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Chemical Engineering Journal 114 (2005) 1–7

Chemical Engineering Journal

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Liquid mixing and gas–liquid mass transfer in a three-phase inverse turbulent bed reactor

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Received 19 October 2004; received in revised form 4 July 2005; accepted 24 August 2005

Abstract

In this research work, hydrodynamic characteristics and gas–liquid mass transfer in a laboratory scale inverse turbulent bed reactor were studied. In order to characterize internal flow in the reactor, the residence time distribution (RTD) was obtained by the stimulus-response technique using potassium chloride as a tracer. Different solid hold-up (0–0.37) and air superficial velocity (2.7–6.5 mm s^{-1}) values were assayed in RTD experiments. The parameters that characterize the RTD curve, mean residence time and variance were independent of the solid hold-up, thus the solid particle concentration did not influence liquid mixing in the reactor. The hydrodynamic of the inverse turbulent bed was well represented by a model that considers the reactor as two-mixed tank of different volumes in series. The value of the volumetric gas–liquid mass transfer coefficient ($k_L a$) was independent of the solid hold-up. This result enhances a previously suggested hypothesis, which considers that the solid and liquid form a pseudo-fluid in the inverse turbulent bed reactor.

Keywords: Fluidization; Mass transfer; Mixing; Moving bed; Multiphase reactors; Modeling

1. Introduction

Biofilm reactors with microorganisms naturally attached on small suspended particles, e.g. fluidized bed, airlift reactor, inverse fluidized bed and circulating bed reactor [1–5] have been used for organic matter and ammonia removal from domestic and industrial wastewaters. Compared to the activated sludge system, higher biomass concentration can be obtained in biofilm reactor, and higher volumetric loading rate of pollutants can be treated at the required removal efficiency. When microorganisms required for biological transformation of certain pollutants in a wastewater have low growth rates and yields, such as the nitrifying microorganisms (ammonia-oxidizing bacteria, $\mu_{max} = 0.014$–$0.092\,h^{-1}$ and nitrite-oxidizing bacteria, $\mu_{max} = 0.006$–$0.06\,h^{-1}$) or the methanogenic (aceticlastic methanogens, $\mu_{max} = 0.003$–$0.014\,h^{-1}$) [6], the use of biofilm reactors offers several advantages for treatment of this type of wastewater [7].

The inverse turbulent bed (ITB) is a three-phase reactor recently applied for anaerobic treatment of winery wastewater [8]. In this reactor, bed expansion was induced by injection of biogas (CH_4 and CO_2) at the bottom of the reactor. The ITB can also be used for aerobic wastewater treatment by injecting air instead of biogas. As a result, nitrification or aerobic matter removal can be carried out in this reactor [9].

Liquid recycling is not necessary to induce bed expansion in the ITB, and this is an advantage compared to the operation of two-phase fluidized bed and two-phase inverse fluidized bed reactors. Superficial air velocity in ITB is lower than in other biofilm reactors, i.e. airlift and three-phase fluidized bed reactors, since particles of low density and small diameter are used as support. This decreases the energy cost for support expansion.

Hydrodynamic studies in ITB have been carried out in reactor filled with particles of different densities ranging from 106 to 934 kg m^{-3} [10–12]. These works focused mainly on establishing bed expansion characteristics at different gas and liquid superficial velocities. However, hydrodynamic studies aiming liquid mixing model determination in ITB reactors have received less attention. Although, flow models are scale dependent, availability of hydrodynamic model for laboratory scale reactors may

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doi:10.1016/j.cej.2005.08.009

Nomenclature

A	cross-sectional area of the column (m^2)
C_i	tracer concentration ($mg\,l^{-1}$)
C_o	oxygen concentration in the liquid ($mg\,l^{-1}$)
C_o^*	saturation oxygen concentration ($mg\,l^{-1}$)
C_p	oxygen concentration probe response ($mg\,l^{-1}$)
d_p	mean support diameter (mm)
D	distance between particles (mm)
E,E'	dimensionless residence time distribution function
H	bed height (m)
k_La	volumetric air liquid mass transfer coefficient (s^{-1})
M	mass of solid (kg)
Pe	Peclet number dimensionless
t_i	time (s)
U_g	superficial air velocity ($m\,s^{-1}$)
U_l	superficial liquid velocity ($m\,s^{-1}$)
V_{R1}	volume of the first reactor (l)
V_{R2}	volume of the second reactor (l)

Greek letters

ε_s	solid hold-up of the bed
ε_{s0}	solid hold-up of the fixed bed
ρ	solid density ($kg\,m^{-3}$)
μ_{max}	maximum specific growth rate (h^{-1})
τ	probe constant (s^{-1})
θ,θ'	dimensionless time

improved model predictions from studies carried out in this type of reactors.

Mass transfer characteristics of ITB reactor have received less attention than its hydrodynamic behavior. In other three-phase reactors, the air–liquid mass transfer rate has been measured [13–15], but results about the influence of solid hold-up on the gas–liquid mass transfer coefficient are not conclusive.

The objectives of this work were to investigate the flow pattern and the gas–liquid mass transfer capacity of a laboratory-scale ITB reactor. Residence time distribution and volumetric gas–liquid mass transfer coefficient in the reactor was measured at different solid hold-up and superficial air velocity. Based on the obtained data, a flow model for the ITB is proposed, relevant mixing characteristics of this reactor are discussed and gas–liquid mass transfer characteristics are compared with other biofilm reactors.

2. Materials and methods

The schematic diagram of the experimental set-up is shown in Fig. 1. The reactor consisted of a PVC column of 0.054 m internal diameter. The height of the fluidization section between the air injection point and the liquid level was 0.55 m. The solid support was extendosphere (PQ Hollows Spheres Ltd) of 0.150 mm in diameter and 690 $kg\,m^{-3}$ in density. The main component of this solid material is SiO_2 (55–60%). The fixed bed solid hold-up ε_{s0} was 0.62.

Flow model determination was carried out using data obtained from stimulus-response experiments [16]. The tracer used was a solution of KCl, 3 M. In each experiment, 1 ml of this solution was injected into the water stream entering the reactor at a flow rate of 1.5 $L\,h^{-1}$. Conductivity values were continuously

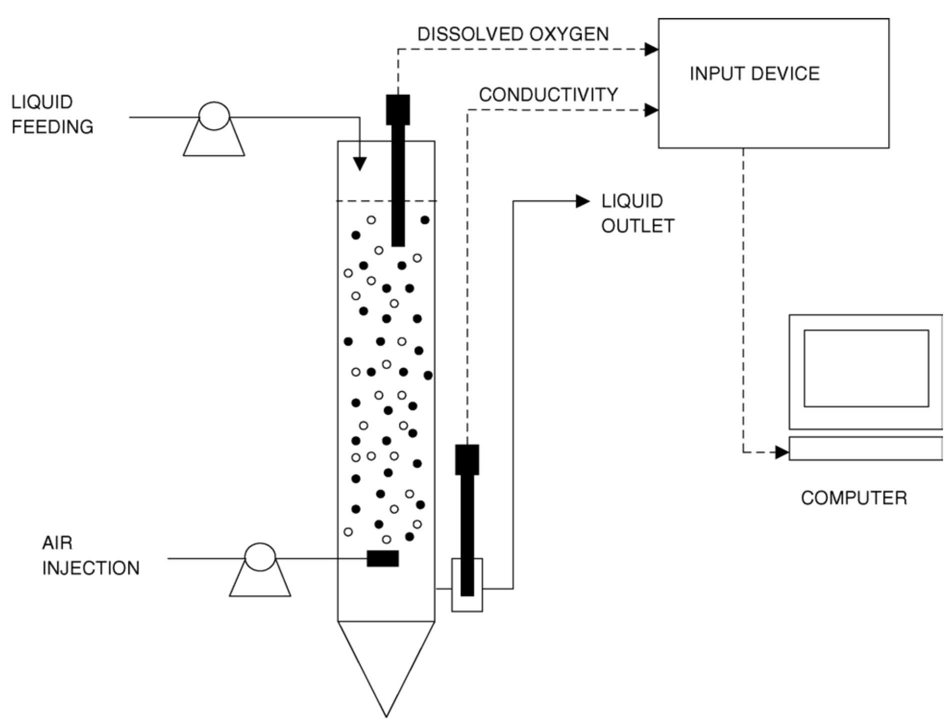

Fig. 1. Inverse turbulent bed reactor with conductivity and dissolved oxygen on-line measuring device.