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Liquid hold-up and gas–liquid mass transfer in an alumina open-cell foam

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HIGHLIGHTS

- Hydrodynamic features of a ceramic open cell foam are determined.
- Experiments performed at trickle-flow regime for air–water system.
- Determined parameters: dynamic and static hold-ups, L–G mass transfer coefficient.
- Parameters correlated as a function of dimensionless numbers.

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ABSTRACT

Open-cell foams are solid structures formed by an intricate network of macroporous interconnected channels. The high porosity and tortuosity of the channels results in high external surface area, so open-cell foams are very efficient for promoting phase contact, e.g. in gas–liquid packed-bed reactors. In addition, the tortuous path of the channels breaks up the flow and enhances mass transfer with respect to other structured beds, such as honeycomb monoliths, and pressure drop is comparatively low.

The liquid hold-up (system water–air), and the mass transfer coefficient (oxygen from water to nitrogen), have been measured for a ceramic foam, specifically a 20 ppi alumina foam bed of 50 mm diameter and 100 mm length (average pore diameter 1.25 mm and strut diameter 0.42 mm), for co-current down flow. Gas and liquid flow rates have been varied in the range corresponding to 0–8.5 $\cdot$ 10^{-2} and 0–3.2 $\cdot$ 10^{-3} m/s superficial velocities, respectively. At these conditions, the bed operates at trickle flow regime. The dynamic liquid hold-up and the mass transfer coefficient have been correlated as a function of relevant dimensionless numbers.

1. Introduction

Conventional particulate packed beds, consisting of randomly stacked particles, are commonly used in chemical processes. They provide medium surface area and high turbulence, but with the drawback of high pressure drop. Honeycomb monoliths are an alternative, because of their low pressure drop. However, the low turbulence in the straight channels of the monolith, derived from a flow pattern close to laminar, results in low gas to liquid mass transfer rates (Cybulski and Moulijn, 2005; Roy et al., 2004).

Open-cell foams are macroporous reticulated 3D structures that contain interconnected channels of high porosity and tortuosity. These structures are made of metal (aluminium, steel), ceramics (alumina, silicon carbide, etc.), or carbon materials with different geometries and physical properties.

Open-cell foams are currently used in the process industry as filtration media, particularly when exigent operating conditions are required (e.g. high temperature and pressure) (Buciuman and Kraushaar-Czarnetzki, 2003; Twigg and Richardson, 2007). These materials are also used in compact heat exchanger, due to the improved heat transfer rate accomplished with its high surface area (Hutter et al., 2011; Madani et al., 2013; Tadrist et al., 2004; Topin et al., 2006).

In the last years, the interest on foams as structured beds for chemical reactors has increased, as the high surface area and tortuosity of the foams contribute to enhance interphase mass transfer with respect to honeycomb monoliths, while pressure drop is maintained very low.

Foams have been proposed as catalyst support in different processes, especially for gaseous reactants. In the field of the treatment of gaseous effluents, catalytic foams have been tested

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for the oxidation of CO and hydrocarbons, and the reduction of nitrogen oxides (Marín et al., 2012; Pestryakov et al., 1996; Thompson et al., 2013). Ceramic foam beds have also been considered for methane reforming, because ceramic foams can operate at high temperature (Faure et al., 2011; Li et al., 2013; Palma et al., 2013).

Studies regarding foams in multiphase reactions are scarcer. In this case, the reactants are in two (or more) fluid phases, e.g. gas and liquid, and the role of the bed is to create surface area and turbulence for high phase contact. Foams are a good alternative to particulate beds or honeycomb monoliths for this purpose. The foam can also act as support for heterogeneous catalysts. Examples of reactions of interest at industrial scale are oxidations and hydrogenations of different types (Cerri et al., 2000; Chin et al., 2006; Fino et al., 2005; Jhalani and Schmidt, 2005; Leon et al., 2012; Panuccio et al., 2006; Sirijaruphan et al., 2005; Tschentscher et al., 2011; Van Setten et al., 2003; Williams and Schmidt, 2006; Wörner et al., 2003).

The morphology of foams has been extensively studied in the last years with the aim of modelling their geometrical properties and optimizing the foam manufacturing process (Buciuman and Kraushaar-Czarnetzki, 2003; Fourie and Du Plessis, 2002; Richardson et al., 2000). It has been found that the use of a tetrakaidecahedron cell to describe the foam geometry gives the best results for this purpose.

Characterization of hydrodynamics and mass transfer is very important for the design of mass transfer operations and multiphase chemical reactors. There are several published studies on hydrodynamics and mass transfer for multiphase systems in foams. Schouten and cols. have measured liquid hold-up and mass transfer for gas and liquid (air–water) flowing through a 2D aluminium foam bed in counter-current, co-current upflow and co-current downflow (Stemmet et al., 2008, 2005, 2007, 2006). They have also characterized mass transfer in a reticulated vitreous foam covered with Pd on carbon nanofiber (Wenmakers et al., 2010), and in a rotating foam reactor (Tschentscher et al., 2010). Tourvieille et al. (2015) have studied mass transfer in a milli-channel filled with metal foam under a gas–liquid pulsing regime. The same authors proposed a correlation, based on the Reynolds number and the Lockhart–Martinelli parameter, in order to predict the liquid holdup under the same flow regime (Tourvieille et al., 2015).

Gas–liquid packed beds are often operated with co-current downflow, as this disposition avoids flooding even for high throughputs, and the pressure drop is lower than in upflow. Co-current downflow packed beds, commonly called trickle beds, present different hydrodynamic regimes, depending on the gas and liquid superficial velocities. These regimes (e.g. tricking, pulsed, spray and bubbling) have been studied by different authors for particulate beds (Duduković et al., 2002; Joubert and Nicol, 2013; Kan and Greenfield, 1978; Levec et al., 1986; Loudon et al., 2006; Saez et al., 1986; Van der Westhuizen et al., 2007). Trickle regime corresponds to low gas and liquid superficial velocities, and is characterized by gas being the continuous phase and liquid the dispersed phase. For foam beds, different authors observed the occurrence of trickle and pulse regimes depending on the superficial velocities and foam pore density (Mohammed et al., 2013; Zalucky et al., 2015).

Experimental data on liquid holdup and gas–liquid mass transfer coefficients for co-current downflow foam beds are very scarce in the literature. Stemmet et al. (2008) measured liquid holdup and gas–liquid mass transfer coefficients for the air–water system in a 2D bed (1 cm width) containing 10 and 40 ppi aluminium foams. They studied the effect of gas (0.1–0.8 m/s) and liquid superficial velocities (0.02 and 0.04 m/s), and viscosity and liquid surface tension, and got good fitting of their mass transfer results. Liquid holdup for the air–water system has been measured by (Edouard et al., 2008; Mohammed et al., 2013; Saber et al., 2012a, 2012b). Edouard et al. (2008) used silicon carbide foams in a 3.7 cm internal diameter bed and superficial velocities 0.077–0.22 m/s for air and 0.0016–0.0078 m/s for water, while Mohammed et al. (2013) used 10 and 20 ppi polyurethane foams in a 10 cm internal diameter bed at superficial velocities 0.1–0.4 m/s for air and 0.03–0.018 m/s for water. Mohammed et al. (2013) proposed a correlation for the total liquid hold-up as a function of the bed pressure drop. The same authors also studied the liquid–solid mass transfer (Mohammed et al., 2014) and the gas and liquid distribution along the column (Mohammed et al., 2015).

The experiments regarding gas–liquid mass transfer in foam beds at the trickle regime are scarcer. To the best of our knowledge, the only studies of Stemmet et al. (2008), using 10 and 40 ppi aluminium foams, and Grosse and Kind (2012), using a 10 ppi silicon carbide foam, have been published. There is then a need of information on hydrodynamics and especially mass transfer for gas–liquid flow through foam beds. Thus, a generalised correlation for gas–liquid mass transfer valid for foams of different geometries and materials would be very useful for the application of foams in industrial-scale reactors. The present work aims to increase the knowledge in this field. First, the alumina foam used is characterized, with an emphasis in the geometrical properties affecting mass transfer. Then, liquid hold-up (static and dynamic) is measured and correlated as a function of relevant dimensionless numbers. Finally, the gas–liquid transfer of oxygen in the foam bed is measured and fitted to a model.

2. Methodology

2.1. Materials and characterization

The reticulated foam structures used in the present work have been supplied by Fraunhofer IKTS in the form of cylindrical blocks of 50 mm diameter and 100 mm length. The foam blocks are made of Al_2O_3 (99.9% purity) with 20 ppi (pores per inch) pore density and 87.7% outer porosity. The surface of the reticulated foam was coated with porous γ-Al_2O_3; the fraction of the washcoating is 5.4 wt%.

The geometry of the reticulated foam structures has been characterized by means of a stereomicroscope (ZEISS) and nitrogen physisorption.

2.2. Foam fixed bed

The experimental device (Fig. 1) is formed by a flanged stainless steel tube of 50 mm diameter and 600 mm length. This tube can house one or two foam blocks (100 mm length each). The blocks are maintained in place with the help of a holey support. The bed is operated in co-current downflow. The liquid and gas streams are introduced in the tube through the top flange, which is connected to 1/4″ tubing. Inside the tube the liquid is distributed uniformly over the cross-sectional area with a holey tube acting as distributor. The gas flow rate is measured and controlled using a BRONKHORST mass flow regulator (maximum capacity 20 L/min, n.t.p.). The flow rate of liquid (water) is set by a piston pump (maximum capacity 1 L/min and discharge pressure 64 bar), which is fed from a feed tank. The discharge of the pump is connected to a filter and a pulse absorber to reduce the characteristic pulsing of piston pumps.

The bottom flange of the tube, connected to 1/4″ tubing, collects the gas and liquid that exit the foam bed to a phase separator. The liquid is recycled to the feed tank, while the gas is purged. A valve situated at the bottom of the tube allows the sampling of the liquid or, if required, the rapid discharge of the tube. The gas