Distributor Effects in Liquid Fluidized Beds of Low-Density Particles

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The effect of flow nonuniformities existing near the distributor of a liquid fluidized bed containing very low-density particles (ρ_s = 1.05 g/mL) has been investigated experimentally. Immobilized enzyme or cell bioreactors operated as liquid fluidized beds often employ low-density particles as the support matrix containing the immobilized biocatalyst. With poorly designed multihole distributors, dead zones can be created which seriously undermine the performance of the bioreactor due to the lack of nutrients. Design guidelines are provided for distributors to minimize the inlet flow disturbances, and hence eliminate potential distributor region problems. As a result, the dispersion model, which is normally used for design purposes, can then be applied.

Introduction

The advent of immobilized biocatalyst technology has opened new avenues of research and application of continuous flow reactors for achieving various biochemical transformation reactions. Fluidized bed bioreactors show great promise in this respect, since they offer the unique advantage of lowering the mass transport resistances thereby enhancing the efficiency of the process.

The most crucial step in the design and scale-up of any chemical or biochemical reactor is the proper characterization of the hydrodynamics. Realistic models are required to enable accurate prediction of the level of the conversion in fluidized bed bioreactors as pointed out by Oertzen et al. (1989) and Ching and Ho (1984).

The influence of the solid-liquid interactions on liquid fluidized bed hydrodynamics has been well researched and well understood (Cairns and Prausnitz, 1960; Chung and Wen, 1968; Kikuchi et al., 1984; Tang and Fan, 1990). However, the effect of the distributor on the bed hydrodynamics has received no attention thus far. Recently, it has been shown by Asif (1991) that the nonideal flow behavior in the distributor region can cause significant distortion of the bed flow dynamics which ultimately leads to incorrect estimation of the dispersion parameter of the bed in the modeling process.

Often, the main characteristic feature of a fluidized bed bioreactor is the small density difference between the particles (solid support matrix for immobilized cells or enzymes) and the fluidizing medium (liquid phase). With this in mind, the system chosen for the present study consists of polystyrene (ρ_s = 1.05 g/mL) as the solid phase and water as the fluidizing medium.

Recently, Tang and Fan (1990) investigated the dispersion characteristics of liquid fluidized beds containing low-density particles (1.05–1.30 g/mL). They pointed out that the extent of axial liquid dispersion in a fluidized bed of low-density solid particles is significantly less than that of high-density solid particles. Consequently, existing correlations (Chung and Wen, 1968; Krishnaswamy et al., 1978) for the prediction of the dispersion coefficients in a fluidized bed containing high-density solid particles cannot be extended to the low-density operating regime. Similar conclusions were drawn by Kikuchi et al. (1984) who considered very low-density polystyrene particle in their study of axial liquid dispersion in liquid fluidized beds. By the same token, we expect that the distributor region will be similarly influenced by the density of solid particles present in the system. In fact, it has been shown by Asif (1991) that the distributor can cause severe distortion in the bed hydrodynamics when the solid phase consists of medium density polypropylene particles (ρ_s = 1.61 g/mL). On the other hand, no such effects were observed when the fluidized bed contains heavier particles (ρ_s = 2.46 g/mL).

Studies concerning the distributor region in gas-solid fluidized beds has received considerable attention in the literature

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with the main emphasis on finding the height of the distributor region (Hetsroni, 1982). In this case (that is, gas-solid fluidization), the flow dynamics responsible for the existence of the distributor region are well understood. They are attributed to stirring effects of high-momentum gas jets issuing forth from the orifices of the distributor, as originally pointed out by Behie and Kehoe (1973). Any analogy between liquid-solid fluidized beds and gas-solid fluidized beds is not valid, since the fluidizing medium in the latter case is a gas that has a negligible density as compared to the density of the solid phase present in the bed. Unfortunately, there is no information available in the literature about distributor effects in the liquid-solid fluidized system of light particles.

In this context, the objectives of this study are to: Investigate the influence of various parameters associated with the distributor design on the fluidized bed flow dynamics; and characterize the flow behavior existing in the distributor region that results in the distortion of the bed hydrodynamics.

To this end, two different sets of residence time distribution experiments were carried out. In one case, a pulse of the tracer was injected away from the distributor so that the response was free from any kind of flow nonuniformities existing in the distributor region and reflected only the effect of the liquid-solid interaction in the bed itself (bed region). In another set of experiments, the tracer was injected immediately above the distributor. The response recorded for this latter experiment included the effect of the distributor as well, as a part of the liquid fluidized bed (distributor/bed). The response data obtained from these two experiments were processed in conjunction with an appropriate model to extract the quantitative information about the effect of the distributor on the bed hydrodynamics.

Experiments were designed in such a way that the distance between the tracer injection and measurement points was sufficiently long and the same for both of the cases. This precaution was taken to avoid the influence of time-dependent dispersion parameters, ample evidence of which can be found in the work of Han et al. (1985) for packed beds and Asif (1991) for fluidized beds.

Experimental Details

Experiments were performed at room temperature in a plexiglas column of 7.86-cm internal diameter and length of either 120 cm or 145 cm. A distributor was placed at the bottom of the bed preceded by a calming section. A low pressure drop wire mesh was placed on top of the distributors to prevent the backflow of solids when the column was shut down. Important aspects of the experimental set-up are described in the following sections. See Asif (1991) for further details.

Tracer injection and monitoring systems

The tracer injection system was designed to avoid disturbing the flow dynamics of the fluidized bed. In the present case, a plane source of pulse injection was employed that was similar to the technique of Tang and Fan (1990). A 3-mm-OD steel tube was used, on both sides of which ten equally-spaced 1-mm holes were drilled. The end of the tube was sealed. Its orientation along the diameter of the column cross-section was such that the tracer ejecting from the holes of the tube under pressure provided a uniform plane source of tracer injection across the cross-section of the column. Time and duration of the tracer injection were controlled with the help of a switch-to-open solenoid valve operated with a Taurus data acquisition and control system interfaced with an IBM personal computer. The pulse duration of the tracer injection was 100–120 ms. The tracer, methylene blue, was kept air-pressurized in a 1-L tracer tank.

Table 1. Liquid Distributor Design Parameters

No. of Holes	N_{or} holes/cm^2	F_{or}	D_{or} cm
1	0.022	0.040	1.52
4	0.088	0.040	0.76
20	0.44	0.045	0.36
60	1.32	0.042	0.20
1	0.022	0.010	0.76

The tracer measurement system consisted of a fiber-optic Brinkmann probe colorimeter (Model 700) for measuring the color of the solution. The probe tip for the on-line measurement of the tracer concentration was 9 mm in diameter with its light path along the diameter of the column and perpendicular to the direction of flow. Probe colorimetry was preferred in the present experimental investigations over the commonly used conductivity measurement technique for two reasons. First, the response of the probe colorimeter was very fast. Total time lag in the measuring and recording instruments was found to be less than 80 ms. Second, the output of the colorimeter, in terms of absorbance, was found to be linear with the color or concentration changes of the tracer solution.

Distributors

The design parameters of distributors considered in this study are shown in Table 1. The density of holes in the distributor N_{or} was varied from 0.02 to 1.33 holes/cm^2 to have a complete picture of distributor effects from a worst possible case of liquid distribution (one-hole distributor) to a very uniform liquid distribution (60-hole distributor). This also helped in studying the influence of the orifice diameter, since increasing the number of holes in a distributor, while keeping the fractional open area F_{or} constant, leads to a smaller distributor orifice hole, as evident from Table 1. Another important design variable of the distributor is the fractional open area that affects the liquid orifice velocity and the distributor pressure drop. For most distributors, F_{or} was kept constant at 0.04 and the distributor pressure drop was varied by changing the liquid flow rate. One distributor was designed to have a fractional open area of 0.01 to study the effect of the distributor fractional open area. Table 2 shows the range of important variables in the present study.

Solid particles

The solid phase present in the fluidized bed consisted of polystyrene particles of 2.2-mm equivalent diameter. These

Table 2. Operating Ranges for Distributors

F_{or}	U_{or} cm/s	ΔP_d kPa	Fr			
			60-Hole	20-Hole	4-Hole	1-Hole
0.040	25–79	0.05–0.90	3.5–31.6	1.8–15.8	0.9–8.3	0.45–4.2
0.010	100–315	0.9–14.0	—	—	—	14.8–133.0

Table 3. Experimental Conditions for Dynamic Testing of Distributor/Bed Region (Case 1) and Bed Region (Case 2) of the Fluidized Bed

			Distributors		
zo	*zl*	*L*	Holes	F_{or}	Case
0.0	105.0	105.0	1	4%	1
0.0	105.0	105.0	4	4%	1
0.0	105.0	105.0	20	4%	1
0.0	105.0	105.0	60	4%	1
0.0	105.0	105.0	1	1%	1
25.0	130.0	105.0	60	4%	2

particles were cylindrical with length L_p 3.0 mm, diameter D_p 2.5 mm, and sphericity 0.85 ($U_{mf}=0.44$ cm/s and $U_t=4.9$ cm/s). The density of the solid particles was 1.05 g/mL. Particles were inert and no adsorption of the tracer on the surface of the particles was observed.

Experimental methodology

A summary of experiments and their configuration is shown in Table 3. Over 5,000 data points were collected in this study. The experimental strategy adopted involved two different kinds of experiments, as described in the following.

Case 1: Investigation of Bed/Distributor Region. These experiments were specifically designed to investigate the distortion caused by the presence of the distributor on the fluidized bed flow dynamics. At the same time, they helped explore the behavior of the distributor region itself. In this case, the tracer injection was immediately above the distributor and the detection point was 105 cm away from it in a fluidized bed, 120 cm in height (Table 3). As a result, the residence time distribution of tracer particles obtained in this experiment was influenced by the flow behavior prevailing in the bed including the distributor region.

Case 2: Investigation of Bed Region. The purpose of these experiments was to investigate the true dispersion characteristics of the fluidized bed in the absence of any distributor effects and to compare results with published correlations. Here, the tracer injection was kept 25 cm away from a 60-hole distributor, which ensured the tracer injection to be always free of distributor effects. This was achieved by adding another similar 25-cm-long plexiglas column to the pre-existing 120-cm-long column, making it 145 cm long. The distance of 25 cm (*zo* = 25 cm) was selected, because the influence of the distributor, as discussed later, was found to be absent at this height for the 60-hole distributor.

To have a reliable database, seven replicate runs were carried out for each individual experiment. During data analysis for the evaluation of parameters, data from all the seven runs were used as described in the section of parameter estimation.

Mathematical Model

The liquid-phase concentration distribution in a liquid fluidized bed is usually represented by the conventional dispersion model. The quantitative difference between the value of the actual dispersion coefficient D_{ac} obtained for the bed region only (experiments of case 2) and the apparent dispersion coefficient, D_a obtained for the whole fluidized bed including influence of distributors (experiments of case 1) could be interpreted as the distortion introduced by the distributors on the hydrodynamics of the fluidized bed.

Dispersion model

The one-dimensional unsteady-state dispersion equation governing the concentration distribution in a liquid fluidized bed containing nonporous and nonadsorbing solid phase is given by:

$$\frac{\partial C}{\partial t}=D_a\left(\frac{\partial^2 C}{\partial z^2}\right)-U_i\left(\frac{\partial C}{\partial z}\right) \tag{1}$$

where D_a is the dispersion coefficient and U_i is the liquid interstitial velocity. The contribution of the radial dispersion to the mass transport was eliminated by use of the plane source of tracer injection.

The location of the tracer injection and measurement points has important implications on the choice of the boundary conditions to solve Eq. 1 as described in detail by Levenspiel (1984).

For experiments of case 2, the tracer injection and detection points were sufficiently far from the boundaries of the fluidized bed. Therefore, this system was treated as an infinite medium for the solution of the dispersion equation. The solution to a pulse of tracer injection is given by:

$$C=\frac{U_i}{(4\pi D_a t)^{0.5}}\exp\left(-\frac{(L-U_i t)^2}{4D_a t}\right) \tag{2}$$

where L is the distance between tracer injection and measurement point.

For experiments of case 2, in which the tracer injection was close to the bed inlet, we imposed the well-known Danckwert's type of boundary condition given by:

$$-Da\left(\frac{\partial C}{\partial z}\right)+U_i C=U_i\delta(t)\ \text{at}\ z=0 \tag{3}$$

Since the measurement point was away from the outlet boundary of the bed, it could be treated as a semi-infinite medium for the solution of the dispersion equation. The solution of Eq. 1 subject to boundary conditions (Eq. 3) for a semi-infinite medium is given by:

$$C=\frac{U_i}{(\pi D_a t)^{0.5}}\exp\left(-\frac{(L-U_i t)^2}{4D_a t}\right)-\left[\frac{U_i^2}{2D_a}\exp\left(\frac{U_i L}{D_a}\right)\times \operatorname{erfc}\left(\frac{L+U_i t}{(4D_a t)^{0.5}}\right)\right] \tag{4}$$

Parameter Estimation

The evaluation of the axial dispersion coefficient from the raw data involved two steps. First, the experimental measurements from seven replicate experiments were averaged, normalized and the standard deviation was computed for each measurement point. The latter is needed for the statistically correct determination of D_a from the experimental data.

In the second step, we determined D_a by minimizing a suitable objective function. By considering not only the error in the measured concentration but also in the measured interstitial velocity, the most appropriate objective function to be minimized from a statistical point of view (error-in-variables method; Reilly and Patino-Leal, 1981) is given by:

$$S(D_a,U_i)=\sum_{k=1}^{N}(C_e(t_k)-C_p(t_k,D_a,U_i))^2\frac{1}{\sigma_k^2}+(U_{ie}-U_i)^2\frac{1}{\sigma_u^2} \quad (5)$$

where σ_u is the standard error in the measurement of U_i, and σ_k is the standard error in the average concentration measurement at time t_k. A value of $0.05U_{ie}$ was used for σ_u representing the uncertainty in the measurement of the interstitial velocity. σ_k^2 is given by $(\sigma_{jk}^2/7)$ where σ_{jk}^2 is the variance computed by the seven replicate experiments. U_{ie} is the experimentally measured value of the interstitial velocity, and U_i is its fitted value. The objective function was minimized over D_a and U_i simultaneously.

The maximum deviation in the estimated true values of the liquid interstitial velocities never exceeded more than 10% of the measured value. Moreover, Rangaiah and Krishnaswamy (1990) have recently shown that better results are obtained by not treating U_i constant in the minimization procedure. This is due to the fact that D_a is very sensitive to U_i. This approach was also followed by Tang and Fan (1990) and Goebel et al. (1986). In this article, we also search for D_a and U_i. However, we minimize the statistically correct objective function based on the error in variables method.

Results and Discussions

Effect of distributor on the flow dynamics of the fluidized bed

The effect of various distributors on the response of the fluidized bed containing polystyrene particles ($\rho_s = 1.05$ g/mL) at a high liquid superficial velocity of 3.15 cm/s ($Re_p = 58$) is shown in Figure 1. In this case, the response curve for the bed region in Figure 1 (experiments of case 2) shows the actual hydrodynamics of the fluidized bed away from the distributor. On the other hand, response curves for the complete bed with four different distributors (distributor/bed) show both the distributor effects as well as the dispersion characteristics of the fluidized bed (experiments of case 1).

As seen from Figure 1, there is not much difference in the behavior of the fluidized bed due to the presence of various distributors. The dispersion characteristics are almost the same for all cases. However, as the flow rate is decreased from 3.15 to 1.46 and then to 1.05 cm/s, a marked change is observed in the hydrodynamics of the bed as shown in Figures 2 and 3. For distributors of low hole density, the effect on the response becomes more apparent by diminishing peaks and longer tailings. Even two distinct peaks could be observed with the one-hole distributor when the liquid superficial velocity is 1.05 cm/s (Figure 3). On the other hand, no significant distortion of bed hydrodynamics is observed in the case of the 60-hole distributor.

To quantify the effect of distributors, an apparent axial liquid dispersion coefficient D_a was computed using the conventional dispersion model, which assumes that the fluidized bed has uniform dispersion characteristics. It was evaluated from the response curve when the tracer injection was immediately above the distributor (experiments of case 1). On the other hand, the actual bed value of the dispersion coefficient D_{ac} was evaluated from the response curve when the tracer injection was free from distributor region irregularities (experiments of case 2). Consequently, D_{ac} was a measure of the dispersion characteristics of the bed only (bed region). The difference between the value of D_a and D_{ac} provided a quantitative measure of the distortion of the bed hydrodynamics caused by the presence of the distributor.

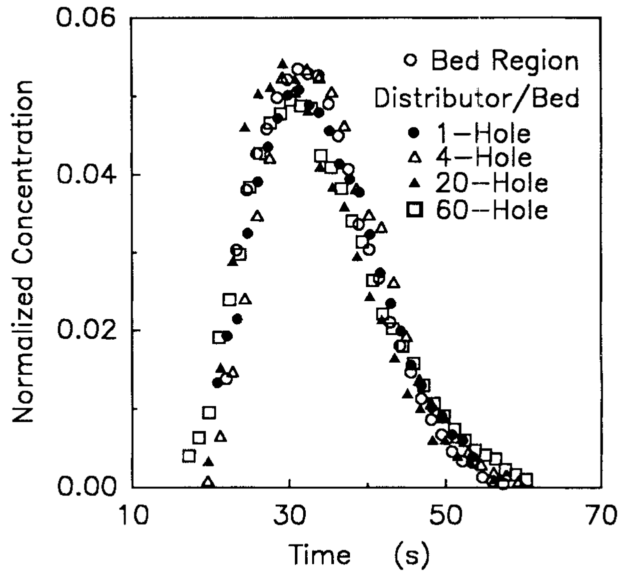

Figure 1. Effect of distributors on the response of the liquid fluidized bed at high liquid velocity.

U_o = 3.15 cm/s, Re_p = 58, and F_{or} = 0.040.

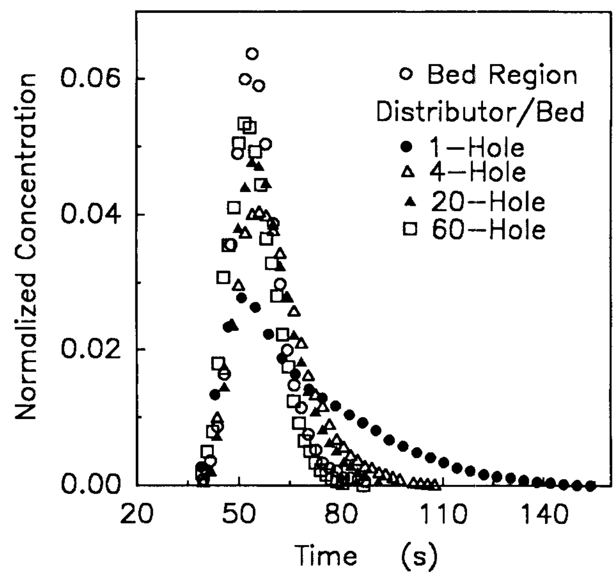

Figure 2. Effect of distributors on the response of the liquid fluidized bed at low liquid velocity.

U_o = 1.46 cm/s, Re_p = 27, and F_{or} = 0.040.

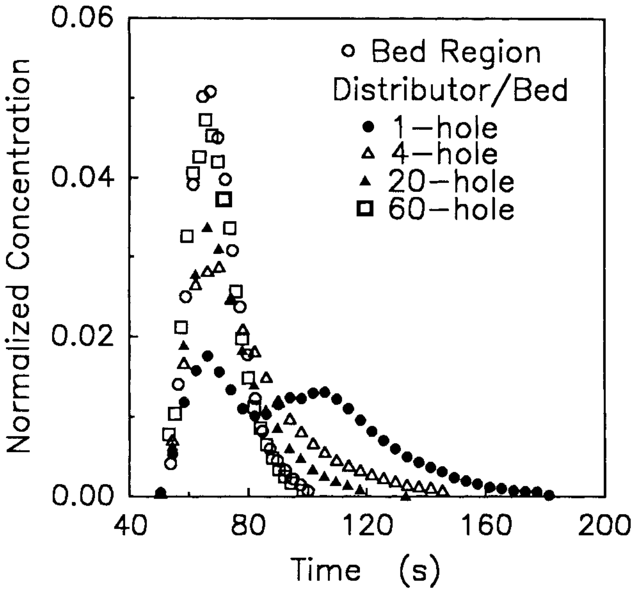

Figure 3. Effect of distributors on the response of the liquid fluidized bed at very low liquid velocity.
U_o = 1.05 cm/s, Re_p = 19, and F_{or} = 0.040.

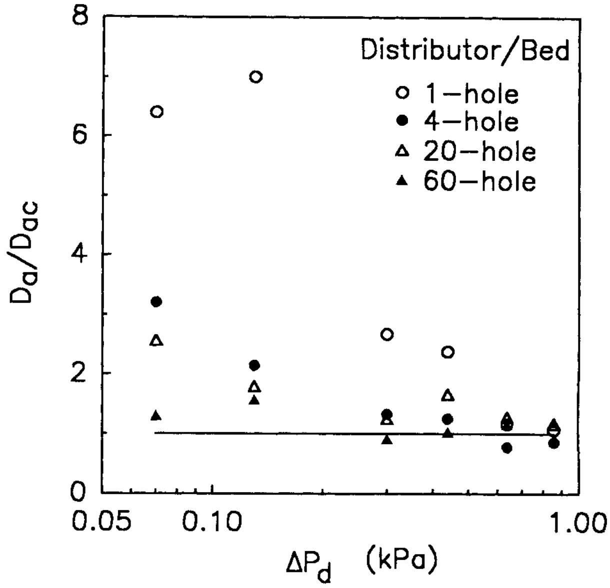

Figure 5. Effect of distributor pressure drop and hole density on the hydrodynamics of the liquid fluidized bed.
F_{or} = 0.040.

Figure 4 shows the influence of the liquid superficial velocity U_o on the value of the apparent axial liquid dispersion coefficient D_a. It is obvious from this figure that distributor effects become more pronounced as U_o decreases. The value of the apparent dispersion coefficient D_a does not show a monotonically decreasing trend, which is observed for the case of the bed region. The deviation of the apparent dispersion coefficient from the actual dispersion coefficient is almost negligible for distributors of high hole density with small diameter orifice holes (Table 1). Apparently, small orifice diameter D_{or} holes

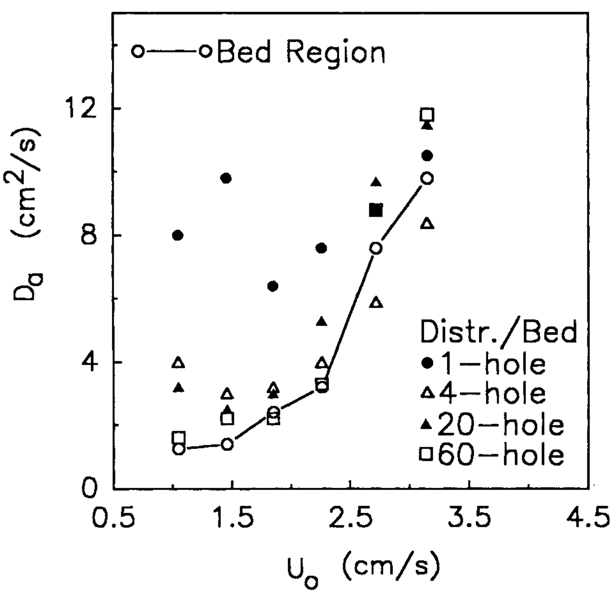

Figure 4. Comparison of apparent dispersion coefficients D_a at different liquid superficial velocities.
F_{or} = 0.040.

reduce distributor effects. This is consistent with findings for gas fluidized beds where the height of the distributor region has been found to be a strong function of D_{or} (Yates et al., 1986; Yang and Keairns, 1979; Merry, 1975). For the range of U_o (1.0 to 3.1 cm/s) in Figure 4, the bed porosity ϵ varies from 0.56 to 0.71, respectively.

It is worthwhile to examine the effect of the distributor pressure drop, an important variable of design interest, on the hydrodynamics of the bed (Figure 5). The ratio of the apparent dispersion coefficient D_a to the actual dispersion coefficient D_{ac} is plotted against the distributor pressure drop. The higher the value of the ratio D_a/D_{ac}, the greater is the influence of the distributor. From Figure 5, it is seen that the distributor effect is more pronounced at low ΔP_d where the ratio of D_a/D_{ac} is high. This figure also shows that for the 60-hole distributor, the deviation from the bed hydrodynamics is negligible throughout the range of the distributor pressure drop considered in the present investigation, whereas for distributors of low hole density N_{or}, the deviation of D_a from D_{ac} is large at low distributor pressure drop.

Response curves for U_o = 1.05 cm/s in Figure 6 show that the double peak, which is a characteristic of the 4%-F_{or} distributor, is no longer present for the 1%-F_{or} distributor. A double peak suggests the existence of recirculation patterns in the distributor region and is, undoubtedly, caused by the presence of dead zones near the distributor. Reducing F_{or} results in higher values of liquid orifice velocities, which tend to eliminate the stagnant zones in the distributor region owing to the higher degree of turbulence.

Identification of distributor region flow dynamics

It is important at this stage to identify the nature of the nonideal flow behavior in the distributor region, which distorts the overall bed hydrodynamics and results in the overprediction

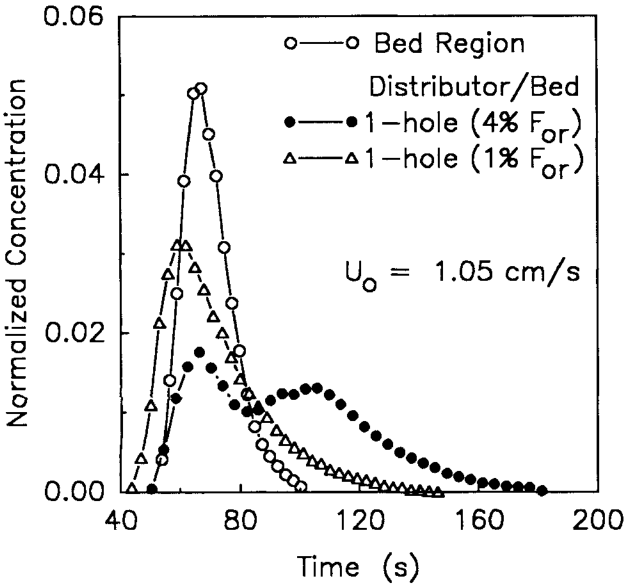

Figure 6. Dynamic response curves for the liquid fluidized bed at different distributor fractional open areas.

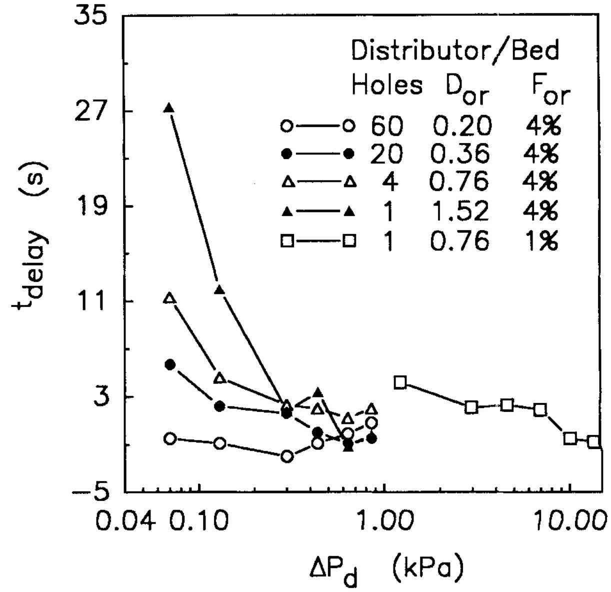

Figure 7. Effect of distributor pressure drop ΔP_d and hole density on the delay time t_{delay}.

of D_a at low flow rates. This is done by computing the delay time which is defined by:

$$\bar{t}_{delay} = \bar{t}_{distributor} - \bar{t}_{bed} \tag{6}$$

where $\bar{t}_{distributor}$ is the mean residence time computed from the response curve including the distributor effect, and $\bar{t}_{bed}$ is the mean residence time computed from the response curve that is free from distributor region irregularities.

The value of the delay time is a quantitative measure of the presence of dead zones in the distributor region. When the tracer is injected in the distributor region (experiments of case 1), a part of it gets trapped in dead zones. As a result, a long tail is observed in the response curve. Due to the tailing, the mean residence time of the tracer particles increases dramatically. On the other hand, no tailing is observed in the response curve for the bed region (experiments of case 2). The difference of mean residence times in these two cases, as shown by Eq. 6, is the delay time. The larger the value of the delay time, the greater is the presence of the dead zones in the distributor region.

It is important to point out that if tailing is observed in the response curve as a result of dispersion or CSTR-like behavior in the distributor region, the value of the delay time will be zero (Asif, 1991).

The delay time in a fluidized bed containing low-density particles of polystyrene is plotted against the distributor pressure drop in Figure 7. It is evident from the figure that as the distributor pressure drop decreases, the delay time dramatically increases suggesting the presence of dead zones in the distributor region. This phenomenon also causes the dispersion model to predict much higher values of D_a at low ΔP_d. At the same time, we can safely rule out any possibility of attributing the overprediction of D_a to the stirring effects of high-velocity jet issuing forth from the distributor orifice holes. This is due to two reasons. If stirring effects of the orifice jet were the cause of the overprediction of D_a for the fluidized bed of polystyrene and water, the distortion or the overprediction of the dispersion coefficient would be more severe at high distributor pressure drop where jet velocities are high. However, we observe the reverse here that the distortion is more visible at low ΔP_d. Secondly, the stirring effects of jets would lead to CSTR-like behavior in the distributor region, for which the delay time is zero. This reasoning is further substantiated by the 1%-F_{or} distributor (Figure 7), where the distortion of hydrodynamics is negligible, and the delay time is close to zero or more specifically, dead zones are absent owing to high ΔP_d. Note that the delay time is substantially higher for a similar one-hole distributor with 4%-F_{or}. It is also evident from the figure that a large hole density distributor eliminates the presence of the dead zones in the distributor region due to a uniform distribution of the liquid across the cross-section of the fluidized bed.

The local nonhomogeneities of the distributor region, which has been identified to be dead zones, are not expected to prevail away from the distributor. To confirm this, an experiment was carried out by keeping the tracer injection away from a one-hole distributor ($zo = 30$ cm). Results are shown in Figure 8. The value of the dispersion coefficient in the presence of the one-hole distributor is almost the same as the value obtained for the bed region. However, this is not the case when $zo = 0.0$, for which substantial deviations are observed. This means that close to the distributor, flow nonuniformities do exist and are local in nature. Moreover, these results also justifies the choice of keeping $zo = 25$ cm in experiments of case 2, where the main concern was to design RTD experiments for a fluidized bed free from distributor effects.

It is important to compare the values of the bed region dispersion coefficient D_{ac} obtained in the present experimental study with those predicted by correlations reported in the literature. In Figure 9, the prediction of the Tang and Fan (1990) correlation is shown only in the range applicable for their correlation. It slightly underestimated the values obtained in the present experimental investigation. On the other hand, the

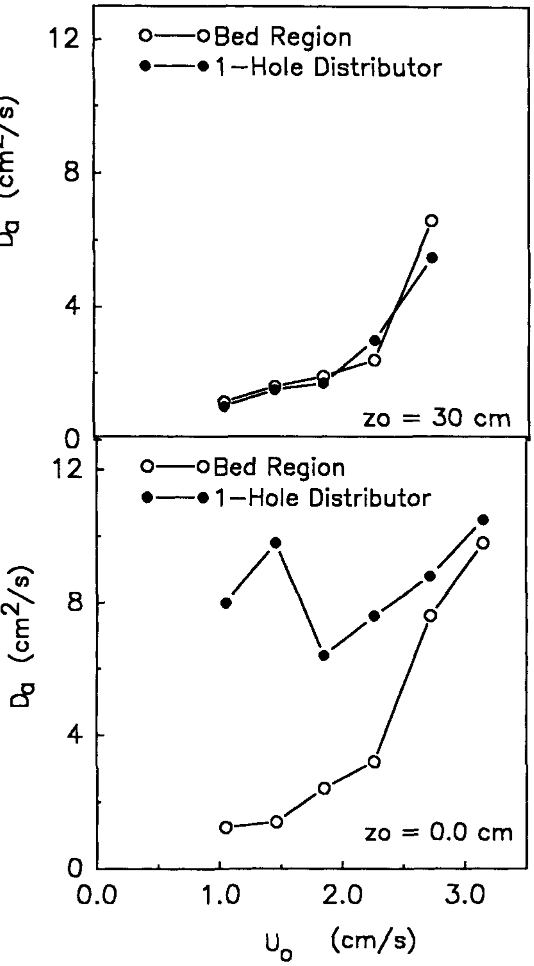

Figure 8. Influence of the tracer injection location on the apparent dispersion coefficient D_a for one-hole distributor.

zo = 0.0, zo = 30 cm and F_{or} = 0.040.

predictions of the Krishnaswamy et al. (1978) correlation are found to be poor at low flow rates.

Distributor design guidelines

For low-density solid particles ($\rho_s = 1.05$ g/mL) such as those often found in liquid fluidized bed bioreactors, care must be taken to eliminate dead zones in the distributor region where nutrient depletion could cause the death of live cells, thereby undermining the efficiency of the entire bioprocess. To avoid the presence of dead zones, a distributor with a hole density as large as possible should be used. In the present case, the 60-hole distributor ($D_{or} = 0.20$ cm) with a hole density of 1.32 holes/cm^2 approached the ideal of a porous distributor giving an excellent liquid distribution for a wide range of operating conditions.

In practice, it may be necessary to use large distributor holes for full-scale industrial bioreactors. While it is prohibitively expensive to make a distributor with thousands of holes, biomass is much more prone to plug small holes. In this case, care must be taken in operating the bed to ensure a good liquid distribution. These requirements translate into a narrower operating range of superficial velocities. For example, for

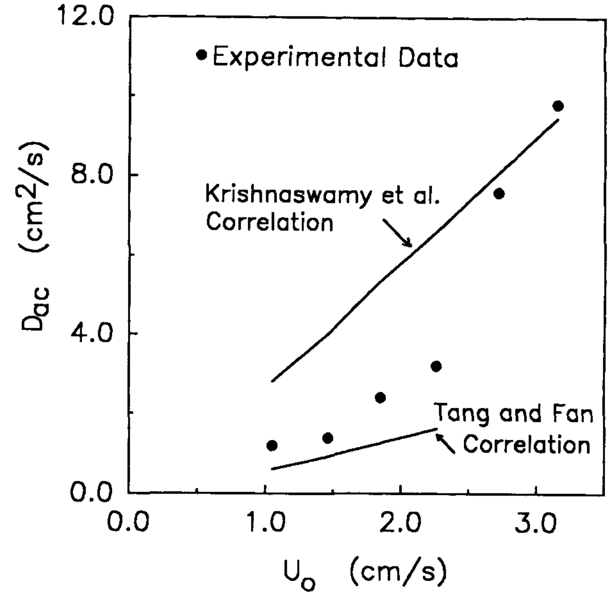

Figure 9. Comparison of the actual dispersion coefficient D_{ac} with predictions of two correlations.

$D_{or} = 0.76$ cm ($F_{or} = 0.04$ and $N_{or} = 0.088$ holes/cm^2), distributor region distortions are negligible for $U_o > 1.8$ cm/s as shown in Figure 4.

Conclusions

This study quantifies the effects of distributors on the hydrodynamics of a liquid fluidized bed containing very low-density particles. These effects were found to be quite pronounced at low distributor pressure drops and low hole densities. This was caused by the presence of dead zones in the distributor region of multihole distributors.

Acknowledgment

Professors NK and LAB would like to thank the Natural Sciences and Engineering Research Council of Canada (NSERC) for financial support of this project.

Notation

- C = concentration of the tracer
- $\bar{C}_e(t_k)$ = experimental average normalized concentration
- $C_p(t_k)$ = prediction of the model at time t_k
- D_a = axial liquid dispersion coefficient, cm^2/s
- D_{ac} = actual axial liquid dispersion coefficient, cm^2/s
- D_{or} = distributor orifice diameter
- $\bar{D}_p$ = particle diameter, mm
- D_p = equivalent particle diameter, mm
- F_{or} = distributor fractional open area
- Fr = Froude number = $(U_{or}^2/g\,D_{or})$
- H_s = total height of the fluidized bed, cm
- L = distance between tracer injection and tracer measurement point, cm
- L_p = length of the particles, mm
- N = total number of data point in an experiment
- N_{or} = distributor hole density, holes/cm^2
- ΔP_b = bed pressure drop, kPa
- ΔP_d = distributor pressure drop, kPa
- Re_p = particle Reynolds number = $(D_p U_o \rho/\mu)$
- S = quadratic objective function defined by Eq. 5
- t = time, s

$\bar{t}_{bed}$ = mean residence time for the bed region, s
$\bar{t}_{distributor}$ = mean residence time for the bed/distributor, s
t_{delay} = delay time, s
U_i = liquid interstitial velocity, cm/s
U_{ie} = experimentally measured liquid interstitial velocity, cm/s
U_{mf} = minimum fluidization velocity, cm/s
U_o = liquid superficial velocity, cm/s
U_{or} = liquid distributor orifice velocity, cm/s
U_t = particle terminal velocity, cm/s
z = axial coordinate, cm
zl = distance of the tracer detection from the distributor, cm
zo = distance of the tracer injection from the distributor, cm

Greek letters

ϵ = fluidized bed porosity
μ = fluid viscosity, mPa·s
ρ = fluid density, g/mL
ρ_s = solid particle density, g/mL
σ_k = standard error in the measurement of concentration at time t_k
σ_u = standard error in the measurement of U_i
$\delta(t)$ = dirac delta function

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Manuscript received Aug. 16, 1991, and revision received Sept. 30, 1991.