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Gamma-ray computed tomography SCANNERS for applications in multiphase system COLUMNs*

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Abstract. Gamma-ray tomography experiments have been carried out to detect spatial patterns in the porosity, in a 0.27 m diameter packed steel column using a first generation computed tomography (CT) system. The CT scanner consists of a NaI(Tl) detector 5.08 cm in diameter, and an encapsulated ^{137}Cs (3.7 GBq) radioactive source, located opposite to the center of the detector. The detector and the source, mounted on a fixed support and the column, can rotated and dislocate by two stepping motors controlled through a microprocessor. Different sizes of stainless steel Raschig rings (12.6, 37.9 and 76 mm) have been examined. The primary objective of this work is to detect spatial patterns and statistical information on porosity variation in packed distillation columns. Horizontal scans, at different vertical positions of the packed bed were made for each size of Raschig rings. Radial porosity variation within the packed bed has been determined. This study has demonstrated that the porosity and its spatial distribution in a metallic packed column can be measured with adequate spatial resolution using the gamma-ray tomography technique. After validation of this first generation CT, the turntable design to rotate and dislocate the ^{60}Co or ^{137}Cs sealed gamma-ray sources and multidetector array for the third generation industrial computed tomography was also developed.

Key words: industrial computed tomography • multiphase flow systems • non-destructive testing • gas absorption column • industrial process optimization • packed distillation columns • scanning systems

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Introduction

Nowadays, a wide range of chemical and petrochemical industries shows a great interest in using the industrial computed tomography for improving design, operation, optimization and troubleshooting of industrial processes [1–3]. The column scan by gamma rays is a well-known technique and has been widely applied in industrial routines for these purposes [7, 8, 11]. However, the column scan is able to analyze and identify failures in industrial processes, while gamma computed tomography permits to visualize failure points in three-dimensional analysis and in sections. The tomography system is an update methodology used to determine the cross-section density profile inside a processing vessel.

Random packed distillation and absorption columns are used extensively in chemical and petrochemical industries to perform highly efficient separation [12]. In the past three decades, the hydraulic performance and the mass transfer efficiency in random packed columns have been the subject of a considerable amount of researches. With the recent advances in computational fluid dynamics, it is now possible to model the effects of heterogeneities in the bed on flow profiles and hence on the mass transfer efficiency. Experimental

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data on porosity variation are thus extremely useful. The porosity variation in random packed columns has been recognized as a potential source of misdistribution and it has been studied extensively since the early works. The porosity distribution has a significant effect on the liquid flow distribution within a packed column, especially near the wall region [4–7].

To meet these requirements, the Radiation Technology Center of the Institute for Nuclear and Energy Research (IPEN-CNEN/SP) has developed gamma-ray computed tomography systems on laboratory scales [9–11]. The data acquisition board, the mechanical control interface, the software for movement control and the image reconstruction were specially developed to be used in these computed tomography systems [5]. For testing these developments, a first generation tomography – a NaI(Tl) detector/^{137}Cs source combination – was used to carry out the CT experiments, applying the hardware and software developed, with a simulator of 0.27 m diameter packed steel column with different sizes of stainless steel Raschig rings (12.6, 37.9 and 76 mm). The packed column simulator was rotated and dislocated, while the detector and the source were mounted on a fixed support [11].

However, the real situation in chemical and petrochemical plants is such that it is necessary to move a multidetector array and a radioactive source, due to the fact that the large packed column is already installed and it cannot be moved. Thus, a rotating table design was also developed and projected in order to rotate and dislocate the collimated radiation source and multidetector array.

Methodology

A first generation parallel beam computed tomography (CT) scanner system was used in this study [5]. The CT scanner consists of a NaI(Tl) detector, 5.08 cm in diameter, as well as, an encapsulated ^{137}Cs radioactive source located opposite to the center of the detector. The detector and the source are mounted on a fixed support and the column can be rotated and dislocated by two stepping motors controlled through a microprocessor.

The collimator is made of lead, 4.5 cm in depth and 5 cm in height, so that the detector is completely shielded by the collimator. There is a rectangular hole of 2.38 × 4.38 mm at the location appropriate to the detectors for sampling the beam. In each movement, the column was rotated by 2.78° (approximately 130 views) and dislocated by 2.55 mm (approximately 106 positions). To obtain statistically significant results and to reduce the effect of the position, the CT scans were obtained by scanning 360° and dislocating 0.27 m (diameter of the packed column simulator), using a collecting numerous beam path attenuations (approximately 13,780 projections). The source collimator provides a perfect gamma-ray beam horizontal plane. The source is further collimated using a 4.5 cm lead brick with a central slit. In the vertical direction, the measurements were carried out on one plane $L/D = 2$. The radioactive source used was 100 mCi (3.7 GBq) of ^{137}Cs. The experimental system consists of a 0.27 m diameter packed column simulator with steel Raschig rings of different

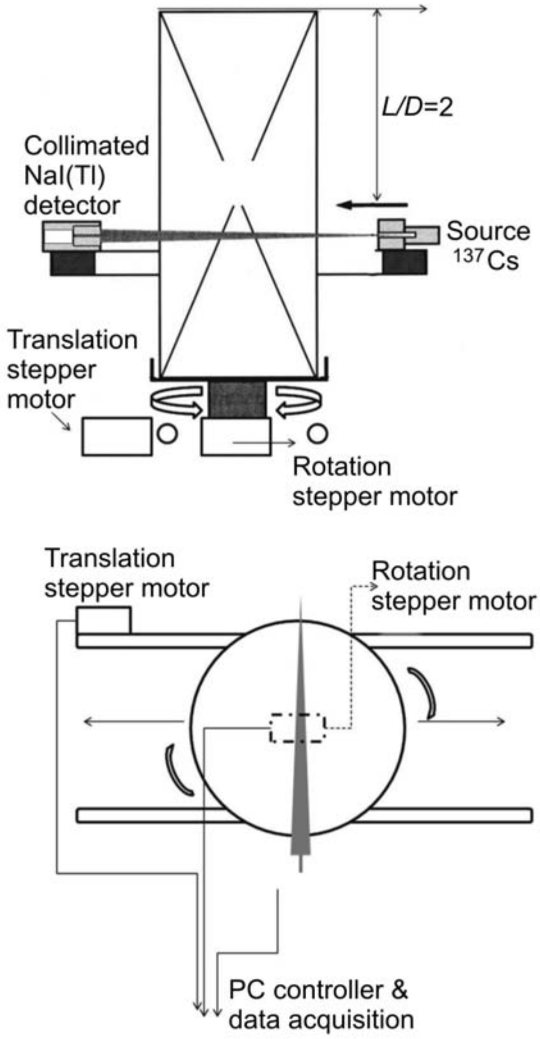

Fig. 1. Schematic diagram of the first generation computed tomography.

sizes: 12.6, 37.9 and 76 mm. The experimental setup is schematically shown in Fig. 1. The procedure details were described in our previous paper [11].

To detect spatial patterns and statistical information on porosity variation in packed columns, horizontal scans at different vertical positions of the packed bed were made for each size of Raschig rings. A filtered back projection (FBP) tomographic reconstruction algorithm was used to calculate the spatial variation over the column cross-section. The probability density function for porosity variation has been constructed from the experimental data and it can be represented by the normal distribution. The measurements were first made for an empty column to obtain the base line data for the scanning plane. The same measurements were later made for the packed columns.

The rotating table design, which is consisted of two stepping motors for rotation and displacement movements of the radioactive source and the scintillator multidetector array around the six inches (152.4 mm) diameter laboratory gas absorption column, was developed. It has been designed to rotate and dislocate one ^{60}Co or ^{137}Cs sealed gamma-ray source on opposite side of the multidetector array. The source and the seven NaI(Tl) detectors, with 5.08 cm in diameter, were housed in

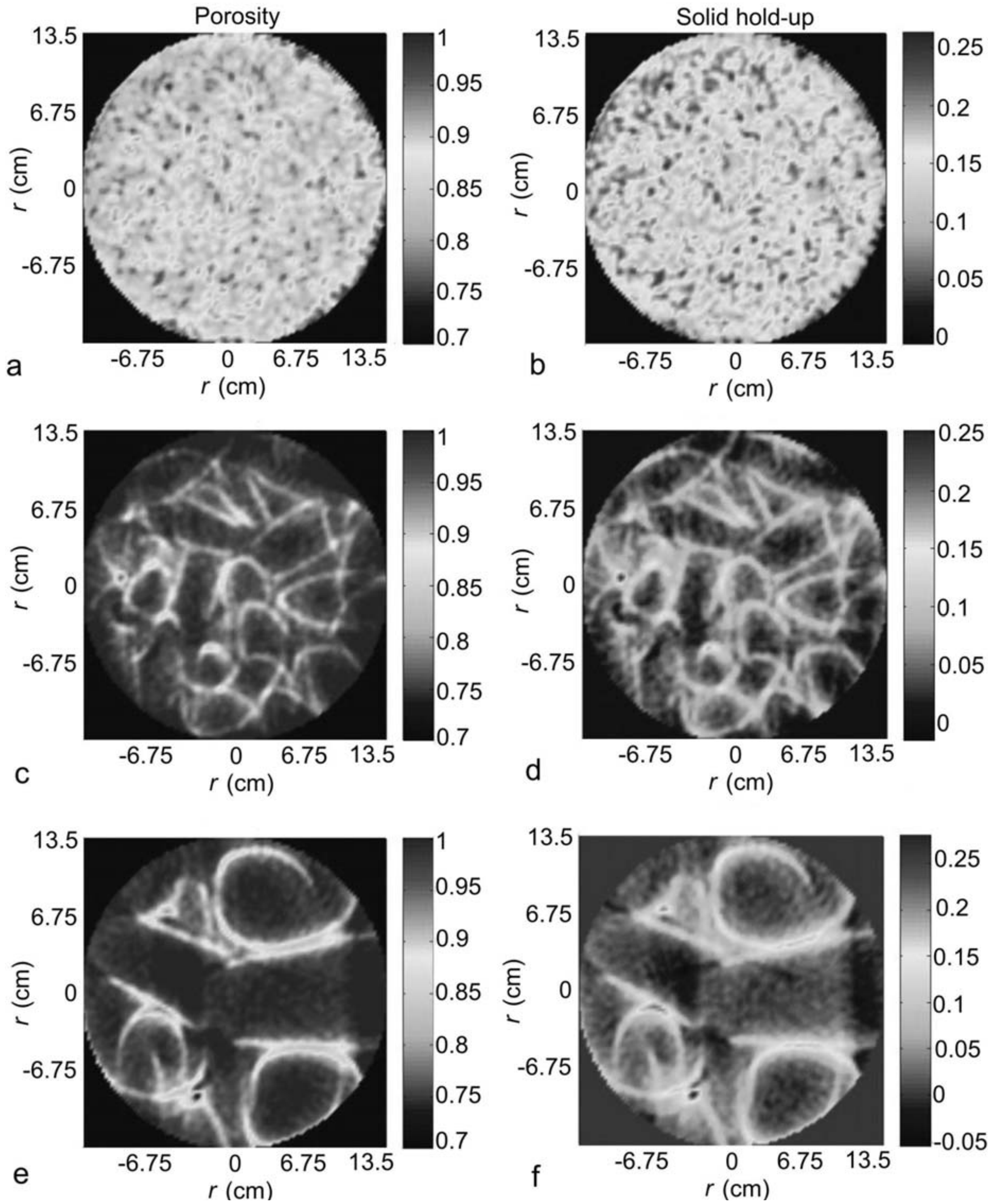

Fig. 2. Cross-sectional porosity and solid hold-up distributions by $L/D = 2.0$; (a, b) 12.6 mm; (c, d) 37.9 mm and (e, f) 76 mm.

lead collimator devices. A fan beam arrangement of source-detectors is used for measuring the transmission of the gamma-ray photons across the multiphase experimental setup.

Results and discussion

Figure 2 shows the cross-sectional porosity and the solid hold-up distributions for 12.6, 37.9 and 76 mm steel Raschig rings, respectively. The porosity distribution for all systems is almost symmetric and depends on the size of the packing; with a higher porosity near the wall and a lower gas holdup in the center.

This study has demonstrated that the porosity and its spatial distribution in a metallic packed column can be measured with an adequate spatial resolution using the gamma-ray computed tomography technique. The experiments have been carried out successfully to measure the spatial porosity distributions in a 0.27 m diameter packed column using three different sizes of stainless steel Raschig rings (12.6, 37.9 and 76 mm) by $L/D = 2$. A FBP tomographic reconstruction algorithm used to calculate the spatial variations over the column cross-section, and the radial porosity variation has shown a good performance of a faster convergence. The estimated errors, calculated by the Poisson model, on project measurement are 2.5% and 1.5% in the regions of highest and lowest (air) densities, respectively. The error calculated by the normal distribution is 1.7% (standard deviation).

The results indicate that the spatial porosity distribution in random packed columns is not uniform. There are always some pockets in the packed beds where the porosity is higher than the average value. For the circumferentially averaged radial porosity distribution, the porosity in the column wall region tends to be higher than that in the bulk region, due to the effect of the column wall. The hold-up radial distributions results are described in our previous paper [11].

These results validated the first generation CT system developed in our laboratory. However, in order to obtain a gamma-ray CT scanner more suitable to be used in real situations (chemical and petrochemical plants), it is necessary to develop a system that allows acquiring the data faster. An alternative is to use a third generation CT configuration, in which a large number of detectors are located on an arc concentric to the source. The size of the multidetector array should be sufficiently large in order to assure that the entire object is within the detector field view at all time.

In our experiments, using the first generation CT scanner, the source and detector remain stationary with respect to each other, while the entire apparatus rotates about the object. To approach a real situation in industrial plants it is necessary to move the source and multidetector array around the column. In this work was developed a mechanical design for the third generation CT scanner to analyze laboratory gas absorption column, turning the ^{60}Co or ^{137}Cs sealed gamma-ray sources and multidetector array, instead of the column. It has also a translation movement along the column axis to obtain as many slices of the process flow as needed. Figure 3 shows the scheme of the turntable design with the source and multidetector array, while Fig. 4 illustrates the laboratory gas absorption column (Mod. UOP7-G, Armfield Ltd.), with the technical details to be used for multiphase system analyses:
- feed tank capacity: 50 L;
- diameter of the column: 152.4 mm;
- volume of packing: 7 L;
- height of the absorption column: 1.4 m;
- type of packing: Raschig rings 10 × 10 mm;
- air compressor capacity: 0.15 m^3/min (0.3 bar);
- air flowmeter range: 20–180 L/min;
- gas flowmeter range: 1–22 L/min; and
- water flowmeter range: 1–10 L/min.

The mechanical assembly for the third generation CT scanner comprised the following items: spur gear system (Mod. 18AT10506F, Correias Schneider), translator, rotary stage, drives (Mod. ST10-Si, Applied Motion Products) and stepper motors (Mod. KML093F07, Kalatec Automacao Industrial Ltd). The use of suitable spur gears has given a good repeatability and a high accuracy for scanning, when acquiring reconstruction data. Repeatability is the ability of a motion control system to return repeatedly to the commanded position. Accuracy is the degree of veracity, while precision is the degree of reproducibility [5].

The mechanical assembly developed has the technical specifications:
- structural frame: stainless and carbon steels;
- source shield: lead with pneumatic exposure system;

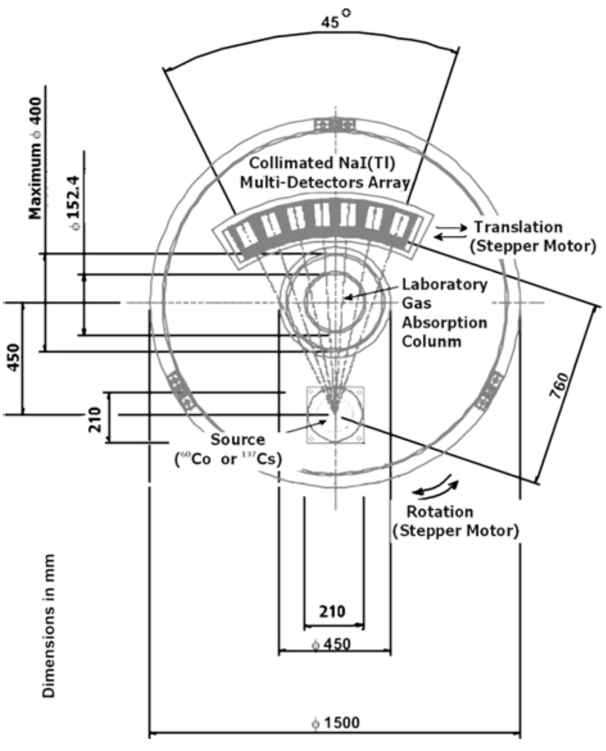

Fig. 3. Turntable design of the third generation computed tomography, with the source and multidetector array.

Fig. 4. Laboratory gas absorption column for multiphase system analyses.

– maximum diameter of the laboratory gas absorption column: 400 mm;
– number of radiation detector: 7 NaI(Tl) detectors of 5.08 cm diameter;
– source and detector-detector collimation angle: 7.5°;
– source and multidetector array collimation angle: 45°;
– stepper motor torque: 6.4–9 N·m;
– multidetector array translation: 0.9 mm per step; and
– turntable rotation: 4444 steps per revolution (0.081° per step).

The structure frame constructed with stainless and carbon steels involves two important aspects in the selection of materials to be used in the CT mechanical system, that is, strength and rigidity. The use of good shielding material and mechanical locking system like a source lead shield with a pneumatic exposure system meets the radiological safety features.

The use of multidetectors speedsup the scans, reducing the overall scanning time. This conception intends to match the industry needs in optimization and troubleshooting solution of industrial processes. The development of the turntable design for the third generation CT scanner was concentrated in this work. In the next step, the tomographic measurements will be carried out using the turntable CT system developed in this study, associated with the laboratory gas absorption column for multiphase system analyses.

Conclusion

The first generation CT system has obtained good spatial resolutions and images. The tomographic reconstruction algorithm used to calculate the spatial variations over the column cross-section, and the radial porosity variation have shown good performance and faster convergence. The mechanical system developed for third generation industrial computed tomography presented a good performance in terms of strength, rigidity, accuracy and repeatability. The turntable CT system designed to rotate and dislocate the radioactive source and the multidetector array synchronously with respect to the column under investigation has a great potential to be used for industrial process optimization in Brazil.

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