Chemical Engineering Science 134 (2015) 129–137

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Influence of fluid-mechanical parameters on volumetric mass transfer coefficient in a spout–fluid bed with a draft tube

Milena Knežević, Dragan Povrenović *

University of Belgrade, Faculty of Technology and Metallurgy, Karnegijeva 4, 11000 Belgrade, Serbia

HIGHLIGHTS

- Increase of water and air flow rate in the annulus increase leakage to the draft tube.
- Reduction of particle circulation due to the presence of air in the annulus.
- Increase of the particle diameter contributes to better fragmentation of bubbles.
- Particle circulation improves oxygen mass transfer in spout–fluid bed with draft tube.

ARTICLE INFO

Article history:
Received 4 January 2015
Received in revised form
30 March 2015
Accepted 17 April 2015
Available online 29 April 2015

Keywords:
Three-phase system
Spout–fluid bed
Draft tube
Volumetric mass transfer coefficient
Particle circulation

ABSTRACT

In order to apply a spout–fluid bed reactor with a draft tube for the nitrification process of wastewater treatment, the influence of fluid-mechanical parameters on volumetric mass transfer coefficient was analyzed. Experiments were carried out in a 1000 mm high 2D semi-column with a draft tube. The draft tube had a cross section of 50×50 mm^2 and the annular region of the reactor had a cross section of 50×140 mm^2. The work described in this paper reports the influence of several fluid-mechanical parameters including liquid and gas flow rates, particle diameters and particle circulation on volumetric mass transfer coefficient, $k_L a$. The liquid flow ranged from 3.5–4.5 m^3/h and gas flow ranged from 300 to 800 L/h. The particles used were glass spheres with diameters of 3, 4, 5 and 6 mm. Tap water and air were used as the liquid and gas phase, respectively. The experimental results have shown that particle circulation through the draft tube contributes to $k_L a$ increase as well as the increase in the particle diameter, the gas and liquid flow rates.

1. Introduction

The excess of nitrogen compounds in water-receptors is often the result of insufficient or inadequate wastewater treatment. The negative influence these compounds present on the environment reflects in eutrophication of natural water resources, toxicity to aquatic organisms, and dissolved oxygen consumption (He et al. 2009; Zhang et al. 2011). Removing nitrogen compounds from wastewater is a necessary measurement for prevention of environmental pollution. Biological removing based on nitrification–denitrification process is considered to be the most cost-effective treatment, so consequently it is the most widely used one. Biofilm reactors are often used for this kind of treatment since they offer a higher concentration of microorganisms per unit volume compared to suspended growth reactors (Mendoza-Espinosa and Stephenson, 1999).

Numerous studies of different biofilm reactors for nitrogen removal include fixed-film reactors (Hamoda et al., 1996; Villaverde et al., 1997), fluid-bed reactors (Aslan and Dahab, 2008; Andalib et al., 2011; Wang et al., 2012), airlift reactors (Heijnen et al., 1993; Nogueira et al., 2002). However, in the available literature, no application of spout or spout–fluid bed for the nitrification process was found.

The advantages of a spout system with a draft tube over a regular fluidized bed were also noticed in biomass pyrolysis process and were mostly reflected in better mass and heat transfer (Fernandez-Akarregi et al., 2013; Makibar et al., 2011; Zhang et al., 2009). It was also noted that it was possible to use bigger and coarser particles. Spout bed with a draft tube systems can also be applied in coating processes (Ijichi et al., 2000; Publio and Oliveira, 2004), phenol degradation (Safont et al., 2012) and a denitification process (Keshava et al., 2014).

* Corresponding author. Tel.: +381 113303790.
E-mail address: povrenovic@tmf.bg.ac.rs (D. Povrenović).

http://dx.doi.org/10.1016/j.ces.2015.04.030
0009-2509/

Two-phase spout–fluid bed systems come in two versions, as gas-particle or liquid-particle systems. Intense particle–fluid contact is typical for both versions, so numerous successful applications have already been reported (Aguado et al., 2005; Plawsky et al., 2010).

The three-phase variation of the aforementioned system also has two versions. The aerated liquid-particle system one has not been thoroughly examined yet, but it is considered that it could be successfully applied in certain bioprocesses (Merchuk and Siegel, 1988) while the gas-particle system with dispersed liquid has found its application in various drying processes (Altzibar et al., 2008; Arsenijević et al., 2002; Berghel and Renström, 2014; Povrenović et al., 1992). Previous examinations of these systems (Grbavčić et al., 1992; Littman et al., 2009; Povrenović, 1996) have shown that the spout–fluid bed reactor with a draft tube has several advantages over the reactor with simple spout or spout–fluid bed reactors.

Due to its flexibility and intensive fluid–particle contact, the three-phase spout–fluid bed reactor with a draft tube can be applied in aerobic processes of wastewater treatment. The limiting factor in these processes is the oxygen mass transfer from the gaseous to the liquid phase as a certain concentration of dissolved oxygen is a necessary precondition for the development of the desired nitrifying bacteria. Considering that oxygen is poorly soluble in water, the absence of dissolved oxygen, as the only form available to the microorganisms, is one of the major causes of process failure. An additional problem is the development of heterotrophic bacteria and the competition between them and autotrophic nitrifying bacteria for oxygen as an electron donor (Morgenroth and Wilderer, 2000; Okabe et al., 1995; Rittmann and Manem, 1992; Rittmann et al., 2002), as well as for the space in biofilms (Ohashi et al., 1995; Tijhuis et al., 1994; Van Benthum et al., 1997). The efficiency of the oxygen mass transfer from the gas phase to the liquid phase is described through values of volumetric mass transfer coefficient k_La (Benyhaia et al., 1996).

Numerous investigations of various three-phase systems with fluidized beds, biofilters, airlift reactors etc. have been performed, examining the effects of gas and liquid velocity, type of gas distributor, characteristics of the solid phase in the system and liquid viscosity on volumetric mass transfer coefficient (Chen and Leu, 2001; Freitas and Teixeira, 2001; Hamdad et al., 2007; Maldonado et al., 2008; Miura et al., 2012).

Particles of different diameters and densities, such as glass, polyethylene or silicon-dioxide ones were used in different experiments as solid phase, as well as nickel powders and Ca-alginate, (Bukur et al. 1990; Chen and Leu, 2001; Freitas and Teixeira, 2001; Hamdad et al. 2007; Herskowitz and Merchuk, 1986; Lee et al., 1993; Schumpe et al., 1989; Sivasubramanian, 2010; Vandu and Krishna, 2004; Yang et al., 2001).

Tap water, ethanol, paraffin and tellus oil, CMC and tetradecan are some of the substances used as the liquid phase (Freitas and Teixeira, 2001; Hamdad et al. 2007; Vandu and Krishna, 2004).

Available literature provides a great deal of contradictory results and conclusions regarding the effects of process parameters on oxygen mass transfer in three-phase systems. Various experiments have proved that volumetric mass transfer coefficient depends on distribution and size of the bubbles in the system (Camarasa et al., 1999) and that bubble behavior, mostly affected by the dispersion system, has a great influence on both mass transfer and system's fluid-dynamics (Deckwer and Schumpe, 1993). It is also experimentaly established that the specific influence of particular process parameters on bubble formation and mass transfer relies on system's fluid-mechanics.

This paper describes experimental examination of fluid-mechanical parameters in the spout–fluid bed reactor with a draft tube and their impact on oxygen mass transfer in the system. The investigation was conducted in order to determine the system's suitability for usage in nitrification processes of wastewater treatment.

2. Experimental system

The experiments were conducted in a 1000 mm high 2D semi-column made of Plexiglas with a cross section of 200×50 mm^2. The draft tube was 400 mm long and had a 50×50 mm^2 cross section. The distance between the inlet flow distributor and the draft tube was 40 mm. A schematic diagram of the experimental system is shown in Fig. 1.

Water was introduced to the system through a spouting inlet nozzle (50×50 mm^2) and through the annulus inlet nozzle over a fixed bed distributor made out of glass particles having 6 mm in diameter. In order to prevent dead zone emersion, the bottom of the annular part of the column was set at the angle of 30°. Annular and spout flows were introduced by two separate pumps of 350 W, with maximum work flow rate of 7.5 m^3/h and the pressure of 1 bar, and for gas introducing a compressor was used. The gas was introduced on the bottom of the annulus over a tube distributor with 1 mm diameter orifices. The fluid flows were measured by rotameters.

Liquid flow rate through the draft tube was set on 2.5 m^3/h and the flow rate through the annulus had values of 0.5, 1.0, 1.5, 2.0 m^3/h. These flow rates were used with each particle diameter in order to examine the particle diameter influence on oxygen mass transfer. Liquid was recirculated through the column. Air flow rate varied from 300 to 800 L/h.

The dependence of particle circulation through the draft tube from fluid flow was examined by using a specially designed catcher that would not disturb the fluid or particle flow pattern in any way. It had negligible resistance to free flow of water and particles. The catcher was set on the surface of annulus by a long handle. This handle enabled quick descending and withdrawal of the catcher in a specific moment of time. The particle mass flow rate was calculated from the mass of particles caught in the catcher for a certain period of time.

Experiments were performed using tap water at room temperature. Dissolved oxygen concentration in the water was reduced to concentration below 1 mg/L by sparging with nitrogen through the gas distributor. After the system was depleted from oxygen, the air was introduced to the system until the concentration of the dissolved oxygen reached the 95% of the saturation concentration for the given temperature. Oximeter WTW Oxi 340i was used to measure dissolved oxygen concentration variation in the column with time. The oximeter probe was set on the top of the column. A dynamic oxygen desorption method, using air to N_2 substitution, was used to measure the volumetric gas-liquid mass transfer coefficient k_La (Letzel et al., 1999; Vandu and Krishna, 2004) with assumption that liquid phase was perfectly mixed. This assumption was tested by injecting methyl violet in both the draft tube region and the annular region and it was confirmed by the visual mixing of these currents in the area where the oxi-probe was set. This assumption was also confirmed by obtaining similar values of dissolved oxygen concentration at the top and at the bottom of the column.

$$\frac{dC}{dt} = k_La(C^* - C_t) \tag{1}$$

In Eq. (1), C^* denotes the oxygen saturation concentration and C_t is the dissolved oxygen concentration for a specific moment in time. After integration of Eq. (1), presuming that C_0 is the dissolved oxygen concentration for $t = 0$:

$$\ln(C^* - C_t) = \ln(C^* - C_0) - k_La \cdot t \tag{2}$$