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BIOREACTORS WITH LIGHT-BEADS FLUIDIZED BED: THE VOIDAGE FUNCTION AND ITS EXPRESSION

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Abstract: Light-beads fluidized bed bioreactors with gel particles are an attractive alternative for the implementation of a system with immobilized cells. They have a number of advantages: soft operating conditions, ability to work in an ideal mixing regime, intensification of heat- and mass transfer processes in the fermentation system. The expansion characteristics of the fluidized bed were investigated in the present work. The fluidized bed expansion was described using the voidage function. It was found that the voidage can be described by nonlinear regression relationships and the regression coefficients were a function of the particles parameters.

Keywords: fluidized bed, gel particles, voidage function, modeling

INTRODUCTION

Biotechnology is a key factor for the development of the manufacture of new food products through application of microbial and enzyme technology, reactor design and separation technology. An important role for the realization of the immobilized cells advantages is the selection of the bioreactor design. The methods of design, modeling, optimization and scaling up of these systems could be found in (Villadsen et al., 2003).

In fluidized bed reactors exist lower mechanical loads on the particles. These systems can work with smaller-size particles without clogging the layer, high pressure losses, channeling and compression of the particles. Smaller particles lead to the minimization of internal diffusion resistance and higher heat- and mass transfer rates. Fluidized beds with high liquid recirculation

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operate under ideal mixing condition (Villadsen et al., 2003). Godia and Sola, 1995 provided detailed information about the application of the fluidized bed reactors in various areas of biotechnology (Godia and Sola, 1995).

According to Glicksman, 2003 the development of new biotechnology equipment starts with laboratory stage. The main problem is which parameters have to be selected for accurate scaling procedure to commercial unit (Glicksman, 2003; Villadsen et al., 2003).

The first stage of the problem was discussed in our previous publication (Kostov et al., 2012). The fluidization of the particles begins when the interaction forces acting on the particle by the surrounding fluid, are equal to the particles weight (Di Felice, 1995). Therefore, the pressure losses are equal to:

$$\Delta P = L(1-\varepsilon)(\rho_S - \rho)g \qquad (1)$$

If we consider a single particle in an infinite expansion, the interaction forces can be represented as the sum of the drag force and the Archimedean force:

$$\mathrm{V}\rho \mathrm{g} = \mathrm{Drag} + \mathrm{Bioyonant} \qquad (2)$$

To avoid difficulties in the interpretation of the interaction forces, the"voidage function” **f(ε)** is used in practice. It is described by the relation:

$$f(\varepsilon) = \frac{F_D}{F_{DS}} \qquad (3)$$

where: F_D is the drag force in the system liquid-particles; F_{DS} is the drag force for the single particle.

Depending on the problem the following characteristics can be examined: sedimentation rate, minimal fluidization velocity or pressure loss in the bed. In these cases, **f(ε)** is associated with characteristics examined by the equation (Di Felice, 1995; Di Felice, 1984):

$$f(\varepsilon) = \frac{4Ga\varepsilon}{\left(\frac{u}{u_t}\right)^2 3C_D \mathrm{Re}_t^2} = \left(\frac{u}{u_t}\right)^2 \frac{C_{Dt}}{C_D}\varepsilon \qquad (4)$$

which for low Re values is simplified to:

$$f(\varepsilon) = \left(\frac{u}{u_t}\right)^{-1}\varepsilon \qquad (4.1)$$

and for the high Re values is simplified to:

$$f(\varepsilon) = \left(\frac{u}{u_t}\right)^{-2}\varepsilon \qquad (4.2)$$

The voidage function is connected with the pressure losses by the equation:

$$f(\varepsilon)=\left(\frac{\Delta P}{L}\right)\frac{4d_p\varepsilon}{3C_D\rho u^2(1-\varepsilon)} \quad (5)$$

As shown in equation (5) to determine the voidage function f(ε) is necessary to know the drag coefficient of fluid particles C_D. It is known from the literature that this coefficient is a function of the Re value and thus the determination of f(ε) is greatly hindered.

In his work Di Felice made a summary of the different relationships used for the voidage function description (Di Felice, 1995; Di Felice, 1984). These dependencies have bound the voidage function with the fluidized bed parameters - porosity and fluidization velocity.

Our studies indicated that the voidage function depended on the particles parameters – density, drag coefficient and etc. (Kostov et al., 2012). This problem is particularly relevant for the fluidized bed with light particles with a density close to that of the liquid phase. In literature the gel beads were treated as "rigid water", and therefore, the ratio between the resistance forces cannot be described with the conventional dependencies.

The aim of this study was to make mathematical relationships for the voidage function discriptions, using the relationship (4.2). It was based on data for the light-beads fluidized bed expansion (1025-1250 kg/m^3).

MATERIALS AND METHODS

The experimental set-up is shown on Figure 1. It consisted of Plexiglas tube (1) with internal diameter (of) 56 mm and height (of) 980 mm. On its bottom were situated a distributor (2) and a glass pearl bed (3). The liquid was recirculated by peristaltic pump (4). Flow rates were measured by a calibrated rotameter (5). A graduated ruler (6) was used for the heights measurements of the transition interface and the total bed. On the upper side of the column was placed cylindrical phase separator with diameter (of) 200 mm and height (of) 120 mm. The pressure losses were determined using differential manometer (14), which was conncected with nozzles (15). Tap water was used as a model liquid phase with approximated density (of) 1000 kg/m^3. The solid phase was 250 g alginate beads with different densities. The beads were produced using the method described by (Wijffels, 2001).

The beads density was increased with 2.5% and 5% sand (fraction below 0,125 mm), which were added to the alginate solution. The terminal settling velocity was determined as described by Chhabra (Chhabra, 1999). Gel-beads characteristics are summarized in Table 1. The porosity and solid hold-up were determined as described by Buffiere and Moletta (Buffiere and Moletta, 1998):

$$\varepsilon_S = \frac{M}{\rho_S SL} \quad (6)$$

$$\varepsilon = 1 - \varepsilon_S \quad (7)$$

where: M – solid phase weight (500 g); ρ_S – solid phase density, kg/m^3; S – column cross-section, m^2 (0,00246 m^2); L – fluidized bed height, m.

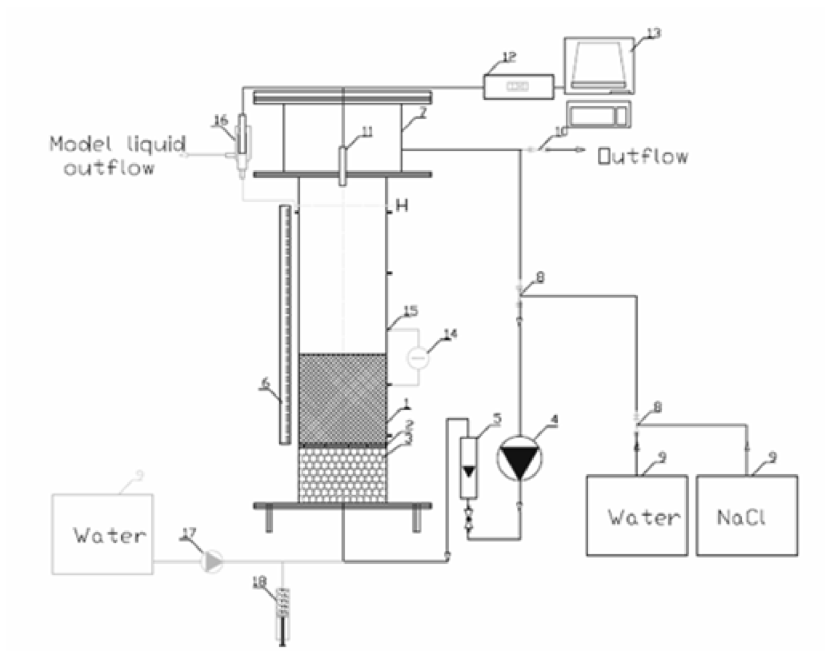

Figure 1.Light-beads column bioreactor.
1-plexyglass column; 2 – distributor; 3 – drainage; 4 – peristaltic pump; 5 – rotameter; 6 – ruler; 7 phase separator; 8 – three-way valves; 9 – reservoirs; 10 – valve; 11 – conductometric cell 12 – conductometer; 14 -differential manometer; 15 – nozzles; 16 – exit cell; 17 – peristaltic pump for nutrients; 18 – syringe;

RESULTS AND DISCUSSION

The bed porosity is shown on Figure 2. The terminal settling velocity $\mathbf{u_t}$ is shown in Table 1. These two parameters are needed for the voidage function calculation. The terminal settling velocity is the velocity at which the fluidization process finishes and it is critical for the fluidization process.
The fluidized bed expansion was described by the Richardson and Zaki's equation (Richardson and Zaki, 1954):

$$u = k\varepsilon^n \quad (8)$$

They showedthat the parameter ***k*** was equal to the terminal settling velocity and the parameter ***n*** was ***n=f(Re)***. If the terminal settling velocity $\mathbf{u_t}$ (Table

1) was compared with the experimental parameter **k** (Table 2), it could be seen that **k** < $\mathbf{u_t}$. The results on the determination of the expansion characteristics are presented in Figure 3 and Table 2.

Table 1. Main characteristics of the polymer particles – size; terminal settling velocity; particle density; drag coefficient;

Particles	**Particles' density**	**d±σ**	$\mathbf{u_t}$	$\mathbf{Re_t}$	$\mathbf{C_{dt}}$
		-	***kg/m³***	**-**	**-**
Alginate 1055	**1055**	2,49±0,25	0,025	56,96	3,82
Alginate 1125	**1125**	2,00±0,15	0,038	72,2	2,26
Alginate 1175	**1175**	2,39±0,15	0,049	115,92	2,13

Table 2. Values of different constants in equations (8), (9)

Particles	Empirical parameters for eq.8		Equation (9)			Flow regime
-	K	n	α	β	β=-1-n	-
Alg. 1055	0,0128±0,0005	1,98±0,012	0.9977	-2.97	-2.98	laminar
Alg. 1125	0,0298±0,0006	2,80±0,015	1.002	-4.59	-3.8	transient
Alg. 1175	0,0247±0,0003	1,93±0,011	0.9858	-2.89	-2.93	turbulent

Our research showed that the value of the expansion coefficient n differed significantly from the one calculated according to the models of Richardson and Zaki, Rowe, Garside and Al-Doubini, Khan and Richardson et other (Garside and Al-Doubini, 1979; Al-Doubini and Garside, 1977; Grbavcic et. al., 1991; Khan and Richardson, 1989; Richardson and Zaki, 1954; Rowe, 1987). This is mainly due to the nature of light particles (Grbavcic et. al., 1991; Kostov et al., 2012]. It is interesting to note that a relatively small change in the particles dimensions provoked a significant change in the fluidized bed expansion (see (Kostov et al., 2012)). Therefore, for the voidage function discription was used equation (4.2), and the terminal settling velocity was taken to be equal to K.
The voidage function is presented on Figure 4 and Table 2. The experimental data were compared with the equation:

$$f(\varepsilon) = \alpha\varepsilon^{-\beta} \quad (9)$$

The first observed difference was that all the values of the coefficient α in the equation (9) were approximately equal. This phenomenon was interesting, because we expected that the voidage function spacing would result in the increase in the solid phase density. Obviously this was not valid for light particles. Interestingly, however, the voidage function was close to the generalized dependence cited in the work of Di Felice (Di Felice, 1995; Di Felice, 1984):

$$f\left(\varepsilon\right)=\varepsilon^{-\beta} \tag{10}$$

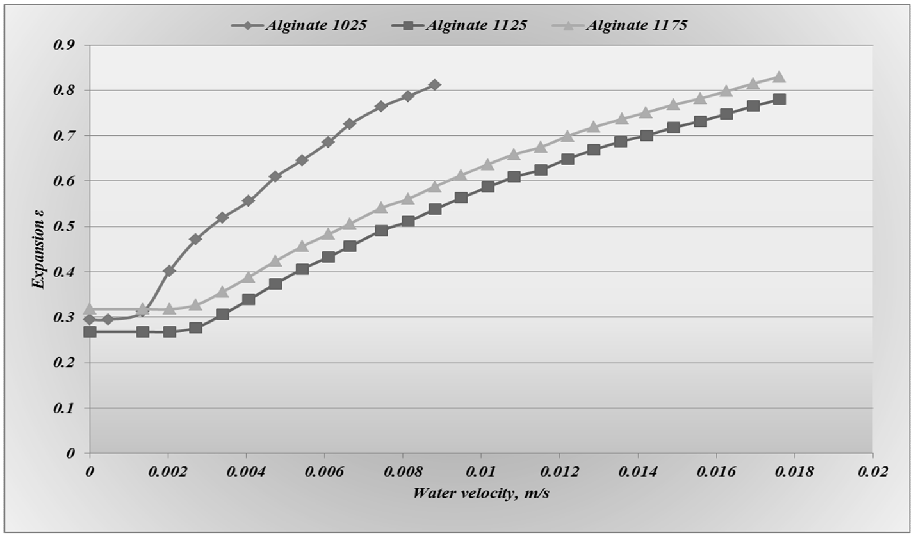

Figure 2. Expansion characteristics of light-beads fluidized bed

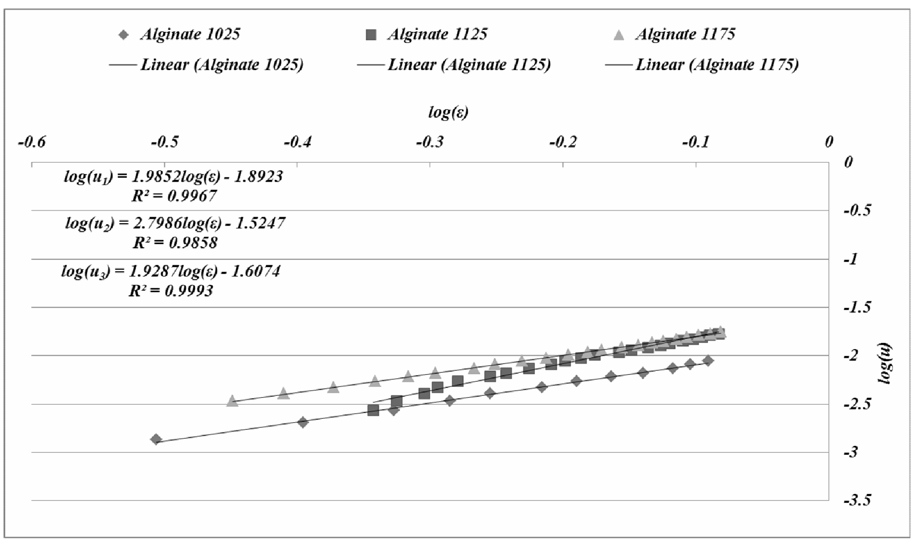

Figure 3. Determination of the expansion characteristics of light-beads fluidized bed

The behavior of the coefficient β was more interesting. In the first case studied (Kostov et al., 2012) it could be associated with the expansion degree. In this case one of the variants deviated significantly from the others.

Our prevoius study showed that this variant was located in the transition zone between the laminar and the turbulent flow of these particles. Therefore, the fluidization zone development in the transitional regime was undesirable for the stable working of the fermentation system. In the area of the transit system it was more convenient to use equation (4.1).

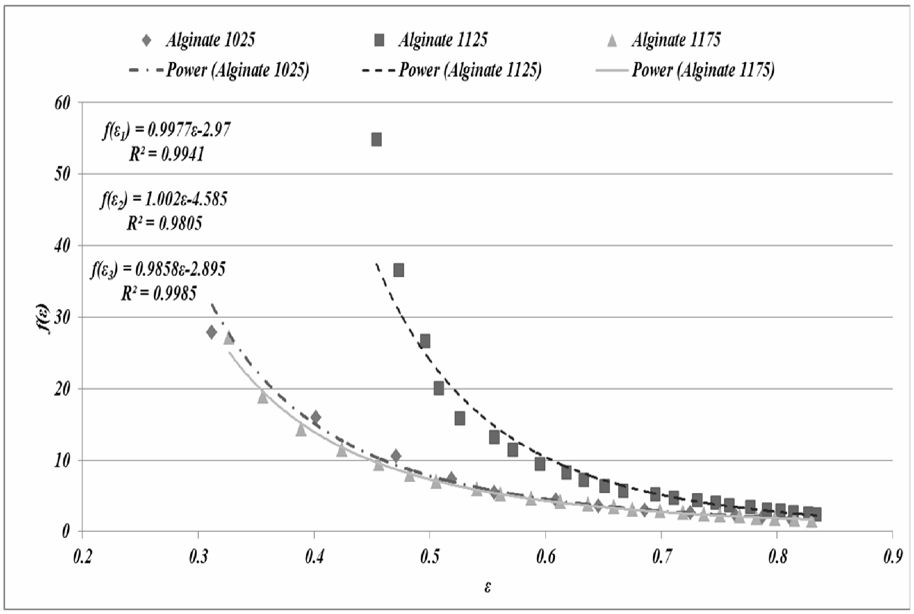

Figure 4. Determination of voidage function

It is interesting to note that the coefficient β changed its form – from **1-n** to **-1-n**. This was a result from the expansion characteristics changes. A similar phenomenon is not cited elsewhere in the literature. It can be ascribed to the particles nature and their rigid surface.

CONCLUSION

The obtained results allowed to be identified the areas for the optimal development of the light particles fluidization. The comparative study of two methods for the voidage function description indicated that each of the two methods had its own advantages.

Detectable changes in the voidage function coefficients indicated that this function was affected by the flow regime.

The results will be used for the development of a mathematical model for a fluidized bed bioreactor with light particles.

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