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Industrial Equipment Troubleshooting with Imaging Technique Improved Gamma-Ray Absorption Scans

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Abstract: Gamma scanning is one of the most common nuclear techniques on troubleshooting industrial equipments like distillation columns and reactors. With a very simple concept, the technique is easy to implement. Searching for a competitive edge the industry has been long developing solutions to achieve better results. On the last decades, significant development has been done with the advent of new equipments, electronics, portable computers and software. Continuous scanning and wireless detection systems are examples of successful field solutions, while new software aid on reporting and data presentation. However the type and quality of the results itself has not dramatically changed since its beginning. A scan profile is simple to understand, although the process to build it can be very complex as it requires a specific blend of knowledge and abilities. Process engineering, chemical engineering, internal hydraulic project, nuclear engineering and field abilities are pre requisites for of any scan specialist. Correct data gathering, interpretation and reporting are abilities often difficult to match or requires a long time of training. The industry faces a similar difficult on the customer side, as it is always necessary to train end users to understand a report and how to use its best. This paper describes our effort on developing a new approach on the gamma scan test using image reconstruction techniques that would result on a graphic image rather than a XY plot. Direct and easier to understand, a report with graphic images would be also be accessible to a wider audience, not limited to the customers experienced with gamma scan interpretation.

Key words: Industrial equipments, gamma ray, troubleshooting, image reconstruction, gamma scanning.

1. Introduction

In continuous production plants like refineries and petrochemical sites, the process equipment performance are analyzed with the help of a process model, according to this operational variables, quality of feed and products [1]. With increasing complexity and restricted boundaries of process, design and operations, the use of non-destructive testing (NDT) has been widely used to on-line validate, check and troubleshoot these process models.

Among the available technologies, nuclear techniques stand out by not perturbing or affecting the process in analysis, allowing that on-line testing be performed. Modern equipments and methods permit that nuclear techniques found only in literature migrate to the field. Distillation column gamma scanning, neutron backscattering, chemical and radioactive tracers and industrial computerized tomography are common practices nowadays and represents one of the most powerful techniques to on-line analyze process equipments.

Within these technologies, the distillation column profiling consolidated as one of the best options to perform a mechanical and operational troubleshoots.

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However, although it relies on simple principles, the practical use is complex due to the high specific knowledge required on all phases of a typical project. This barrier also turn out to be an extra difficulty for a wider divulgation and acceptance on the market, as the final customer need to have a good experience with the technique.

To solve technical difficulties and in the search of a competitive edge, the industry developed several solutions. However they did not resulted on higher quality information. All technologies on the market are based on the same principle: register gamma ray attenuation to generate a median density profile. This paradigm would be brake if a new technology presents a more direct and comprehensive result, with much better acceptance.

The computerized tomography is available for medical use for more than 30 years and, to this date, reaches a surprising level of complexity and precision. Imaging industrial equipment with the gamma scan profiling technique appears as a good alternative for a new approach. Although it users the same concepts, imaging industrial equipments faces a series of new challenges, difficulties and limitations, which imposes the need of a development plan to transpose the technique from lab scale to the field.

2. Process Equipment Analysis

2.1 Process Equipment

The performance of equipments can be measured, understood and designed trough a process model, which input variables can be directly measured (temperature, pressure and flow rate) or determinate (composition, heat consume, mixture, reaction and feed stock). Fig. 1 shows a typical layout of a distillation column, with some of the process variables. These models are built, considering some projects premises, and are robust enough to account the normal measuring errors and parameter variations. However there are not models capable of change their project premises.

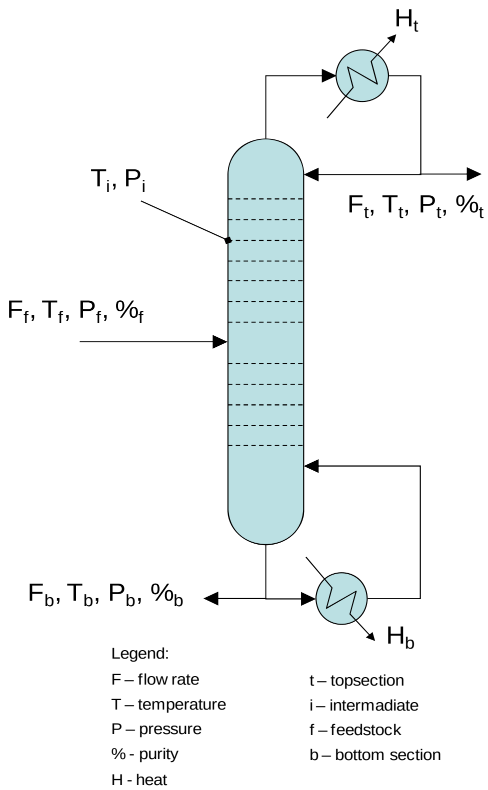

Fig. 1 Typical layout of industrial process equipment.

The process models are based on certain known characteristics considered constant and controlled:

- Physics: dimensions, area, volume, equipment and component functioning, level and vibration;
- Process: purity, preponderant physical-chemical phenomena and composition;
- Operation: resident time, pressure, temperature and distribution.

Obviously the process model cannot account for characteristics of random, uncontrolled, unknown and even human nature:

- Physical: corrosion, mechanical damage and assembly faulty;
- Process: contamination, unexpected physical-chemical phenomena, fouling and saturation;
- Operational: operational disturb, instrument lecture error and coking;
- Human: project problems, in house solutions and human mistakes.

This is the context where some special

Non-Destructive Testing (NDT) has their main focus, because it is possible to validate process and troubleshoot problems in equipments, while they are on-line [2]. Nowadays the use of these techniques had been spread beyond the process and operations engineering to other fields of industrial plant engineering [3]:

- Maintenance: on-line evaluation of equipments;
- Shutdown planning: opening equipments, supply parts purchasing and extent of field work;
- Projects and revamps: critical points verification, start up monitoring, baselines and performance study;
- Predictive practices: critical equipment monitoring.

2.2 Gamma Ray Profiling or Gamma Scan

Gamma ray column profiling or gamma scan is one of the most used NDT techniques to evaluate the on-line mechanical and operational behavior of process equipments. On this technique, a radioactive source and detector are positioned around the equipment and simultaneously moved along its length. The radiation attenuation values measured thought the vessel results on a density longitudinal profile. The profile or scan plot is then analyzed and the results are present on a report [4-6].

The Fig. 2 shows a schematic view of a column scan. On the left side there is an orientation view of the scanning and on the right side a representation of the density profile obtained. On a real gamma scan plot the density profile is on the felt side and a sketch of the column is on the right side.

2.2.1 Limitations of the Technique

Column scan gamma scanning has some disadvantages that restrict it use to some applications:

- Count rate: as the available time on field tests are finite, gamma scans are limited to those cases where a statistical count rate can be obtained. Source activity and energy, detector size and efficiency, column diameter and lenght, wall thickness and constitution of the analyzed equipment are fundamental variable on

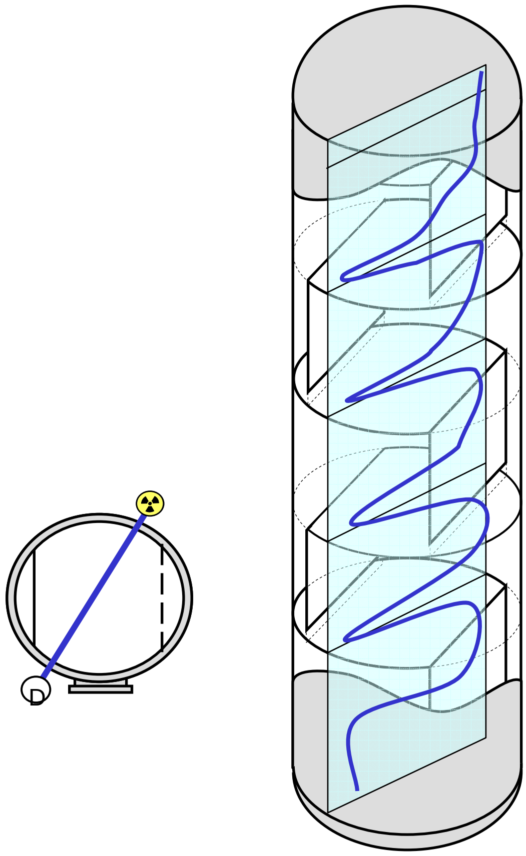

Fig. 2 A general sketch of gamma ray scans positioning and profile.

verifying the viability of a project. Radiation safety issues are equally relevant due to limitation of personal equivalent dosis [7];

- Mean density: every single point on a gamma scan plot are related to the mean density along the scan cord. Any analysis of a gamma scan data should take into account the mean behavior, not the punctual, of the density profile. Additionally, on bigger or trickier equipments the gamma ray profile tends to smooth problems and phenomena. This limitation has been partially contoured with baseline scanning, a common practice for the most critical equipments. Baselines can be performed with equipment off-line (dry-scan) or on-line (operational baseline) at optimum operational conditions;
- Positioning: since the gamma scan is a mean density profile, a data interpretation is possible only where the proprieties of the object are constant along the gamma ray path. That would considerably limit the

positioning possibilities and the type of density profile that can be obtained. Many times, complex design equipments are hard, limited or impossible to be properly analyzed;

- Dimensions: a density profile offers a unidimensional view (elevation wise) of the mean density of equipment. Multiple scans or grid pattern scans are often utilized to obtain some space notion of the density distribution.

2.2.2 The Art of Gamma Scanning

Although conceptually simple, the technique of gamma scanning requires a combination of knowledge, skills and talent of the work team, that directly interfere on the quality of the gathered information and trueness of the written report. In general, a gamma scanning specialist should master the following subjects:

- Preliminary evaluation: limitations and possibilities of the technique, possible results and relevant information estimation, preliminary evaluation of required source and count rate obtained, work and data collection strategy;
- Field work: mechanical, electrical, electronic, interference and noise problems, outdoor field work and weather, long and strenuous work journeys, self independence and manual skills;
- Radiation: absorbed doses care, radioactive source handling, radiation attenuation, detector saturation, collimation, scattering, back scattering, radiation physics, source energy and nuclear instrumentation;
- Previous knowledge: knowledge about the process and equipment under analysis, experience with similar cases and proposition of alternative testing;
- Data interpretation: experience to judge and filter all type of interference on the gathered data as a result either of a problem or an inherent characteristic of the equipment;
- Reporting: ability to explain and write down on a technical report the gamma scan, its limitations, the problems found and propositions of solutions;
- Interpersonal: team work with the scanning crew and other parties involved on the project, relationship with industrial safety crew, radiation myth, communication and persuasion abilities, oratory skills, multi language and technical terms mastery, leadership and stillness.

The combination of these characteristics that compound a typical profile of gamma scan specialist are so restrict that historically it is one of the biggest difficulties that the industry faces. On these circumstances the industry of gamma scan has invested on some solutions:

- Field work: automatized or automatic movement systems, wireless detectors and pre-adjusted electronics;
- Data view: automatic report and plot generation, on-line web visualization of data gathering.

Even though there was a clear advance with some of these improvements, there are some remarks:

- User friendly equipments and procedures normally implies on less flexible systems and thus harder to adjust in the field;
- As a result of an easier training, less experience and more subject to mistakes crews reach the field;
- Distance monitoring do not eliminate the presence of an specialist on a gamma ray scan job, as many tests cannot be repeated;
- Not rare, some improvements resulted in loss of quality of the collected data.

2.3 Computed Tomography

The processes of obtaining a space image of an object through some of its projections are called reconstruction. The human brain is highly specialized on converting a bidimensional image into a tridimensional map. Thus, as example, it is possible to know a chair spatially is simply looking to it, as the human brain combines two bidimentional images onto a stereoscopic image. The process of reading a technical drawing is similar, a tridimentional image, or spacial notion, of an object can be built with bidimensional views of the object. It is possible to infer a tridimensional object through its orthogonal projections.

A mathematic process that permits an image reconstruction was published only in 1963/64 by the South African Allan Cornack and implemented on the first tomographic machine in 1972, at EMI laboratories, by Godfrey Hounsfield. This work awards then a Nobel Medicine Prize in 1979. Nowadays medicine, research and laboratory tomographs have a high degree of sophistication with good imagem quality and high reconstruction velocity. The first tomographs used the radiation attenuation principles, but other physical principles can be used as electrical resistivity and sound propagation speed.

2.3.1 Physical Principles

Vision is human's most important sense. As an example, it is easier to recognize a circle with a drawing than through its equation. Similarly, any object (a patient, a distillation column, a tree or a casted iron piece) can be easily analyzed with images where the eventual problems can be visualized (a cancer, an obstruction, a crack or a foundry fail). That´s is why a good image reconstruction is important.

There are several physical principles that can be used on a tomography:

- Radiation attenuation: conventional tomography [8-12];
- Velocity of sound: seismic, acoustic and ocean tomography [13];
- Electrical properties: resistivity, impedance and capacitance tomography [14];
- Light absorption: optical tomography;

Usually any physical property of an object that can be measured and varies only with its constitution is analyzed. The equation 1 of radiation attenuation can be expressed as:

$$I = I_0 \cdot f(\mu, x) \qquad (1)$$

where "I" and "Io" are respectively the initial and final radiation intensities, "μ" is linear attenuation coefficient for a given median and energy and "x" is the object thickness [15]. If the physical property varies

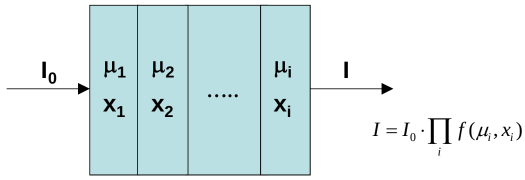

Fig. 3 Radiation attenuation along a path.

along the path on the object, the function can be expressed as a product of functions as it is shown in Fig. 3. The process of image reconstruction calculates the property distribution within a region, with a limitated number of measurements using a mathematical or iterative algorithm.

2.3.2 Conventional Tomography Basics

In principle, as long as the emission and detection coordinates are known, it is possible to obtain a tomographic image of any spatial arrangement. On most of the cases, the layout of the apparatus imposes a geometry or the design starts with a know geometry for construction convenience or due to the data treatment routine. Specifically for this work, the conventional tomograph uses the radiation attenuation principle, expressed by the Beer-Lambert law.

There are several tomographic equipment configurations. Fig. 4 shows the general arrangements of the five tomography generations, where the differences basically reside on increasing complexibility with reducing data time acquisition and flexibility [16]. Thus a 1st generation apparatus is versatile, but it can take hours of sampling, on the other hand there are already 5th generation tomographic machines registering ten thousands frames per second [17].

2.4 Tricom's Tomography Project

During the years of 2008 to 2009, several laboratory experiments were carried out at TRICOM´s installations, with the objective of obtaining knowledge and test solutions to implement industrial tomography systems. As a result, it was possible to validate models, procedures and designs for tomography systems of 1st and 2nd generation for small equipments (up to 50 cm diameter) and medium

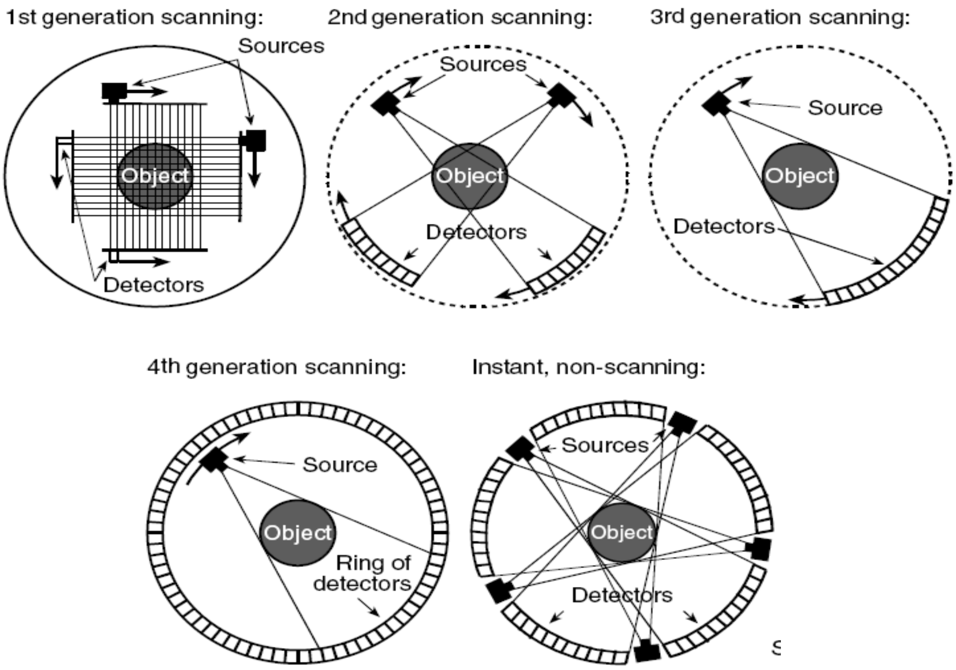

Fig. 4 General tomographs types as shown in Radioisotope Gauges for Inndustrial Process Measurements [18].

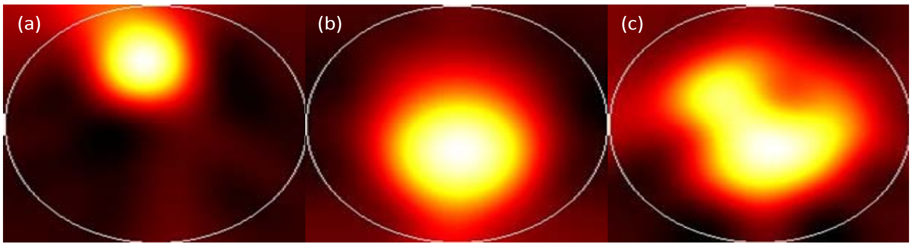

Fig. 5 Reconstructed tomography images obtained on a metalical vessel: (a) empty with a plumb cylinder, (b) plumb cylinder on water and (c) empty pipe (air) and polyurethane cylinder on water. Color represents relative densities.

and large equipments.

Initially, to simulate some of the conditions usually found in the industry; several arrangements of lead, steel or polyurethane cylinders and different medias (air and water) were tested on a 200 liter metal vessel. The Fig. 5 illustrates some of the reconstructed images obtained with a 2nd generation tomography system, using a 17 m Ci Co-60 source, with 1 or 2 inches NaTl detectors.

All reconstructions were done with an iterative algebraic method originated from ART (Algebraic Reconstruction Technique). This algorithm accepts any spatial arrangement between source and detector and also permits that the set of data be incomplete, which is relevant for real field situations. Depending on the applied image filter, the algorithm can privilege smooth or sharp density transitions. The algorithm uses concept similar to the Compressed Sense Theory, recently developed.

Nowadays, Tricom´s industrial tomography system is capable of obtaining images with several source-detector arrangements, as can be seen on Fig. 6. Linear, circular, fan-type source to detector relative montions are among the geometries that can be employed. The reconstruction technique opened the possibility to wider options of simetric, assimetric or missing cords layouts.

Some industrial scale services results performed by TRICOM in 2009 [19] and 2010 are shown on Fig. 7. Nowadays, Tricom's industrial tomography project is in the phase of automation, with the construction of 1st and 2nd generations' tomography.

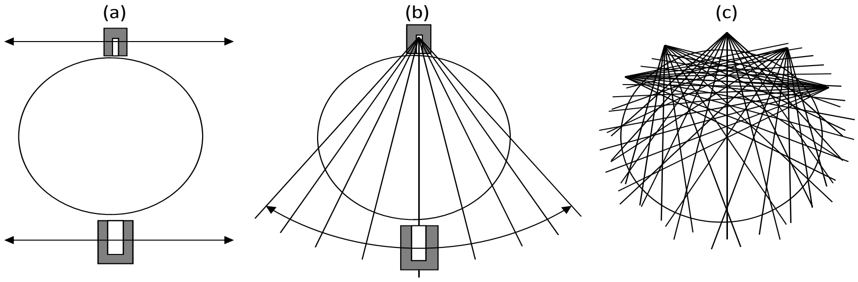

Fig. 6 Some of Tricom's industrial tomographys layouts possibilities: (a) linear, (b) fan, (c) assimetric.

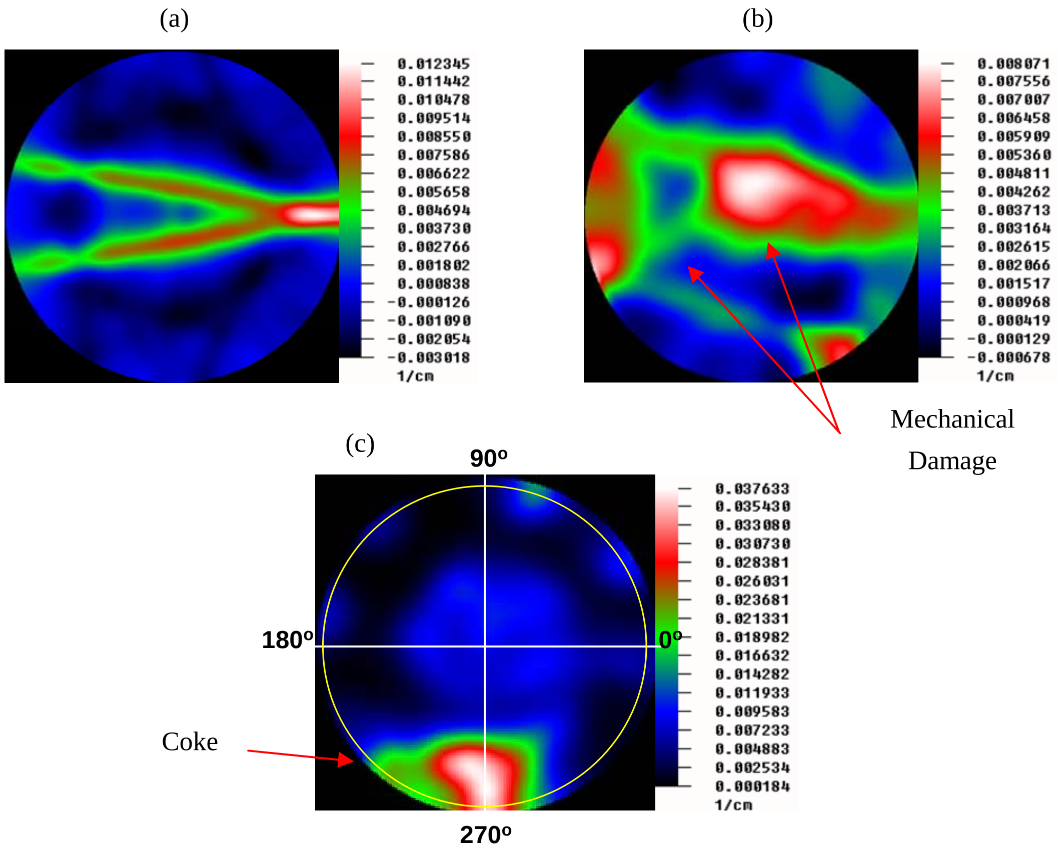

Fig. 7 Some of Tricom's industrial tomography results: (a) Simulated ideal image of a 9 m diameter distillation column vapor distributor, 9 sources × 17 detectors incomplete layout, (b) tomographic image of the real vapor distributor, (c) tomographic image of a 2 m diameter transfer line, 9 sources × 17 detectors.

The effort on the development of this technology represents the milestone of the work presented on this work, from the knowledge with the hardware setup, thought the data acquisition procedures, until the simulation and reconstruction software.

3. Objectives

3.1 Image Improved Gamma Scans

In this work, we propose to obtain a two dimensional longitudinal density profile of industrial equipments representing an advance over the conventional gamma ray profiling techniques with some advantages:

- Dimensional: a two dimensional density distribution image would ease the visualization and identification of problems, process and phenomena on an equipment;
- Positioning: as a second spatial dimension is included, the number of longitudinal profiles needed

are reduced. Furthermore, features hidden on a conventional (gamma scan) technology, due to the mean density values, would be revealed on an image technology. Similarly, density profiles or equipments that cannot be scanned with gamma ray profile have now possibilities of testing;

- Interpretation: image results are much easier to analyze and present compared to the conventional technique. This might result on a better acceptance of the inspection by the customer and also easier the training of field personal.

3.2 Project Phases

The project goal is to develop an industrial equipment imaging system using the gamma ray absorption technique. The project was divided into three phases:

- Data simulation: study of optimum experimental parameters and image reconstruction;
- Experimental testing: verifying the effect of parameters change and reconstructed image quality; and
- Field testing: equipment, material and procedures optimization and possibilities.

4. Results and Discussion

In this article we describe the results obtained in phases I and II of the project.

4.1 Phase I - Simulation

Several resources and tools from Tricom's previous experience in industrial tomography system were revised or adapted for this new technology. One direct application was the ability to simulate irradiations and reconstruct images which opened possibilities to:

- Compare several source-detectors positioning arrangements with resulting image quality;
- Fine tune reconstruction algoritm parameters.
- Reduce personal radiation exposition

Figs. 8 and 9, show examples of two simulated column arrangements, the resulting gamma ray scanning, and the reconstructed image of the column. On Figs. 8 and 9 the images in the left represents two types of typical distillation columns cross sections, with tray and packing assembly. The simulations are numerically performed were each pixel color represents different μ (linear attenuation coefficients). In those simulations air, water, stell, stell packing and

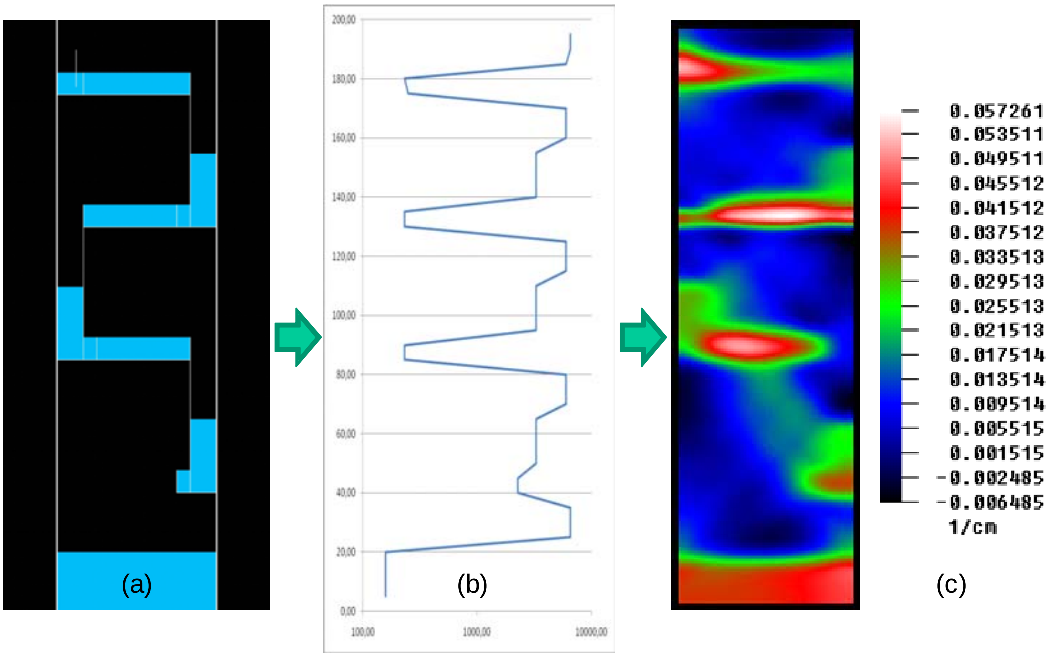

Fig. 8 Computed simulated column arrangement (a), resulting gamma ray profile (b) and reconstructed tomographyc image of the trayed column (c).

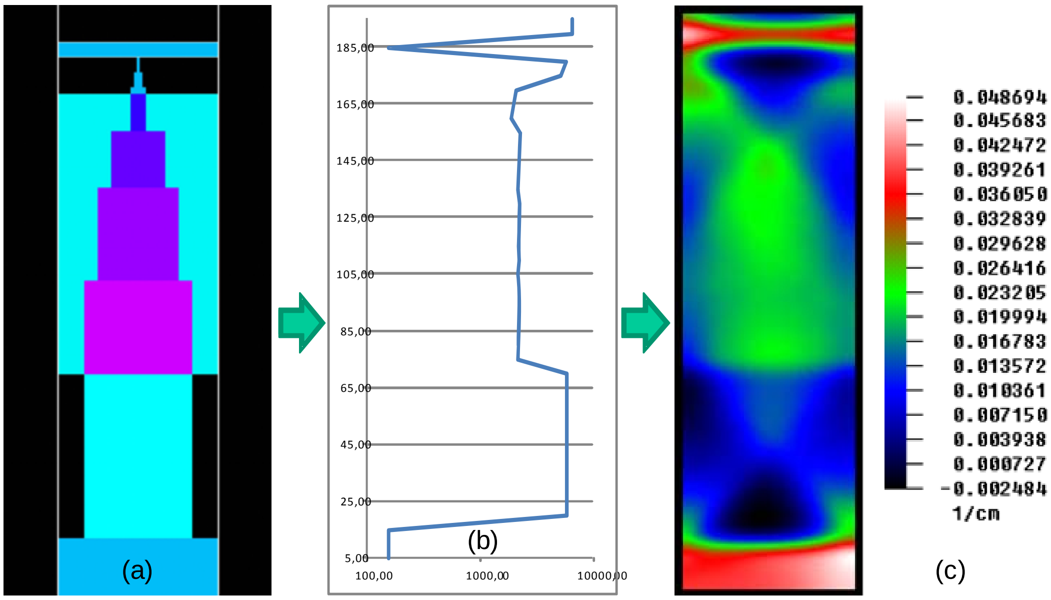

Fig. 9 Computed simulated column arrangement (a), resulting gamma ray profile (b) and reconstructed tomographyc image of a packed column (c).

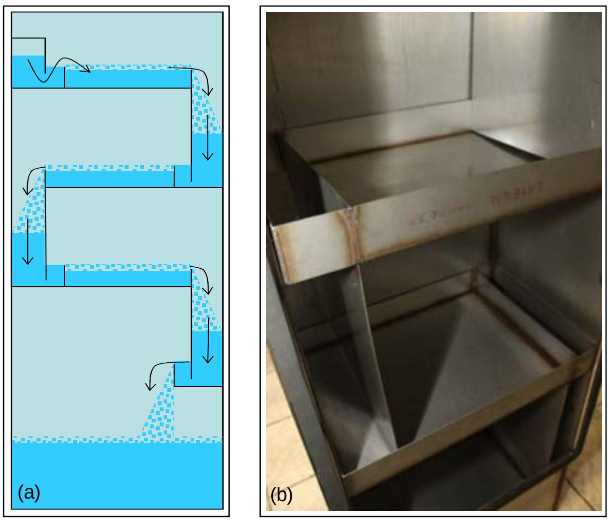

Fig. 10 Liquid flow path scketch in a one pass trayed column (a) and detail of the experimental trayed column built (b).

liquid distribution were considered. The software simulates the count rate obtained from a Cobalt 60 source with NaTl detectors.

4.2 Phase II – Experimental Testing

Images obtained from two practical experiments will be presented in this article. A 485 μCi Co-60 source was employed to irradiate a 1 pass trayed column model as shown in Fig 10. Eletronic collimation was employed to register only high energy fotons.

4.2.1 Experiment 1

A 1 inch diameter × 1 inch tick NaI(Tl) detector with 1 inch window colimator were used in this experiment. Count rate though the air was 14,106 counts/minute, count rate though liquid (water) was 414 counts/minute and background count rate was 207.6 counts/minute. Count time were arbitrarily limited to 10 seconds so all the data could be sampled in approximately 4 hours to mimetic the available time on real field jobs. Source and detector movements were set to 10 cm increments. The tomographic image was reconstructed from 355 irradiation positions and can be seen on Fig. 11 with the corresponding trayed column layout and gamma scan profile.

4.2.2 Experiment 2

A larger 2 inch diameter × 2 inch tick NaI(Tl) detector with 2 inch window collimator were used in the second experiment. Count rate though the air was 63,180 counts/minute, count rate though liquid (water) was 2,380 counts/minute and background count rate was 1,050 counts/minute. Count time were arbitrarily limited to 3 seconds so all the data could be sampled in approximately 4 hours and 21 minutes. Source and detector movements were set to 5 cm increments. The data file obtained generated three set of data with 5 cm,

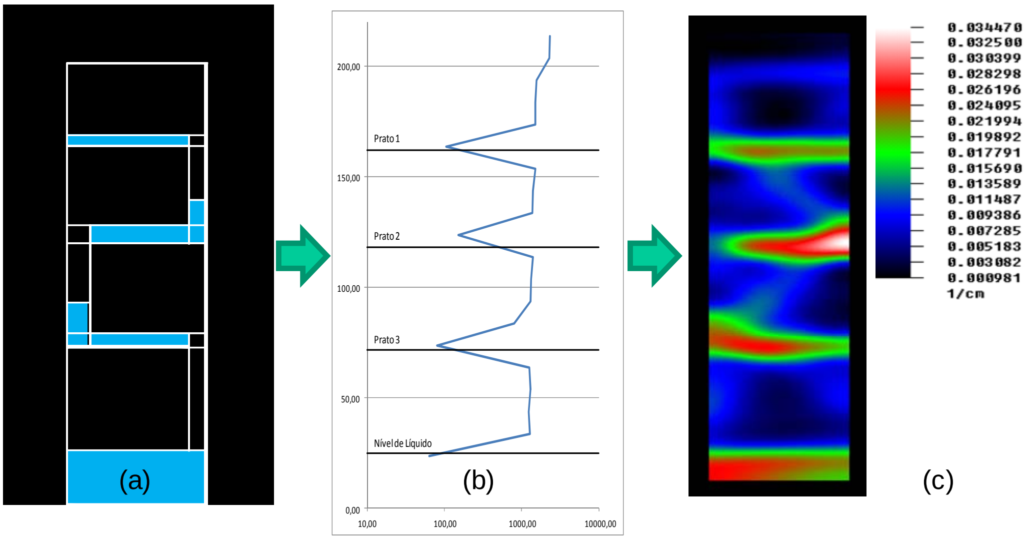

Fig. 11 Experiment 1: 1 inch diameter x 1 inch thick NaI(Tl) detector with 1 inch collimation window: trayed column layout (a) , resulting gamma ray profile (b) and reconstructed tomographyc image (c).

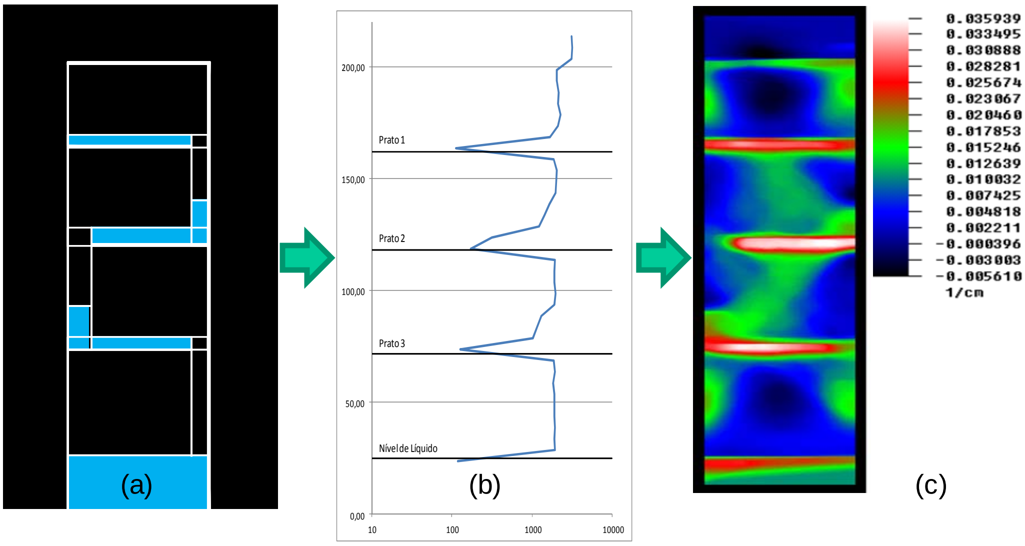

Fig. 12 Experiment 2: 2 inch diameter x 2 inch thick NaI(Tl) detector with 2 inch collimation window: trayed column layout (a) with resulting gamma ray profile (b) and reconstructed tomographyc image (c).

10 cm and 15 cm movement increments which resulted on three tomographic images reconstructed from 1,388, 356 and 149 irradiation positions respectively. On Fig. 12 the results for the 5 cm set of data are shown with the corresponding trayed column layout and gamma scan profile.

4.2.3 Images Comparition

The tomographic images obtained on the experiment 2 were compared, as shown in Fig. 13, to understand the influence of source and detector movement increments on the image quality.

The 10 cm movement increment reconstructed images for 1 inch and 2 inches detectors were compared as shown in Fig. 14.

4.3 Discussion

The bidimentional images obtained with tomographic reconstruction tools were much easier to understand as heir interpretation are very intuitive, as it can be seem on Fig. 15. With the conventional gamma ray scan plot some of the same informations can be also obtained, but that would require much more knowledge

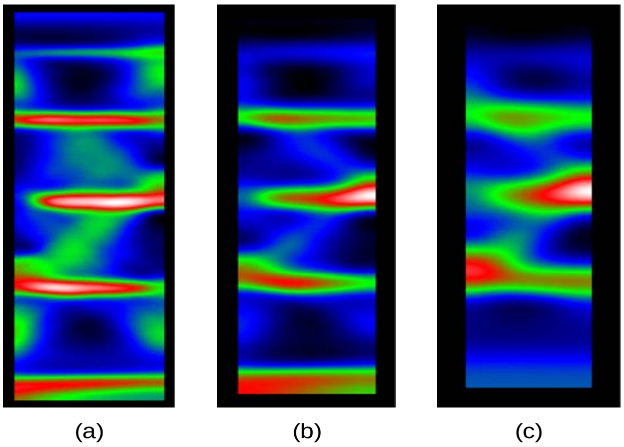

Fig. 13 Experimental reconstructed tomographyc images with varing irradiation increments: (a) 5 cm, (b) 10 cm and (c) 15 cm.

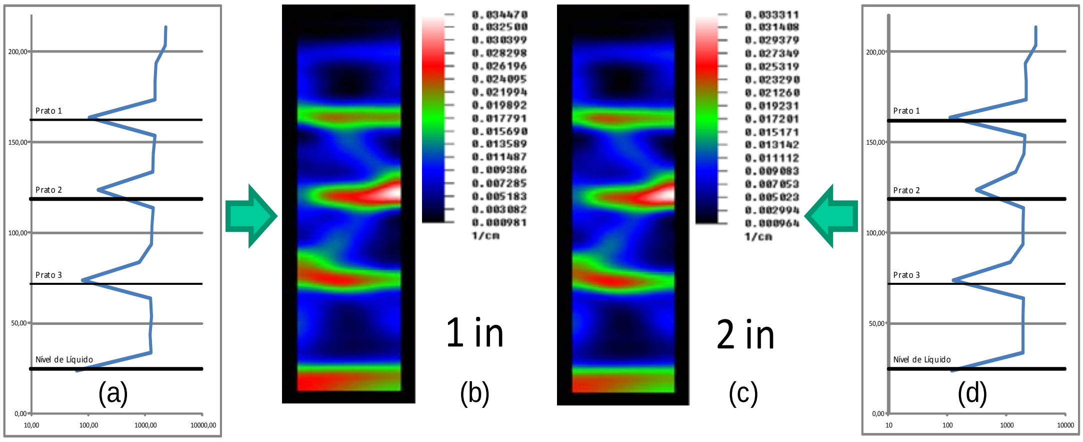

Fig. 14 Gamma ray profile with 1 inch NaI(Tl) detector, 1 inch window and 10 cm increment (a), resulting tomographic image (b), tomographic image with 2 inches NaI(Tl) detector, 2 inches window and 10 cm increment (c) and corresponding gamma ray profile (d).

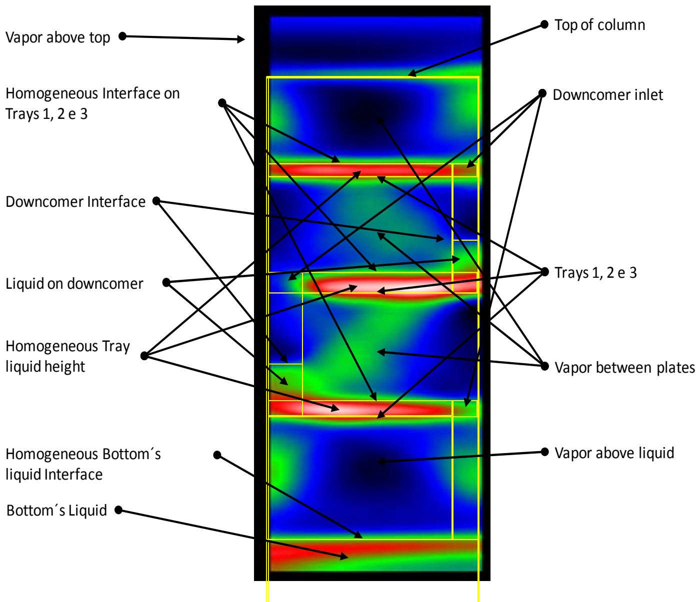

Fig. 15 Mechanical and a process diagnostics features observed on a tomographic image.

from the reader. On the other hand, some of the features observed in Fig. 15 could be indicated only with the aid of a tomographic image, as it introduces second spacial axis information: homogenity of phases, interface appearance, spacial positioning.

As it can be seem on Fig. 13 the quality of the image diminishes with the increase of the source and detector movement increments. The resolution (understand here as the minor detectable feature observed) appears to have the same magnitude order than the movement increments.

Surprisingly the quality of the images obtained with 1 and 2 inches detectors were very similar although they had totally diverse statistical basis. One hypothesis suggests that even individually weak, the reconstruction program when dealing with hundreds of measurements counter compensate the error in the data.

The experiments showed that images can be obtained with different source and detector movement increments or NaI(Tl) crystal sizes., That would indicate that good images can be obtained with different phisical arrangements (movement, increments) and equipments (source, detectors). An important part of the choose would be related with the quality of the required image, available time physical space for the test.

5. Conclusions

The inicial objective of this work was truly achieved with tomographic images of process equipment revealing the bidimentional density distribution. Features hidden on a conventional gamma ray density profile were seem with this technique adding new perspective on thoubleshotting process coluns and other industrial equipments were a conventional gamma scanning would only offer limited informations.

Although promising there are some fields that need improvements or futher development such as softwares, equipments, filters, data acquisition, calibration, etc. The simulation tools developed proven to be very useful on fine tunning the results and also planning the irradiation process saving time and personal exposition. The experience gathered indicated also concepts to be employed when adapting the technologie from labscale to real field work.

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