Chemical Engineering Science 138 (2015) 118–127

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Qualitative and quantitative insights into multiphase flow in ceramic sponges using X-ray computed tomography

M. Wallenstein [a], N. Hafen [a], H. Heinzmann [a], S. Schug [b], W. Arlt [b], M. Kind [a], B. Dietrich [a,*]

[a] Institute of Thermal Process Engineering, Karlsruhe Institute of Technology (KIT), Kaiserstr. 12, 76131 Karlsruhe, Germany
[b] Institute of Separation Science & Technology, Friedrich-Alexander-University (FAU), Erlangen-Nürnberg, Egerlandstr. 3, 91058 Erlangen, Germany

HIGHLIGHTS

- X-ray computed tomography of multi-phase flow in ceramic sponges.
- Data processing routine for tomographic images.
- Phenomenological study about hydrodynamics in solid sponges.
- Local hold-up distribution inside a sponge packing.
- Effective gas-liquid interfacial area distribution.

ARTICLE INFO

Article history:
Received 24 March 2015
Received in revised form
28 July 2015
Accepted 8 August 2015
Available online 20 August 2015

Keywords:
Ceramic sponge
Open-celled foam
Liquid hold-up
Effective interfacial area
X-ray computed tomography

ABSTRACT

Hydrodynamic parameters of ceramic sponges as column internals are investigated using X-ray computed tomography. New qualitative and quantitative insights into multiphase flow in ceramic sponges are gained and a phenomenological study is performed to investigate the flow paths, the hold-up and the effective gas–liquid interfacial area of the trickling liquid inside the sponge packing. The formation of rivulets inside the sponge packing and a redistribution of the liquid at intersections are detected. Additionally, it was observed that the liquid paths inside the sponge start to fluctuate with a higher superficial liquid velocity. A specially designed data processing routine is developed. In the experiments, the test column is operated in co-current (downwards) as well as countercurrent mode with an air–water system. The results are compared to literature data to evaluate the accuracy. The sponges investigated are varied in material, porosity and cell density to obtain knowledge concerning dependencies. The cell density and the superficial liquid velocity turned out to be the significant parameters for the hold-up and the effective gas–liquid interfacial area.

1. Introduction

Many unit operations in the process industry involve the contacting of gases and liquids. For example gas–liquid reactions, e.g. hydrogenations, oxidations, halogenations, hydrodesulfurization, Fischer–Tropsch, but also physical purification processes such as distillation and gas stripping. These gas–liquid contacting processes are commonly performed in a packed column (Green, 2008).

In general, two different design principles of packings can be distinguished. On the one hand, there are random packings that consist of dumped beds of particles of different shapes made of ceramic, metal or plastic (e.g. spheres, Raschig rings, Berl saddles). On the other hand, there are structured packings which have homogenous bed structures, commonly consisting of vertically arranged corrugated metal sheets. An important factor that determines the contacting performance of packed columns is the gas–liquid interfacial area. Additionally, a low pressure drop of the gas and a uniform liquid distribution is very important for the good performance of a column (Mersmann et al., 2011). Ceramic sponges are an alternative to the two classic design principles.

Sponges are solid network structures with high porosities, typically of about 75–95%. They are bicontinuous with respect to the solid and fluid phase. They are also often called open-celled foams in literature. Fluid flowing through sponges has a comparably low pressure drop due to the high porosity (Dietrich et al., 2009b). Sponges can be manufactured from a large variety of materials, such as ceramics (e.g. alumina, mullite, oxidic-bonded silicon carbide: OBSiC, silicon infiltrated silicon carbide: SiSiC) and metals (e.g. aluminum, copper).

* Corresponding author. Tel.: +49 721 608 4 6830; fax: +49 721 608 4 3490.
E-mail address: dietrich@kit.edu (B. Dietrich).

http://dx.doi.org/10.1016/j.ces.2015.08.015

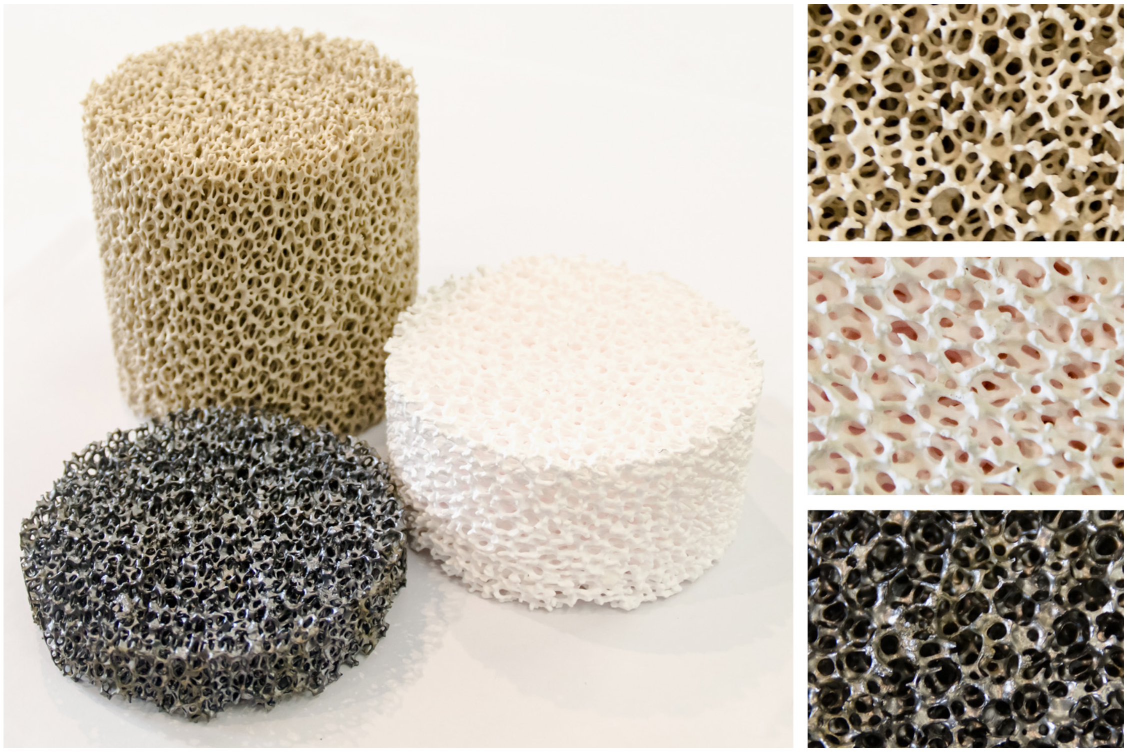

Fig. 1. Sponges investigated in this work; top: silicate, nominal porosity $\psi_N=91\%$, 10 ppi; right: alumina, $\psi_N=85\%$, 10 ppi; bottom: SiSiC, $\psi_N=88\%$, 10 ppi.

In order to design a column with sponges as internals, knowledge of its hydrodynamic properties is essential. Two of these hydrodynamic properties are the liquid hold-up and spatial distribution of the gas–liquid interfacial area. Many publications in the literature deal with these properties for conventional column internals, such as packed beds of spheres or structured packings. Classically, the liquid hold-up is determined by column draining or weighing methods and the effective gas–liquid interfacial area by mass transfer experiments (Kolev, 2006).

Some publications about hydrodynamics in sponges also exist. Schouten and colleagues (Stemmet et al., 2005, 2007, 2008; Wenmakers et al., 2010) investigated the liquid hold-up, the mass transfer coefficient, the flooding point and the axial liquid dispersion coefficient of metal sponges. The hold-up was measured by replacement of fluid by gas. The fluid systems used were varied to obtain different surface tensions and liquid viscosities.

Edouarda et al. (2008), Grosse and Kind (2011) and Lévêque et al. (2009) determined the hold-up in operational mode (dynamic hold-up) and the mass transfer coefficient with the water–air system in ceramic sponges. Additionally, it was found that flooding occurs at lower gas and liquid flow rates than in packed beds of conventional packings with the same porosity. In contrary to Stemmet et al. (2005) who postulated that inadequate contact between two adjacent solid sponge sections may induce flooding and is viewed as the largest contributing factor, Grosse and Kind (2011) postulated that flooding is induced due to the hindered draining at the very bottom of the sponge packing. Moreover, they postulated the formation of rivulets inside the packing. These behaviors were indicated, but not verified.

The restriction of the classic approaches is the fact that these methods only give an integral measured value. It is not possible to differentiate between various parts of the column, and these methods assume a uniform behavior in the column. The noninvasive measurement technique of X-ray computed tomography avoids this lack of information. This alternative measurement technique for packed beds has been the subject of research for nearly two decades. In this publication, the postulates of Grosse and Kind (2011) will be verified in a categorical manner with X-ray computed tomography.

A great effort in the field of X-ray tomography was made by the working group of Toye (Aferka et al., 2007, 2011; Toye et al., 1999, 2005; Viva et al., 2011). They investigated the liquid distribution in a trickle bed reactor, static and liquid hold-up in structured packings, and the interfacial area distribution. Furthermore, Green et al. (2007), Janzen et al. (2013), Mahr (2007) and Schmit and colleagues (Schmit and Eldridge, 2004; Schmit et al., 2004) investigated the hydrodynamic properties in structured packings using X-ray tomography. All authors compare a dry packing with a wet (with water flowthrough) packing to describe the hydrodynamics. This procedure requires at least two measurements of exactly the same cross-section in the packing.

However, there is only one publication that deals with the hydrodynamics of sponges and X-ray tomography as a measurement technique. Calvo et al. (2009) investigated structural parameters with X-ray microtomography and liquid hold-up data on 2D radiographic images, but did not look into 3D imagery.

The aim of this publication is to eliminate the deficit of spatial information regarding the hydrodynamics of ceramic sponges. A phenomenological exploration is performed to identify the liquid behavior in the trickle bed. The local differences of the hydrodynamic parameters are identified. Furthermore, a new analysis of the data given is presented without comparing dry and wet packings. The introduction of this new method was necessary due to the mechanical restrictions of the test facility which has an offset while approaching a measurement height. As an advantage, this new method leads to less measurement time and to a wide application spectrum compared to the standard methods used previously.

2. Experimental methods

2.1. Description of the sponge samples

The sponges investigated are made of alumina (Al_2O_3), SiSiC and silicate ceramics (see Fig. 1). The cells and the struts can be