Table 1. Cases of no packing, one and two stage packing were examined.

A porous plate of diameter 0.06 m mounted on the bottom lid carried out the gas distribution. Gas flow controller and two liquid pumps were used to operate the fluids in up-flow mode with counter-current liquid recycle. Air was used as the gas phase. The bioreactor was equipped with a pH electrode, pH titration unit, O_2 probes, and thermometer probe (not shown). During the fermentation process inlet and outlet dissolved oxygen concentration, temperature of the medium inside the reactor, air and liquid flow rate were measured and controlled on-line, while pH was measured and controlled off-line.

The experiments were carried out in both continuous and semi-batch arrangement at continuous gas flow and at zero or very low liquid feed flow rate. Superficial gas velocity was varied between 0 and 22 mm/s and superficial liquid velocity was varied in the range 0–12.6 mm/s involving a liquid recycle 25–280% of liquid feed.

Table 1
Characteristics of the reactor and packing used.

Parameter	Value
Column diameter (m)	0.1
Clear liquid height (m)	0.6
Height of a pack module (m)	0.13
Packing material	Polyethylenevinylacetate (PEVA)
Packing specific area average (m^2/m^3)	1800
Packed bed porosity (%)	70
Gas distribution plate diameter (m)	0.06

Table 2
Physicochemical properties of the solutions used.

Concentration	Surface tension, σ (mN/m)	Viscosity, μ (mPa s)	Density, ρ ($kg\,m^{-3}$)
0 (water)	71.40	1	998
20% saccharose	73.00	1.97	1104
40% saccharose	74.10	6.22	1176
1 g/l methanol	61.02	1	998
2 g/l methanol	54.11	1	997
5 g/l methanol	42.74	1	996
10 g/l methanol	34.87	1	993
2 g/l biomass	57.7	0.98	1020

2.2. Reactor start-up and operation

Growth and non-growth conditions were studied.

At growth conditions, a biofilm containing *Pseudomonas putida* was cultivated in aqueous saccharose solutions to remove aniline from the up-flowing water. The aerobic strain *Ps. putida ATCC 21812* was cultivated. The inoculum was prepared in advance in flasks for 24 h starting with a sample culture in 10 cm^3 LB medium. A rotary shaker for 24 h at 37 °C and 180 rpm was employed.

The bioreactor with volume 6 dm^3 was inoculated by 0.4 dm^3 initial culture. Liquid batches of nutrients were prepared in tap water by adding 10 g/dm^3 saccharose, 0.5 g/dm^3 aniline and salts, as follows: KH_2PO_4 0.5 g/dm^3, K_2HPO_4 1 g/dm^3, $(NH_4)SO_4$ 0.5 g/dm^3, Na_2SO_4 0.5 g/dm^3, NaCl 0.5 g/dm^3, $MgSO_4$ 0.5 g/dm^3, $CaCl_2$ 0.02 g/dm^3, and $FeSO_4$ 0.02 g/dm^3. The reactor temperature was maintained at 22 ± 2 °C. Air was fed in the bottom section for the experiments. The liquid feed was maintained constant. Gas flow rate (at 22 °C and atmospheric pressure) and liquid circulation were varied. The pH value of the culture was maintained at 7–7.5.

Prior to continuous operation, the reactor was operated batch wise for 24 h with culture medium (5.6 dm^3) and 0.4 dm^3 culture; then the liquid feed was started (at 0.04 dm^3/h) and the reactor was operated continuously for 48 h to develop the biofilm.

At non-growth conditions, analytical grade methanol and saccharose were used to arrange the physicochemical properties of the model solutions. Pure water was used as reference. Table 2 contains the physical properties of the systems employed.

2.3. Measurement techniques

The surface tension was measured using a *TD1 Lauda* tensiometer. The viscosity was measured using viscometer *Micro – Ubbelohde* (*Schott-Geräte GmbH*).

Determining gas hold-up both at growth and non-growth conditions, the gas displacement technique was used. Recent experiments in structured packing by Monsalvo and Böhm [17] showed good reproducibility of the method when checked against pressure tap technique, especially so in the range of gas hold-up 0–30%. The percent volumetric gas fraction was determined as

$$\varepsilon_G = \frac{H_D - H_0}{H_D} \quad (1)$$

where H_0 stands for initial liquid level corresponding to equilibrium level in water, and H_D indicates additional head in gas presence.

Bubble size distribution was determined by photographic imaging technique, as follows: using electronic digital camera *Nikon GSP 25*, the dispersion field of the flow outlet off the fibrous bed at 5 mm over the bed top surface was photographed and the images were processed by scanning the images electronically on a PC screen. Number size distributions and average bubble size were determined. Sauter mean bubble diameter d_S was calculated, as follows:

$$d_S = \frac{\sum_i n_i d_{bi}^3}{\sum_i n_i d_{bi}^2} \quad (2)$$

where n_i is the number of bubbles of size d_{bi}.