Chemical Engineering and Processing 66 (2013) 20–26

Contents lists available at SciVerse ScienceDirect

Chemical Engineering and Processing: Process Intensification

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

Investigation of dynamic liquid distribution and hold-up in structured packings using ultrafast electron beam X-ray tomography

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ARTICLE INFO

Article history:
Received 20 August 2012
Received in revised form 22 January 2013
Accepted 23 January 2013
Available online 1 February 2013

Keywords:
Structured packing
Separation column
Dynamic liquid distribution
Ultrafast X-ray tomography
Liquid hold-up
Flooding conditions

ABSTRACT

Dynamic cross-sectional liquid distribution and hold-up in a DN80 separation column filled with structured packings was studied using an ultrafast electron-beam X-ray tomograph with high temporal resolution of 2000 images per second. The modality allows visualisation and characterisation of the counter-current flow before and at the flooding point representing the upper operation limit. Two packings of the same type (Montz B1-MN) with different specific surface area were used to investigate the influence of the packing geometry on the spatial liquid distribution. The system studied was water/air at different gas and liquid loads. The results of the tomographic imaging and corresponding post-processing routines were validated by comparison with conventional draining measurements.

1. Introduction

Structured packings are column internals widely used in counter-current separation processes, such as distillation or absorption. Along with high surface area, structured packings are characterised by low pressure drop and high separation efficiency [1,2]. To fully exploit these advantages, a uniform distribution of gas and, in particular, of liquid over the entire packing bed height is required. The latter depends on physical properties of the system with respect to the wetting ability [3].

A number of modelling approaches towards description of fluid dynamics and separation efficiency of packed columns have been published, each based on an extended experimental data pool (see, e.g. [4–6]). All these approaches assume uniform liquid distribution over the column cross section and exploit correlations for liquid hold-up, a crucial parameter for evaluation of pressure drop and packing capacity. Liquid hold-up is defined as the ratio between the liquid present in the column and the column volume [1]. The knowledge on liquid hold-up over the entire operating range is important for the understanding of fluid dynamics, design of packing support devices, process modelling and packing optimisation [7–9].

The operating range of packed columns can be subdivided into two regions: before the loading point, where liquid hold-up is independent of the gas load, and beyond the loading point, where further increase of the gas velocity leads to an increase of the liquid hold-up due to the shear forces, until the flooding point is reached. The latter represents the upper operation limit of the packed column and, thus, determines the column capacity at a specific liquid load. At this point, high shear stresses between the phases cause a fast liquid phase accumulation accompanied by the dispersion of the gas phase [2]. Liquid hold-up is traditionally measured by column draining or weighting methods [1]. These methods provide the volume of liquid in the entire packing column, and, thus, liquid hold-up is obtained as a mean value, regardless of any radial, axial and temporal variation. Nevertheless, below the flooding point, conventional measurement techniques deliver efficient results sufficient for the development of hold-up correlations in this operating range. However, for more challenging problems, as, for instance, tailored column design and rigorous modelling, an enhanced fundamental knowledge of the fluid dynamics is required. In addition to liquid hold-up values, information of the spatial liquid distribution over the entire operating range is necessary. Cross-sectional liquid distribution is usually quantified with the help of array-type collector devices installed below the packing bed [10]. This method is unable to take dynamics of two-phase fluid flow and local flow patterns within the packing into account. Therefore, *spatiotemporal* gas–liquid distribution data over the entire operation range of packed columns are missing.

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http://dx.doi.org/10.1016/j.cep.2013.01.008

Most promising for the investigation of liquid distribution and hold-up in packed columns seem to be radiation-based tomography methods, such as γ-ray and X-ray computer tomography. A detailed review on a few previous flow imaging studies performed in separation columns with structured packings as well as on hold-up and phase distribution measurement methods is given in [11]. Valuable insights into the flow pattern in packed columns were provided by the University of Liége. Here, comprehensive high-resolution X-ray tomographic studies on counter-current gas–liquid flows in packed columns were performed and characteristic data on packing specific area, liquid hold-up, and gas–liquid interfacial area were determined [12,13].

The main disadvantage of the up-to-date radiation-based tomographic modalities is that the data acquisition is slow, requiring seconds or even minutes to obtain sufficiently high signal-to-noise ratio. Thus, only time-averaged phase distributions can be obtained. For highly dynamic flow conditions, as, e.g., those at the flooding point, these methods are inapplicable. In our work, a new ultrafast electron-beam X-ray tomography is applied to study liquid hold-up and the dynamics of the gas–liquid distribution in a column filled with corrugated sheet packings. The results of the tomographic imaging are compared with conventional draining measurements.

2. Experimental

2.1. Column setup and packing characteristics

The column setup used for both tomographic measurements and conventional draining method consists of an acrylic glass column with an inner diameter of 80 mm and a height of 1.5 m. Deionised water was used as a liquid phase in a recycle mode, with air in the counter-current flow. A schematic flow sheet of the experimental setup is shown in Fig. 1.

The specific liquid load was varied between 14.6 and 25.6 $m^3/(m^2\,h)$ and the gas capacity factor (*F*-factor) between 0.6 and 3.5 $Pa^{0.5}$. Water was distributed using a multiple point source distributor (3976 drip points/m^2). Experiments were carried out at atmospheric pressure and ambient temperature.

Two high-capacity packings of the Montz B1-MN type shown in Fig. 2 were used. The geometric surface area of the investigated packings is 350 m^2/m^3 and 500 m^2/m^3, respectively. The packing element height is approximately 0.2 m. A particular feature of the Montz B1-MN packing type is a bend on the bottom side of corrugations (Fig. 2a) enabling a smooth transition of both gas and liquid between the packing layers. The packing bed contained four packing elements, rotated by 90° with respect to the neighbouring elements below and above.

2.2. Ultrafast electron beam X-ray tomograph

Fig. 3 illustrates the working principle of the ultra-fast electron beam X-ray tomograph as well as the modality used in this work. An electron beam is produced by an electron gun (electron acceleration voltage of up to 150 kV at a maximum beam current of 65 mA) focussed on a semi-circular X-ray production target (opening angle of 240°) made of tungsten which surrounds the packed column. The electron beam is swept rapidly across this target producing a circular focal spot path by means of an electromagnetic deflection system. The focal spot itself has a size of approximately 1 mm. In this way, X-ray fans are generated from a moving focal spot.

X-rays that pass the packed column are recorded by a fast X-ray detector. This detector (comprising 240 pixels with an active volume of 1.33 mm × 1.33 mm × 1.33 mm) is designed as a ring, mounted inside the scanner head with small axial offset relative to the focal spot path. With this configuration, the electron beam

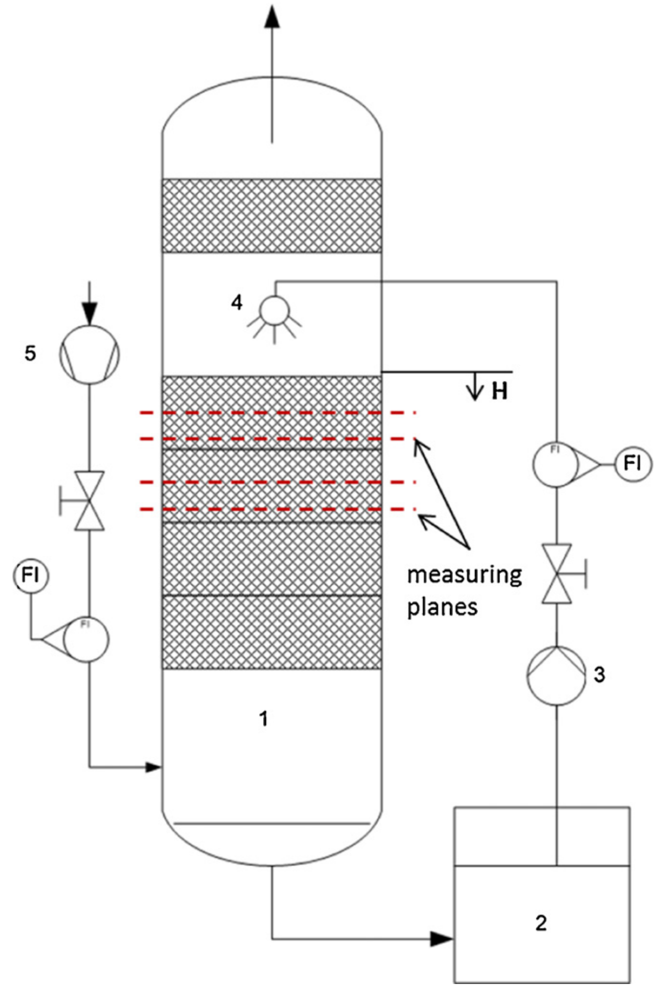

Fig. 1. Schematic flow sheet of the column setup. (1) Acrylic glass column; (2) liquid tank; (3) liquid pump; (4) liquid phase distributor; (5) air compressor. Dotted lines indicate the measuring planes.

tomograph allows ultra-fast scanning imaging up to frequencies of 7000 Hz, with a spatial resolution of up to 1 mm. A detailed description of the tomographic setup as well as the measurement and control procedures are given by Fischer et al. [14]. The whole X-ray tomography system is installed at an elevator, which allows studying the fluid flow at different column heights.

2.3. Tomographic measurements and data processing

Tomographic measurements were performed in packing cross-sections in the two upper packing elements (see Fig. 1). The position of the measuring planes is defined in this work as the distance (in mm) from the top of the upper packing element. The measuring planes in each packing element were selected to be in the middle part (labelled, e.g., as H146 and H346) and in the lower part of the elements (labelled, e.g., as H188 and H390), as shown in Fig. 1. Due to the different packing geometry, the element height varies slightly, and, thus, the measuring planes are at different positions in each packing. After bringing the tomograph at the desired column height by the elevator, reference scans of the dry packing were taken. Subsequently, the tomographic measurements of the irrigated packing were performed for different operating points at loading and flooding conditions. For all experiments, the measurement time was 2000 ms with a frequency of 2000 Hz.

After each experiment, the entire measured X-ray intensity raw data set undergoes resorting and reconstruction steps. The