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Fluidized-bed and packed-bed characteristics of gel beads

E. van Zessen, J. Tramper, A. Rinzema, H.H. Beeftink *

Wageningen University, Food and Bioprocess Engineering Group, P.O. Box 8129, 6700 EV Wageningen, The Netherlands

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Abstract

A liquid-fluidized bed or packed bed with gel beads is attractive as an immobilized-cell bioreactor. The performance of such bioreactors is influenced by the physical behavior of these beads. Three different but related aspects involving the drag force between particles and liquid were studied for five types of gel beads, differing in diameter and density: (1) the terminal settling velocity of a single gel bead, (2) the pressure drop over a packed bed and (3) the voidage in a liquid-fluidized bed. Qualitatively, the same trends in these aspects were observed for gel beads as for conventional solids. Quantitatively, however, these aspects were incorrectly predicted by established models (with one exception).

It was found that the drag force between gel bead and flowing liquid is smaller than that for conventional solids. As an explanation, two hypotheses are suggested. The first one attributes the drag reduction to small amounts of dissolved polymer. The second one attributes the smaller drag force to the surface nature of gel beads: gel beads contain over 95% of water and thus can be regarded as 'rigid' water droplets. Hence, the gel bead surface might show water-like properties.

As an alternative to drag-coefficient relations for conventional solids, the drag coefficient of a single gel bead in a packed or fluidized bed could successfully be described by adapting an existing relation. The success of this description facilitates a more rational design of packed and fluidized beds of gel beads.

Keywords: Gel beads; Packed bed; Liquid-fluidized bed; Drag force; Voidage; Settling velocity; Pressure drop

1. Introduction

A packed bed or liquid-fluidized bed has attractive characteristics for application as an immobilized-cell bioreactor [1,2]. Cells or enzymes can be easily immobilized in solid particles, which facilitates high biocatalyst concentrations in a bioreactor [3]. An elegant way of immobilization is to embed the catalyst in gel beads made of, e.g. κ-carrageenan, alginate or agar [4]. These beads, applied in fluidized-bed or packed-bed bioreactors, can be used for typical bio-processes like the production of ethanol [5] or lactic acid [6].

Because little is known about the hydrodynamic behavior of gel beads in liquid-fluidized beds or in packed beds, and because these highly aqueous beads might behave differently from conventional solids for these types of reactors, we studied the bead behavior in these systems. To do so, gel beads of different diameters and densities were used.

In a packed bed, upward liquid velocities can be applied up to the minimum fluidization velocity. This velocity is attained when the pressure drop equals the specific buoyant weight of the bed. In this paper, pressure-drop experiments with different kinds of gel beads are described that show that—at the same diameter and voidage—the pressure drop over a packed bed of gel beads is much lower than for conventional solids such as lead shot or glass pearls. Consequently, established pressure-drop equations, such as the Ergun equation [7] or the Foscolo equation [8] cannot be applied to predict the minimum fluidization velocity for gel beads.

In a liquid-fluidized bed, the upward liquid velocity is in between the minimum fluidization velocity and the terminal settling velocity of a single particle. At the same time, the solids hold-up ranges from ca. 0.7 (packed bed) to 0 (bead wash out); it is determined by the equilibrium between buoyancy and drag forces. In the present paper, the solids hold-up for different kinds of gel beads was determined as a function of the superficial liquid velocity. Several literature models predict this functional relation. It will be shown, however, that the empirical model of Wilhelm and Kwauk [9] with parameters values according to Richardson and Zaki [10] does not correctly

* Corresponding author. Tel.: +31 317 484204.
E-mail address: rik.beeftink@wur.nl (H.H. Beeftink).

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predict the fluidized-bed gel-bead hold-up from superficial liquid velocity. However, the hold-up data are predicted well if, in the model of Wilhelm and Kwauk [9], the Richardson–Zaki relation is abandoned and if parameters values are obtained by fitting instead. The more fundamental model of Grbavcic et al. [11], using independently determined parameters, was found to predict the hold-up data correctly.

Measurement of the terminal settling velocity of different kinds of gel beads showed that many models for more conventional solids underestimate the terminal settling velocity for gel beads.

The packed-bed pressure drop, the fluidized-bed solids hold-up, and the terminal settling velocity all depend on the drag force on a particle. Gel beads experience a smaller drag force than conventional particles with the same diameter and density. Two hypotheses are suggested to explain this feature. Possibly, drag reduction results from small amounts of dissolved polymer. Alternatively, drag reduction may be ascribed to differences in surface structure of the gel beads, which may be regarded as 'rigid' water droplets.

2. Materials and methods

2.1. Bead production

All κ-carrageenan gel beads (Table 1) were produced with a resonance nozzle as described by Hunik and Tramper [12]. The specific aqueous κ-carrageenan (Genugel 0909 Copenhagen Pectin Factory) solution, kept at 35 °C, was pressed through a nozzle. The drops were collected in a 80 mM KCl solution for hardening of the beads. To obtain spherical beads, butyl-acetate (Aldrich–Chemie) was layered upon the hardening solution. After hardening for approximately 2 h, beads were stored in a KCl solution to prevent the elution of counter-ions from gel beads, which otherwise would dissolve in plain tap water. Alginate beads filled with yeast were prepared with a conventional dripping method [4]. The temperature in each experiment was ambient 26 ± 2 °C.

2.2. Bead characteristics

2.2.1. Diameter

Bead diameters were determined from image analysis (CCD camera with a 50-mm Nikon macro objective). Particle images were digitized and analyzed with Genius software (Applied Imaging). For contrast, the fluid surrounding the beads (10 mM KCl) was colored with blue dextran (Pharmacia Biotech, M_w = 2,000,000 g/mol). The contrast enhancement was used for beads of type A and B, κ-carrageenan beads without any additions, as they are transparent.

2.2.2. Volume and density

To sieved gel beads, a certain amount of liquid adheres that has to be accounted for in the determination of bead volume and specific density T this end, a flask with calibrated volume V_{flask} was weighted (M_{flask}), partly filled with a blue dextran solution, and weighted again (M_1). Sieved gel beads were then added, and the flask was again weighted (M_2). The flask was the filled with a blue dextran solution up to its calibrated capacity and (V_{flask}) weighted again (M_3). After shaking for over 2 h, the 280 nm adsorption of the supernatant (A_{su}) and of the original blue dextran solution (A_{so}) were determined (Ultrospec 2000, Pharmacia Biotech). From these data, the volume and density of the gel beads were determined:

$$
\begin{aligned}
V_{\text{water added}} &= \frac{M_1 - M_{\text{flask}} + M_3 - M_2}{\rho_{\text{water}(T)}} \\
V_{\text{water total}} &= \frac{V_{\text{water added}} A_{\text{so}}}{A_{\text{su}}} \\
V_{\text{gel beads}} &= V_{\text{flask}} - V_{\text{water total}} \\
M_{\text{water adhering}} &= (V_{\text{water total}} - V_{\text{water added}})\rho_{\text{water}(T)} \\
M_{\text{gel beads}} &= M_2 - M_1 - M_{\text{water adhering}} \\
\rho_{\text{gel beads}} &= \frac{M_{\text{gel beads}}}{V_{\text{gel beads}}}
\end{aligned}
\tag{1}
$$

Diffusion of blue dextran into gel beads was not observed during a 48-h incubation in a blue dextran solution.

2.2.3. Terminal settling velocity

The split-times of gel beads settling in a glass column filled with a salt solution (6 cm inner diameter, height 1 m) were measured at different heights, starting at 50 cm from the top. Bead velocities were obtained by linear regression on height versus time data. Wall effects might become important as the particle to column diameter ratio was limited. The terminal settling velocity of type A beads was thus also determined in a wide rectangular vessel (43.5 cm × 29.5 cm × 100.5 cm, $l \times b \times h$).

2.3. Pressure drop of a packed bed of gel beads

A bed of gel beads was packed in a column (inner diameter 2.56 cm, total height 120 cm); its bottom 5 cm were filled

Table 1
Gel-bead characteristics

Bead	Mean ± σ[a] (mm)	Median (mm)	Mean ± σ[a] (mm)	Median (mm)	d_{23}[b] (mm)	Circularity	Elongation	Density (kg m^{-3})
A	1.90 ± 0.28	1.99	1.90 ± 0.28	1.99	1.97	1.03	1.18	1007.4
B	2.99 ± 0.45	3.03	2.99 ± 0.45	3.03	3.12	0.98	1.10	1005.4
C	3.14 ± 0.17	3.14	3.14 ± 0.17	3.14	3.16	1.01	1.06	1029.8
D	2.90 ± 0.42	2.83	2.90 ± 0.42	2.83	2.76	1.02	1.15	1065.1
E	4.25 ± 0.24	4.27	4.25 ± 0.24	4.27	4.27	1.00	1.13	1039.9

[a] σ, Standard deviation.
[b] Sauter mean diameter: $d_{32} = \Sigma d^3/\Sigma d^2$.