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Simplified correlations of axial dispersion coefficient and porosity in a solid-liquid fluidized bed adsorber

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ABSTRACT

The aim of the present work is to propose a simple, reliable and effective model of hydrodynamics in fluidized bed reactor (FBR). The long-term objective of these models is to be able to use them for modeling and optimization of adsorption processes in fluidized bed columns. Residence time distribution (RTD) and porosity (ε) of the bed were determined as a function of flow rate $Q_v = 210–1000$ L/h, and temperature $T = 20–40$ °C. Polynomial models with interaction terms were developed to study the influence of T and Qv on two responses: porosity and axial dispersion coefficient (ADC). The quality of regression model equations was evaluated using the analysis of variance (Minitab16). The porosity of the bed increases with the square of the superficial velocity up to a peak of 0.92 at the rate of 1000 L/h. Among the correlations of the literature on the porosity of the fluidized bed, those of Miura et al. (2001) and Riba et al. (1977) are closest to our experimental data (with a 4% and 16% error respectively). The axial dispersion coefficient of the liquid phase increases monotonically with liquid velocity. A theoretical minimal D_{ax} values can be achieved at temperatures higher than 34 °C and flow rate of 210 L/h.

1. Introduction

Fluidized beds are processing devices in which particles are fluidized against gravity by a fluid, implying the suspension of solids in a gas or liquid or both. Variation in the forces acting on the particles causes variations in fluid velocity, resulting in dynamic behavior [1,2]. Conventional solid-liquid fluidized beds (SLFBs) have been extensively studied since 1950 [3]. They are encountered in many processes in industrial operations, e.g. Water treatment, catalytic cracking, combustion, crystallization, ion exchange, and adsorption [4]. The SLFB adsorber offers better uniformity of temperature and concentration fields, and avoids the formation of dead zones and clogging, frequent in traditional fixed beds [5].

To guarantee optimal operation and/or to maintain the system in its optimal state despite disturbances, this type of reactor can be improved by the addition of process control. However, this is possible only if the process is modeled accurately. The first step in modeling such a system is to study the hydrodynamic influence of the reactor configuration [6].The prime factor that influences the hydrodynamics of liquid-solid fluidized beds is the interaction between the solid and liquid phases, this is generally quantified in terms of the axial liquid dispersion coefficient which provides information about the degree of fluid mixing in the bed.

Axial liquid dispersion affects solid/liquid interphase mass transfer and solute concentration distribution, and thereby the adsorption process. Information on axial liquid dispersion is therefore crucial for reactor design and process optimization. Much work has been done on the axial liquid dispersion coefficient, most extensively by Chung and Wen and Kikuchi et al. [7,8], who studied the liquid fluidized bed in the low Reynolds number region. Tang and Fan [9] focused on axial liquid dispersion coefficients in liquid-solid fluidized beds with lower particle density. Also in turbulent shear flow various studies on the dispersion were realized [10,11]. All the observed values of the axial dispersion coefficient were correlated with particle Reynolds number, Archimedes number, Schmidt number and bed voidage. Since an adequate understanding of axial liquid dispersion is essential for the design and scale-up of industrial reactors, simplified and efficient models are needed to study the axial liquid dispersion in the LSFB adsorbers. The present work undertook to study the hydrodynamics of a solid/liquid fluidized bed using residence time distribution (RTD)

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Nomenclature

ε	the average void fraction of the bed
t	time (s)
E	the function of the residence time distribution (s^{-1})
C	the concentration of tracer at time t (kg/m^3)
$\bar{t}$	the mean residence time (s)
σ^2	the variance (s^2)
σ_θ^2	the dimensionless variance
U	superficial liquid velocity (m/s)
U_{ax}	the liquid interstitial velocity (m/s)
D_{ax}	the axial dispersion coefficient (m^2/s)
$D_{ax,\ min}$	minimal axial dispersion coefficient (m^2/s)
ε,opt	optimal porosity
x	direction of flow through the column (m)
Pe	Peclet number, dimensionless, $\frac{dpU}{Dax}$
H	height of the particle bed (m)
Q_v	flow rate (m^3/s)
T	temperature (K)
x_1	dimensionless variable corresponding to the flow rate (Q_v)
x_2	dimensionless variable corresponding to the temperature (T)
y	the responses predicted by the model, dimensionless
bj	coefficient corresponding to the effect of the parameter xj in the regression equation
e	residue (error)
Re	Reynolds number, dimensionless, $\frac{\rho dpU}{\mu}$
D_c	column diameter (m)
d_p	particle mean diameter (m)
L_B	bed length (m)
m_p	total mass of particles (kg)
A	cross section of the column (m^2)
ρ_p	density of the particles (kg/m^3)
ρ	density of fluid (kg/m^3)
P	probability
R^2	coefficient of determination
U_t	particle terminal-fall velocity (m/s)
R_t	terminal Reynolds number, dimensionless, $\frac{\rho dpU_t}{\mu}$
n	the Richardson-Zaki exponent
µ	viscosity of fluid (kg/m s)
Fr	Froude number, dimensionless, $\frac{U^2}{gd_p}$
M_v	density number, dimensionless, $\frac{(\rho_p-\rho)}{\rho}$
Ga	Galilei number, dimensionless, $\frac{d_p^3 g\rho^2}{\mu^2}$
e	energy dissipation rate per unit mass of liquid (m^2/s^3)
v	kinematic viscosity of liquid (m^2/s)
Sc	Schmidt number
D_{AB}	effective diffusion coefficient (m^2/s)
Pe_{MP}	mass particle Peclet number, dimensionless
Re_{mf}	minimum fluidization Reynolds number, dimensionless, $\frac{\rho dpU_{mf}}{\mu}$

measurement, and simple linear models based on the response surface methodology (RSM).

Residence time distribution studies have proved indispensable in chemical reaction engineering [12]. A tracer is injected at a location in the bed, and its concentration is monitored at a point downstream. The concentration distribution data is then processed to extract quantitative information about the dispersion characteristics of the bed [4,13].

Design of experiments (DOE) is a powerful data mining tool. It offers a simulation black box with potential applications in various research areas and it can be implemented to describe developed model behavior in less time and at lower processing cost than was previously possible [1]. The response surface methodology was used to estimate the relationship between a set of controllable experimental factors and observed results. In this study a central composite rotatable design (CCRD) was used to determine interaction, linear and quadratic effects of the independent variables affecting the response of the LSFB. This design was applied using Minitab statistical software 16.

The hydrodynamic study in fluidized beds by the RTD tracer method was extensively undertaken in terms of flow rate, particle size, and particle diameter or temperature [4,6,8,14–18]. The innovation of our work is mainly focused on combining the experimental design (RSM) and the RTD tracer method for our fluidized bed adsorber which has particular characteristics (L/D = 26 cm, dp = 0.18 cm). Compared to conventional hydrodynamic studies in fluidized bed columns, the particularity of our study is also related to the use of porous particles (activated carbon). NaCl was chosen as tracer after having made preliminary experiments in a batch reactor which involved measuring the variation in the concentration of the salt in solution in contact with a suspension of the activated carbon. The result of these tests confirms that the salt remains approximately inert with respect to our adsorbent.

The objective of this hydrodynamic study is to find statistically reliable relationships for axial dispersion and porosity as a function of operating conditions such as temperature and flow rate of the solution. The regression equations of the models are chosen in a linear form to facilitate their implementation in a program for calculating the performance of the adsorption columns.

The results of tracer pulse experiments performed in the fluidized bed system were exploited using the model of axial dispersion. The effects of flow rate and temperature of the solution on the hydrodynamics of an activated carbon bed were studied using two responses: the axial dispersion coefficient and the porosity of the bed.

2. Experimental

2.1. Materials

The granular activated carbon used in our experiments was an industrial charcoal UP07, supplied by the National Fats Company in Bejaia. This charcoal consisting of particles of different diameters was sieved and the fraction with particle diameters between 1.6 and 2 mm was selected for this study. Before making the fluidized bed, the activated carbon was first washed with distilled water to remove fines, dried at 383 K in a vacuum oven overnight and stored in a dessicator. The main characteristics of the charcoal are given in Table 1.

The NaCl used as a tracer for the pulse experiments was assayed by conductivity; the quantity of salt injected was 50 mL at a concentration of 100 g/L.

Table 1
Characteristics of particles forming the fluidized beds.

Characteristic of the activated carbon particles	Mean
Particle diameter (d_p, cm)	0.18
Specific surface area (A_s, cm^2/g)	7.57×10^6
Particle density (ρ_p, g/cm^3)	1.81
Pore radius (r_p, Å)	11.5
Particle porosity (ε_p)	0.255