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Gas–liquid distribution in tubular reactors with solid foam packings

Iman Mohammed [a,*], Tobias Bauer [a], Markus Schubert [b], Rüdiger Lange [a]

[a] *Technische Universität Dresden, Institute of Process Engineering and Environmental Technology, 01062 Dresden, Germany*
[b] *Helmholtz-Zentrum Dresden-Rossendorf, Bautzner Landstraße 400, 01328 Dresden, Germany*

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ABSTRACT

The axial evolution of gas–liquid distribution patterns in co-current downward gas–liquid two-phase flow through solid foam packings of different pore density expressed by pores per inch was experimentally studied. The experimental results are based on time-averaged capacitance measurements of the liquid phase with embedded wire-mesh sensors, positioned at different axial heights of the solid foam packing. The measurements revealed the spatial distribution of the liquid phase saturation, which was applied to quantify the degree of liquid maldistribution. Both the spray nozzle and the multipoint distributor provide rather uniform initial liquid distributions across the foam packings with low maldistribution factors at superficial liquid velocities above 0.009 m/s. However, the uniform initial irrigation deteriorates along the foam packing length, in particular for foams with low pore density. The gas flow rate does not significantly influence the liquid distribution. Furthermore, the foam's ability to radially spread the liquid phase in the cross-section downstream from a single drip point distributor was studied and found to be low, independent from the pore density.

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1. Introduction

The performance of multiphase tubular reactors with co-current downward gas–liquid two-phase flow through catalyst packings is strongly affected by the quality of the gas–liquid distribution in the packing. Main influencing factors are: (a) the initial liquid distribution provided by a device above the packing and (b) the liquid distribution within the packing as a result of the interaction between flowing gas and liquid phases and the packing structure.

Non-uniform liquid distribution in radial and axial direction, also called 'liquid maldistribution', is a very common flow phenomenon in multiphase tubular reactors. As a result, the catalyst surface is only partially wetted, which leads to lower catalyst utilization and lower effective liquid–solid mass transfer to the catalyst surface [1]. Thus, the space-time-yield is lower in comparison with a completely wetted catalyst surface. Further, liquid maldistribution negatively influences the reactor stability and causes safety issues due to the formation of local dry-outs and hotspots. Hotspots lead to rapid catalyst deactivation and possible reactor runaways [2]. Differences in the liquid velocity profile and temperature gradients may also lower the selectivity of the desired product.

High-resolution gamma-ray tomographic images of the cross-sectional liquid saturation distribution in trickle bed reactors with random particle packings, recorded by Schubert et al. [3], revealed the occurrence of zones with liquid-only flow (rivulets and channels) and dry zones in the investigated packing cross-sections at different heights for a broad range of flow conditions. It was found that the distribution of the liquid phase in trickle bed reactors can considerably change along a certain length of the upper part of the packing [4,5]. This packing-specific length depends on initial liquid distribution above the packing, the liquid flow rate, and the packing structure, which is characterized by the particle shape and size. This phenomenon was revealed, for example, via electrical capacitance tomography performed by Hamidipour et al. [6]. It was found that the degree of uniformity equalizes after a certain flow distance no matter if a full cone spray nozzle or a single point distributor was applied.

Another phenomenon is the (radial) liquid spreading, which can be described as the evolution of the irrigation state of the bed as a function of the axial distance from a single drip point at the top of the packing [7]. Liquid spreading is caused by different mechanisms, namely mechanical dispersion, capillary dispersion, and overloading [4,8,9]. Overloading due to high local liquid throughputs causes the liquid to move radially, either along the liquid-filled pores or the particle surface. The liquid spreading due to dispersion, however, is mainly influenced by the particle size, and to some extent by gas flow rate and packing porosity. Both dispersion mechanisms are not always equally significant, e.g.,

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[*] Corresponding author. Tel.: +49 351 463 35181/+49 351 463 37696; fax: +49 351 463 37757.
E-mail address: Iman.Mohammed1@mailbox.tu-dresden.de (I. Mohammed).

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Nomenclature

a, b	Geometric constants of the sensor (−)
H	Axial height of the measurement position (cm)
K	Relative electrical permittivity (−)
M_f	Maldistribution factor (−)
N_F	Number of frames (−)
N_P	Number of points (−)
u	Superficial velocity (m/s)
V	Voltage (V)

Greek letters

β	Saturation (−)
δ_L	Reduced liquid saturation (−)
$\Phi k_{1,s}$	Effective liquid–solid mass transfer coefficient (m/s)

Subscripts

G	Gas
i	Compartment
log	Logarithmic
L	Liquid
x	Crossing point

Superscripts

H	High
L	Low

smaller particles result in higher capillary pressure and spread factor due to mechanical dispersion decreases [10,11]. Thus, it is obvious that the spreading behavior is linked to the initial liquid distribution and to the ability of a packing to counterbalance liquid maldistribution.

The individual effects of gas and liquid flow rates [12,13], packing porosity [3,9], particle shape [11,14] and dimensions [15] on spreading behavior, liquid phase distributions, and evolving patterns in trickle bed reactors have already been reported in the literature.

In recent years, strong efforts have been made to search for and evaluate alternative catalytically active reactor packings that provide high specific surface area at low pressure drop as well as high catalytic activity. Solid foam catalyst packings were studied as promising replacements of randomly arranged catalyst particles, as they provide high specific surface area up to 2000 m^2/m^3 and high open porosities between 75 and 95%, which result in low two-phase pressure drop and enhanced heat and mass transfer rates due to interconnected pores [16–19].

In principle, the open-cell structure of solid foams allows the liquid radial flow from one cell to another (Fig. 1b). Solid foams are also characterized by a high pore tortuosity that enhances radial and axial mixing. Thus, the overall heat and mass transfer rates are higher compared to particle packings [20]. Recently, Calvo et al. [21] studied the phenomena of liquid spreading with a radiographic technique using a single point distributor in a flat rectangular column packed with a sheet of nickel foam of 1.4 mm window diameter. The column was operated in liquid only flow under trickling conditions. Strong liquid channeling was observed. However, the phenomenon of liquid spreading in order to improve the distribution in the cross-section was not strongly pronounced.

The aim of this study was to investigate systematically the cross-sectional liquid distribution and the resulting liquid saturation in a tubular column packed with solid foams. In particular, the effect of the liquid distributor type on the initial liquid distribution at the entrance of the packing and on the axial evolution of the distribution along the packings were addressed based on measurements of the cross-sectional liquid saturation data at 208 measurement points obtained from wire-mesh sensors. The following influencing parameters were studied: foam pore density, gas and liquid flow rate and pre-wetting conditions applied to the tubular packing.

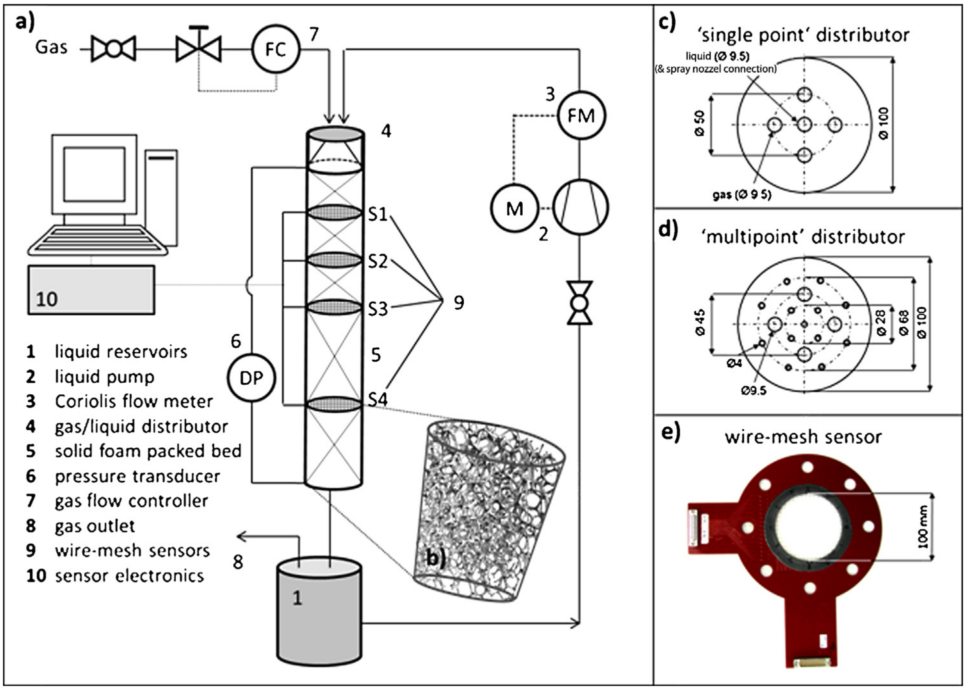

Fig. 1. (a) Solid foam tubular reactor setup, (b) reconstructed 3D micro tomography image of 10 ppi PU foam, (c) 'single point' distributor, (d) 'multipoint' distributor, and (e) wire-mesh sensor.

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