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Development of the Mechanical System on a Third-Generation Industrial Computed Tomography Scanner in Brazil

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Abstract: The development of measurement geometry for medical X-ray computed tomography (CT) scanners was carried out from the first to the fourth-generation. This concept has also been applied for imaging of industrial processes such as pipe flows or for improving design, operation, optimization and troubleshooting. Nowadays, gamma CT permits to visualize failure equipment points in three-dimensional analysis and in sections of chemical and petrochemical industries. The aim of this work is the development of the mechanical system on a third-generation industrial CT scanner to analyze laboratorial process columns which perform highly efficient separation, turning the ^{60}Co, ^{75}Se, ^{137}Cs and/or ^{192}Ir sealed gamma-ray source(s) and the NaI(Tl) multidetector array. It also has a translation movement along the column axis to obtain as many slices of the process flow as needed. The mechanical assembly for this third-generation industrial CT scanner is comprised by strength and rigidity structural frame in stainless and carbon steels, rotating table, source shield and collimator with pneumatic exposure system, spur gear system, translator, rotary stage, drives and stepper motors. The use of suitable spur gears has given a good repeatability and high accuracy in the degree of veracity. The data acquisition boards, mechanical control interfaces, software for movement control and image reconstruction were specially development. A multiphase phantom capable to be setting with solid, liquid and gas was testing. The scanner was setting for 90 views and 19 projections for each detector totalizing 11,970 projections. Experiments to determine the linear attenuation coefficients of the phantom were carried out which applied the Lambert-Beer principle. Results showed that it was possible to distinguish between the phases even the polymethylmethacrylate and the water have very similar density and linear attenuation coefficients. It was established that the newly developed third-generation fan-beam arrangement gamma scanner unit has a good spatial resolution acceptable given the size of the used phantom in this study. The tomografic reconstruction algorithm in used 60 × 60 pixels images was the Alternative Minimization (AM) technique and was implemented in MATLAB and VB platforms. The mechanical system presented a good performance in terms of strength, rigidity, accuracy and repeatability with great potential to be used for education or program which dedicated to training chemical and petrochemical industry professionals and for industrial process optimization in Brazil.

Key words: Industrial computered tomography, third-generation scanner, troubleshooting, industrial process optimization, tomografic reconstruction algorithm.

1. Introduction

Random packed distillation and absorption columns are used extensively in chemical and petrochemical industries to perform highly efficient separation. Unlike the standard aspect of the computed tomography (CT) for medical application, tomography systems for the industrial applications should be adapted to the different size and geometry objects usually placed in a aggressive environment which contains flammable superheated or corrosive materials

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and may be eventually subject to high internal pressure: all these factors bring in many difficulties for setting CT devices around the industrial process columns [1, 2]. Therefore, the development of special CTs is required, inhibiting its production in large scale. In addition, the industrial systems involve dynamic processes and contain solids, liquids and gases mixtures when CT is an excellent option to see the phases' distribution inside the vessels [3-6]. In other words, it is necessary to develop a tomographic system suitable for each purpose in industry [2, 7].

The CT systems based on the transmission use an array of encapsulated radioactive sources and detectors placed in opposite sides of the targeted object [3, 8-10]. First-generation tomography systems consist of a source which emits a collimated radiation linear beam and a radiation detector (Fig. 1a). The source-detector system moves in opposite sides of the object, measuring the attenuation of radiation at each position.

In the second-generation CT systems, a set of detectors is placed opposite to a set of radioactive sources, moving (source and detector) around the object under study, providing a number of projections equal to the number of detectors (Fig. 1b). Sometimes, these second generation systems also use multiple radioactive sources in order to reduce the analysis time of the system.

In the tomography of third generation, the source is collimated so that the path crossed by beams is similar to a fan (Fig. 1c). The system moves around the targeted object, obtaining a particular view for an "x" position of the source-detector array. In this type of system, several sources and arrays of multiple detectors may be used.

Finally, the so-called fourth-generation CT systems use a fixed array of detectors (a large number of detectors mounted on a fixed ring) and a radioactive source that moves around the object (Fig. 1d). Inside,

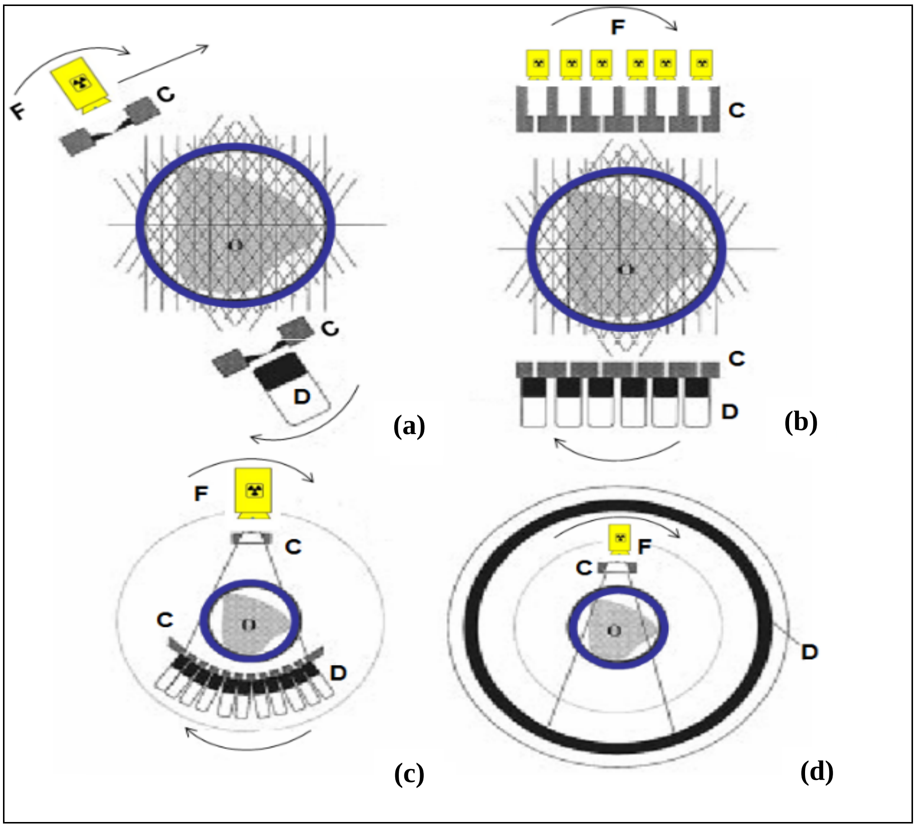


Fig. 1 (a) Translation-rotation of a beam in parallel (first generation), (b) translation-rotation of multiple sources in parallel (second generation), (c) rotation of a fan-beam (third generation) and (d) detector fixed-rotation source (fourth generation). D: NaI(Tl) multidetector array; F: radioactive source; C: lead collimator and O: object of study.

the fan-shaped beam is detected in 10.03 seconds. Records of any measure are from the detector, representing a view of the object. However, all CTs are constituted basically of same parts: radioactive sources, radiation detectors, data acquisition system and suitable microcomputer.

To meet these necessities, Radiation Technology Center of the Nuclear and Energy Research Institute (IPEN-CNEN/SP) has developed a third-generation computed tomography scanner for analysis of industrial multiphase systems [2, 11], as shown in Fig. 2. In its configuration, an array of seven 2” NaI(Tl) detectors is located in an arc concentric to the center of the gamma source(s) (^{60}Co, ^{75}Se, ^{137}Cs and/or ^{192}Ir). In order to increase the number of projections measurements in one view of the studied system, the number of detectors in the arc was effectively increased by using a collimator that moves across the detector arc. The whole assembly of the detectors and the radiation source are mounted on a gantry capable of being rotated round the test section axis through a stepper motor interfaced with a host computer.

Fig. 2 Third-generation computed tomography scanner developed at IPEN-CNEN/SP.

The mechanical assembly for the third-generation CT scanner was comprised of 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 Ltda.). The use of suitable spur gears has given good repeatability and 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 [3, 11].

The mechanical system developed has the technical specifications:

- Structural frame: stainless and carbon steels;
- Source shield: lead with pneumatic exposure system;
- Diameters of the laboratory process columns: 255-400 mm;
- Number of radiation detector: 7 NaI(Tl) detectors with 2” (5.08 cm) diameter;
- Source and detector-detector collimation angle: 7.5^{o};
- Source and multi-detectors array collimation angle: 45^{o};
- Source(s) collimated in fan shaped planar beam: ^{60}Co, ^{75}Se, ^{137}Cs and/or ^{192}Ir;
- Stepper motor torque: 6.4-9 N·m;
- Multi-detectors array translation: 0.9 mm per step;
- Rotating table diameter: 1,500 mm (external);
- Turntable rotation: 4,444 steps per revolution (0.081^{o} per step).

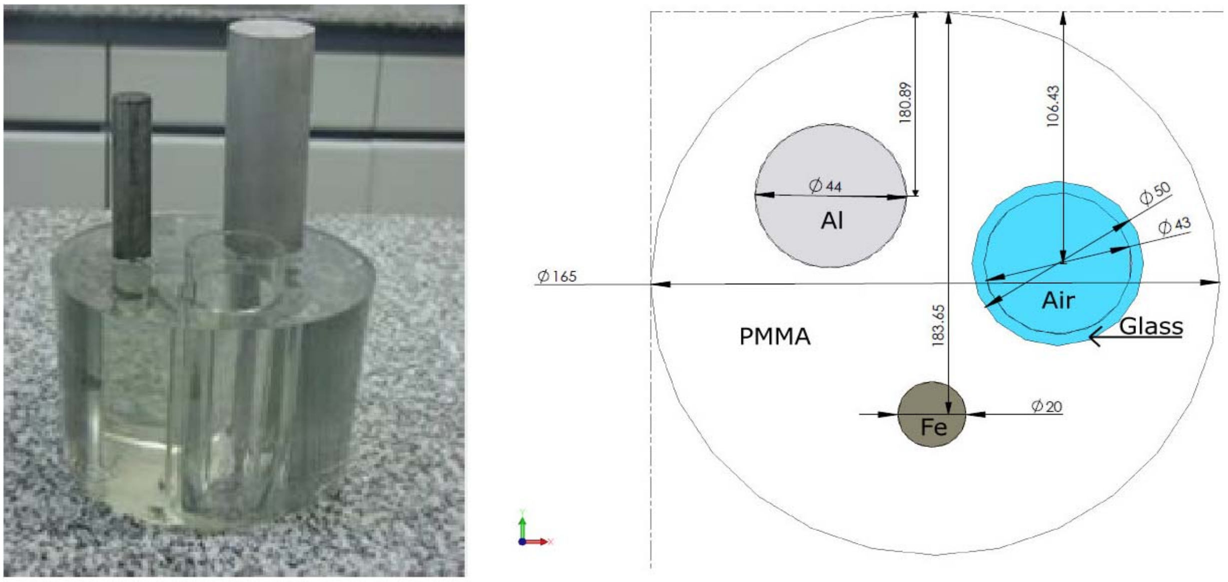
The structure frame which are constructed with stainless and carbon steels reach two important aspects in the selection of materials to be used in the CT mechanical system that is strength and rigidity. The use of the good shielding material and mechanical locking system like source lead shield with pneumatic exposure system meets the radiological safety features. The use of multi-detectors speeds up the scans, reducing the overall scanning time. This conception intends to match the industry needs in optimization and troubleshooting solution of the 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 developed turntable CT system in this study, which is associated with the laboratory gas absorption column for multiphase system analyses [3, 11].

2. Experimental Procedure

For testing the third-generation CT developed, a multiphase phantom was prepared in our laboratory and tomographic experiments were evaluated [2, 11]. Each of the seven 2” NaI(Tl) detectors has an individual collimator made in lead, so that detectors are completely shielded by the collimator. Each collimator has a hole of 5 mm diameter for sampling beams. These dimensions for collimator holes were optimized based on the considerations of providing adequate area for detecting photons with good statistic into the chosen sampling period. The radioactive sealed ^{137}Cs (662 keV) source is 3.7 GBq placed inside a lead collimated shield system which provides a 45° fan beam arc.

A multiphase phantom capable was designed and prepared in order to be able to vary the proportions of the phases (gas, liquid or solid) to validate the third-generation tomography developed at IPEN-CNEN/SP. The 15 cm diameter phantom consists of polymethylmethacrylate solid containing three holes in which one is filled with a steel plug another with an aluminum plug and the third one empty, as illustrated in Fig. 3. The idea was to switch the gas and liquid phases, while maintaining the solids fixed.

The array of seven NaI(Tl) detectors and the ^{137}Cs source were placed on the rotatable gantry and the phantom was installed in the center between the array of detectors and the source. The gantry can be rotated around the axis of the phantom by a stepping motor that is controlled through a microprocessor. The size of the array of detectors is sufficiently large so that the entire phantom was within the field of view of the detectors all the time. Moreover, the whole assembly can be moved in the axial direction along the phantom to perform a scan at different axial levels of the phantom. Fig. 2 shows an illustration of the third-generation CT with the phantom in the center of the gantry. The data acquisition board and the used mechanical control were



(a) (b)

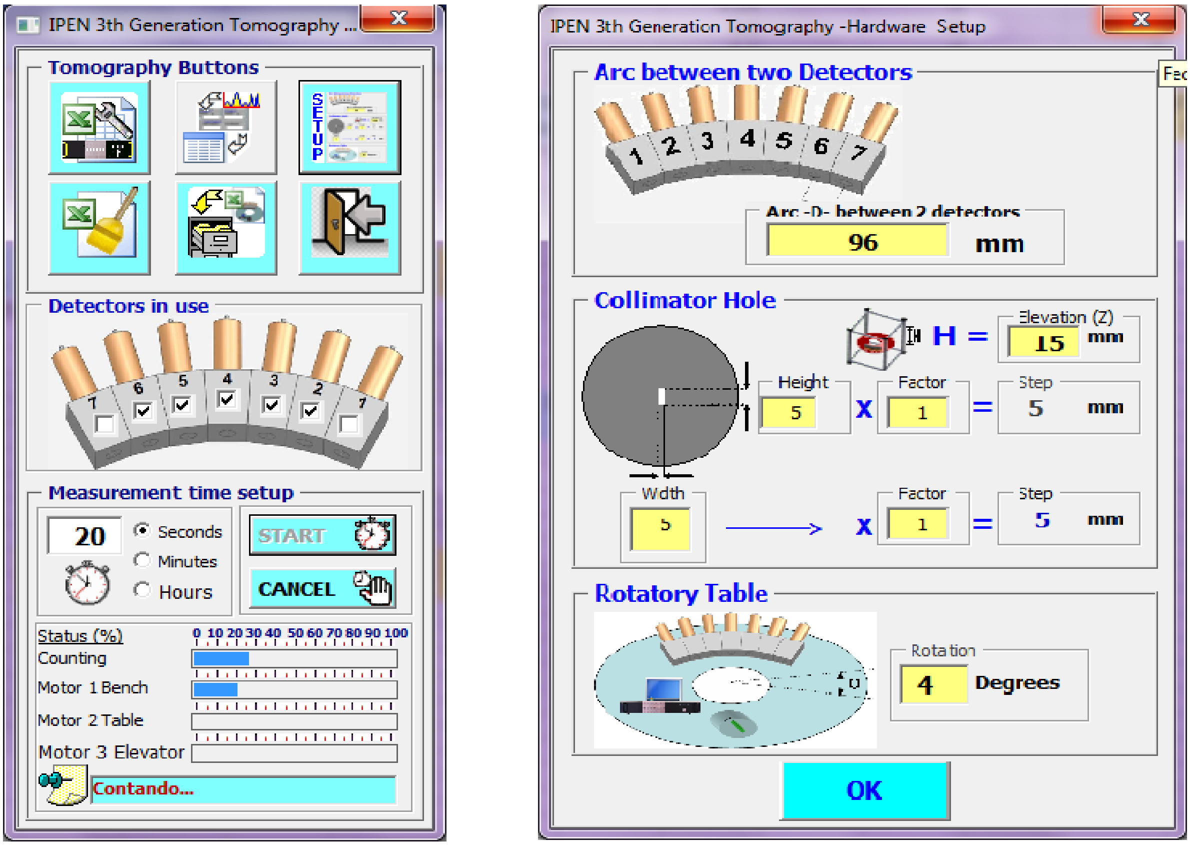
Fig. 3 Multiphase phantom with different density materials (g/cm^3): (a) polymethylmethacrylate (1.2), aluminum (2.7), iron (7.9), water (1.0) and air (0.0012) and (b) geometric dimensioning.

also developed at IPEN-CNEN/SP [2, 11].

The tomographic measurements were carried out using the prepared multiphase phantom in laboratory (Fig. 3). To obtain statistically significant results and to reduce the effect of the position, the CT scans were obtained rotating around the phantom the plate with the source and detectors 360° in 90 views, each view provided 4°. The movement of the detector-collimator assembly was controlled by another steeper motor, in each movement, this assembly rotated by 0.39° generating 19 projection per detector or 133 (19 × 7) projections per view totalizing 11970 projections per image. Previously, each NaI(Tl) detector was evaluated by gamma spectrometry techniques using a associated multichannel electronics and data acquisition board which was developed by IPEN-CNEN/SP. Fig. 4 shows software (Fig. 4a) and hardware (Fig. 4b) arrangement screen controls of the third-generation computed tomography scanner developed at IPEN-CNEN/SP.

The used reconstruction algorithm was the Alternative Minimization (AM) technique and was implemented in MATLAB and VB platforms. This reconstruction algorithm is used, since, it has the following advantages: (1) it accounts for statistical variations which are associated with the radiation decay measurements; (2) it readily incorporates non-uniform beam effects; (3) it ensures that the final reconstruction contains only positive values. The results were reconstructed in 60 × 60 pixels images [10, 12].

To compare the results of the linear attenuation coefficients of the phantom components, it is necessary to know the value of these coefficients for pure materials (pure phase). Hubell and Seltzer [13] created a database called NIST, where figures are available for the attenuation coefficients as a function of energy for



☐ 7 ☑ 6 ☑ 5 ☑ 4 ☑ 3 ☑ 2 ☐ 1

20 ● Seconds ○ Minutes ○ Hours

Contando...

Arc -D- between 2 detectors: 96 mm

Elevation (Z): 15 mm

Height 5 x Factor 1 = Step 5 mm

Width 5 x Factor 1 = Step 5 mm

Rotation: 4 Degrees

(a) (b)

Fig. 4 Software (a) and hardware (b) arrangement screen controls of the third-generation computed tomography scanner developed at IPEN-CNEN/SP.

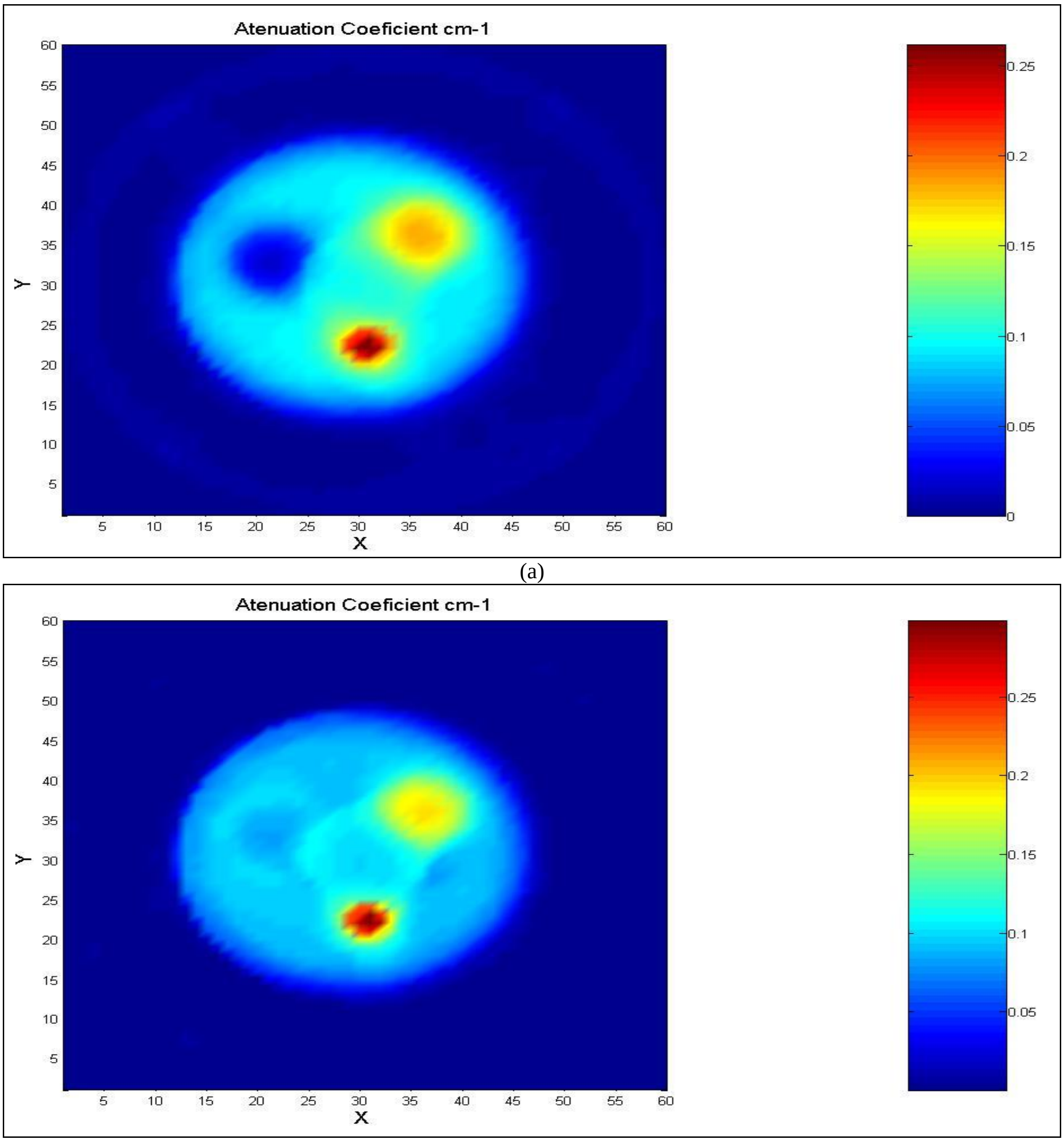
a specific compound or material.

In these experiments, the values of effective linear attenuation were determined using densitometry, a procedure consists of the direct application of the Lambert-Beer equation (4) using in only one detector, where the material to be measured is placed in the path of the radiation.

3. Results and Discussion

Each pixel from the sinograms obtained for phantom with an empty hole and water filled hole represents the transmission value (*I/Io*) corresponding to a given projection and position of the source (view) or rotation angle. The sinograms confirmed dark blue shades to the objects of greater density. A sinogram allows checking the measurements quality obtained in the tomography sampling process. The absence of parallel bands or spots that could be attributed to malfunctioning detectors ensured the end result.

Fig. 5 presents the reconstruction image of the empty



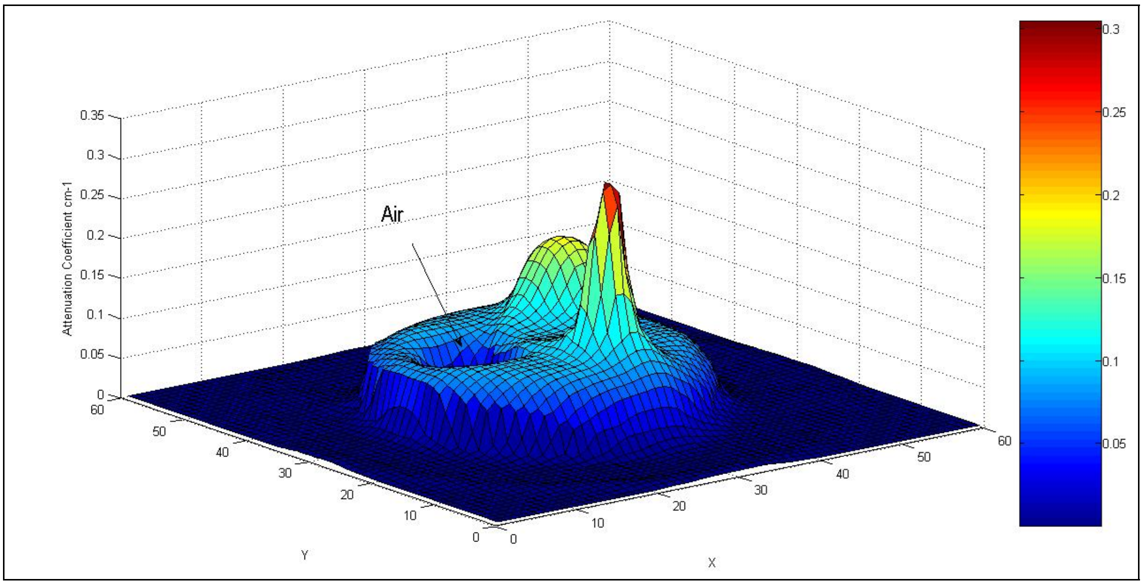
(a)

(b)

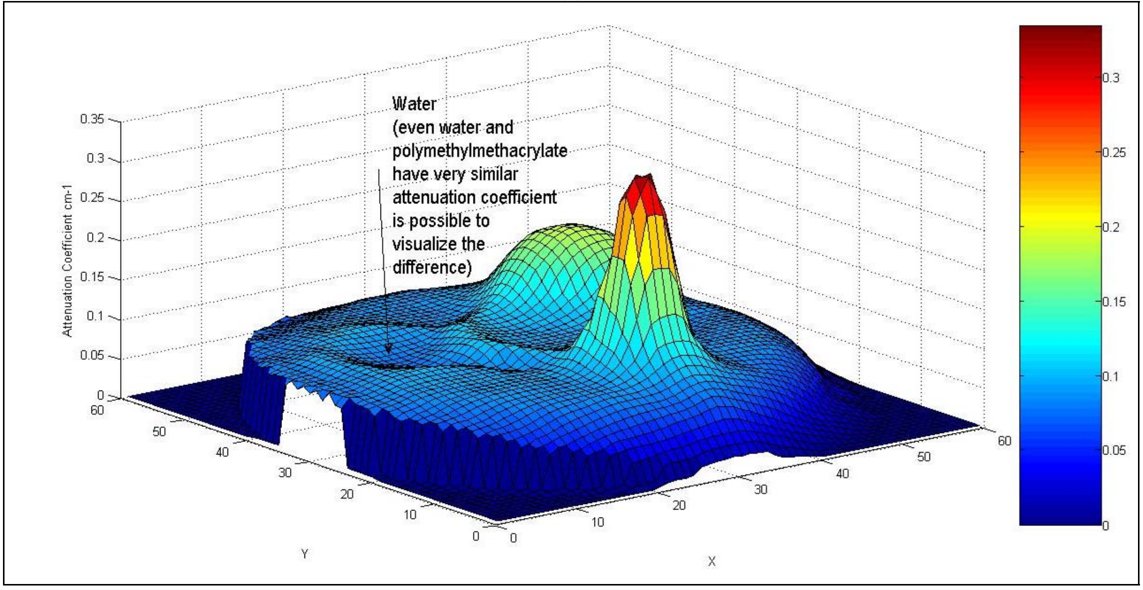
Fig. 5 Reconstruction images (60 × 60 pixels) from (a) the empty hole phantom (gas) and (b) the water filled phantom.

hole phantom (Fig. 5a) and water filled hole phantom (Fig. 5b). A reasonable resolution was observed for both images. As it can be seen from this figure, the different densities of the phantom constituent materials can be clearly identified. The theoretical densities (g/cm^3) of each phantom constituent material are summarized in polymethylmethacrylate (1.2), aluminum (2.7), iron (7.9), water (1.0) and air (0.0012).

Analyzing Fig. 6b, little differences can be observed between the images of the solid material (polymethylmethacrylate) and the water filled hole is due to the close density values of the two materials and consequently of the attenuation coefficients (0.09 cm^{-1}) for plastic and 0.08 cm^{-1} for water. Another way to plot the results of Fig. 5 is shown in Fig. 6 which can distinguish very easily the empty hole in Fig. 6a and the water filled hole in Fig. 6b. Actually it's so possible to obtain and process very rich data sets from the images. In future works more numerical analyses will be studied to demonstrate the powerful of the CT techniques.



(a)



(b)

Fig. 6 Attenuation coefficients difference between the phantom with the empty hole (a) and the phantom with the water filled hole (b).

4. Conclusions

It was established that the newly developed third-generation fan-beam arrangement gamma scanner unit has a good spatial resolution acceptable which is given the size of the used multiphase phanton in this study. The CT is capable of providing phase (liquid or gas) composition information in two phase systems. Although the system is only capable of providing time-average data, it can provide unique information concerning the structure of multiphase systems. The main advantage of the CT include is a non-invasive nature, capability for providing local as well as global information and adaptability for automating entire data acquisition process. However, more experiments need to be done to optimize spatial and time resolution which tests many parameters as collimators width, number of views, sampling number and accounting time. Numerical image analyze and processing will be introduced and improved. The mechanical system developed for third-generation industrial computed tomography presented good performance in terms of strength, rigidity, accuracy and repeatability. The turntable CT system designed to rotate and dislocate the radioactive source and the multi-detectors array synchronously with respect to the column under investigation has great potential to be used for industrial process optimization in Brazil.

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