Contents lists available at ScienceDirect

Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd

Hydrodynamic study of a horizontal-flow anaerobic immobilized biomass reactor: Radial porosity and velocity distribution of wastewater flow

Betânia Hoss Lunelli, Guilherme Henrique Duarte de Oliveira, Marcelo Zaiat*

Biological Processes Laboratory, Center for Research, Development and Innovation in Environmental Engineering, São Carlos School of Engineering, University of São Paulo, Engenharia Ambiental – Bloco 4F, Av. João Dagnone, 1100, Santa Angelina, 13563-120 São Carlos, SP, Brazil

ARTICLE INFO

Article history:
Received 3 April 2015
Received in revised form 12 December 2015
Accepted 29 January 2016
Available online 6 February 2016

Keywords:
Modeling
Horizontal anaerobic reactor
Packed bed
Porosity
Brinkman equation
Wastewater

ABSTRACT

In this work, a mathematical model based on an extended Brinkman equation was used to evaluate the porosity and velocity distribution along the radial direction of a horizontal-flow anaerobic immobilized biomass (HAIB) reactor; the model considers the fluid flow within the bed. The study was performed using two different particle geometries and three tube-to-particle diameter ratios (D/d_p) to understand the effects of the shape and particle size on the flow velocity distribution. The results show that the oscillation in the velocity profile is dependent on the D/d_p ratio, particle shape and bed porosity. Better results were obtained with irregular shapes, such as hollow cylindrical rings, and a D/d_p ratio of 10. The model adapted for this study may be a suitable tool for the design and optimization of horizontal-flow anaerobic immobilized biomass reactors used in wastewater treatment processes.

1. Introduction

Currently, environmental problems have become more frequent and increasingly critical, primarily because of uncontrolled population growth and increased industrial activities. This new scenario has increased the interest in the development of new and efficient technologies applied in wastewater treatment systems. Among the existing technologies, anaerobic treatment processes have been gaining attention because of their efficiency and low energy consumption. The horizontal-flow anaerobic immobilized biomass (HAIB) reactor has been widely used for different wastewater treatment processes because of its high performance and formation of a large microbial mass, obtaining a better contact between biomass and wastewater and thereby reducing the hydraulic retention time for high organic loads (Amorim et al., 2005; Zaiat et al., 1994). The wastewater treatment processes that use a HAIB include paper industry wastewater treatment (Foresti et al., 1995), domestic sewage treatment (Zaiat et al., 2000a), phenol degradation (Bolaños et al., 2001), degradation of benzene, toluene, ethylbenzene and xylenes present in contaminated water (De Nardi et al., 2002), removal of organic matter and nitrogen from domestic sewage (Vieira et al., 2003), ethanol and toluene removal (Cattony et al., 2005), formaldehyde degradation (Oliveira et al., 2004), hydrogen and organic acid production (Leite et al., 2008), pentachlorophenol dechlorination (Damianovic et al., 2009), and the treatment of dairy wastewater with a high fat content (Cammarota et al., 2013).

Packed bed reactors have several applications in the chemical industry and have the advantages of simplicity, low capital

* *Corresponding author*. Tel.: +55 1633738358.
E-mail address: belunelli@gmail.com (B.H. Lunelli).
http://dx.doi.org/10.1016/j.cherd.2016.01.034

Nomenclature

D	tube diameter (m)
D_{ef}	effective diffusivity ($m^2\,h^{-1}$)
d_{in}	inner diameter (m)
d_{out}	outer diameter (m)
d_p	particle diameter (m)
d_{eq}	equivalent particle diameter (m)
F	inertia factor
K	permeability factor
L	tube length (m)
P	pressure (Pa)
R	tube radius (m)
r	radial position (m)
R_{ep}	particle Reynolds number
v_s	superficial velocity (m/s)
$\bar{v}_s$	average superficial velocity (m/s)
z	axial position (m)
ε	porosity
μ	fluid dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
μ_{ef}	effective viscosity ($kg\,m^{-1}\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)

Subscripts

c	center of the bed
ef	effective
eq	equivalent
p	particle
s	superficial

and operating costs and ease of operation, particularly with respect to the handling of the catalyst (Gupta and Bansal, 2010). However, the design of these reactors is often performed with simplifications, e.g., with the assumption of plug flow and an equally distributed porosity and velocity over the entire packed bed (Eppinger et al., 2011). The plug flow assumption may be a serious deficiency in the models and is unsatisfactory under certain combinations of packing size, tube size, and flow rate (Schwartz and Smith, 1953). Packed bed reactors exhibit important radial variations in void fraction; therefore, the flow velocity cannot be uniform in the radial direction (Delmas and Froment, 1988). The assumption of homogeneous fluid velocity and void fraction distributions throughout the bed cannot be true near the container wall, at which the solid particles must arrange themselves differently. The void fraction and thus the fluid velocity will tend to be greater near the wall than in the bulk region (Di Felice and Gibilaro, 2004).

The fluid flow through the packed bed is characterized by a channeling effect at the wall (Bey and Eigenberger, 1997). Several authors studied the radial porosity variation of the bed over the reactor performance (Benenati and Brosilow, 1962; Bey and Eigenberger, 1997, 2001; Chandrasekhara and Vortmeyer, 1979; Daszkowski and Eigenberger, 1992; Delmas and Froment, 1988; Goodling et al., 1983; Mueller, 1990, 1992; Papageorgiou and Froment, 1995; Schwartz and Smith, 1953). The variation in the voids of packed beds in the near-wall region has been studied extensively because of its influence on the pressure drop, bed permeability, fluid hold-up, linear velocity, and residence time distribution (Klerk, 2003). Besides this, when detailed models, which incorporate radial variations in the bed porosity are based on the assumption of uniform plug-flow within the bed, significant differences may appears since this assumption is not strictly valid (McGreavy et al., 1986; Daszkowski and Eigenberger, 1992).

The non-uniform bed porosity generates a radial oscillatory behavior in the velocity profile within the reactor. The amplitude of these oscillations varies according to the geometric characteristics of the bed, particles and packing form, starting from small oscillations near the core of the bed to a peak with the highest amplitude (close to 1.0) in the vicinity of the reactor wall. These oscillations occur mainly because of the contact with the reactor wall, which presents a more regular organization of particles and thus the porosity. Thus, the bed presents a high porosity and permeability near the wall and a less porous region in the core of the reactor (Cybulski et al., 1997). This porosity variation can be evaluated by modeling the void fraction distribution in the bed or the location of the particle. However, the quantitative description of the void fraction distribution of a random bed is not practical (Govindarao and Froment, 1986). In order to overcome this drawback, many literature works have estimated the radial variation of fluid flow just after the particles bed outlet (Schwartz and Smith, 1953; Dorweiler and Fahien, 1959; McGreavy et al., 1986). However, this may not adequately represent what occurs inside the packed bed, mainly due to the transition from a velocity profile inside the bed to a fully developed flow profile in the empty portion of the reactor tube. Moreover, the predictions of the performance are sensitive to any variations in flow distribution, i.e., measured values of mean voidage and velocity, are dependent on the tube to particle diameter ratio (McGreavy et al., 1986).

This study adapted a mathematical model based on an extension of the Brinkman equation, originally proposed by Bey and Eigenberger (1997), to obtain information on the porosity and radial velocity distribution inside the bed of the HAIB reactor used in wastewater treatment.

2. Methodology

The adapted mathematical model was based on an extended Brinkman equation proposed by Vortmeyer and Schuster (1983). The model is one-dimensional and considers in its formulation the porosity and velocity distribution along the radial direction of the bed. The correlations proposed by Bey and Eigenberger (1997) and Bey and Eigenberger (2001) were used to calculate the bed porosity. The study has been performed using two different particle geometries (cylinders and rings) and three tube-to-particle diameter ratios (D/d_p). The aim of this study was to understand the effects of the shape and particle size on the porosity and flow velocity distribution. The particles in the packing are comprised of the identical material but with different geometries. A spatial distribution of equally sized particles in a random assemblage and D/d_p values varying from 5 to 15 were considered in the simulation. It is important to mention that the obtained radial porosity and velocity profiles describes what occurs in an infinitesimal slice ($z + dz$) of the reactor bed; thus it was admitted that these radial profiles are constant along the axial distance of the bed which are in agreement with the previous work of Daszkowski and Eigenberger (1992). The finite volume method (FVM) was used to discretize the model equations, and simulation software (implemented in FORTRAN) was developed to solve the model. The equations were discretized in the radial direction and integrated over the control volume. The fluid