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Original Article

Development of gamma ray scanning coupled with computed tomographic technique to inspect a broken pipe structure inside laboratory scale vessel

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ABSTRACT

This paper presents a laboratory experiment on data acquisition technique that applied to the gamma radiation scanning coupled with computed tomography (CT) technique for inspection of broken nozzle inside the vertical vessel. The acquisition technique was developed to inspect a large diameter vessel when suspicious problem location is not easily accessed. This technique allows the installation of gamma radiation source (Cesium 137, Cs-137), and detectors (Sodium Iodine. NaI(Tl)) from the accessible location to the required location and performs the scanning by designed pattern. To demonstrate the designed technique, top opened tank which installed with six cut steel pipes diameter of 76.2 mm (3") at a certain position was selected. They were assumed to be a gas riser pipes inside the vessel. Three studied cases were performed, (a) projection of well installed six pipes, (b) projection of one out of six broken pipe and (c) one of nozzle was assumed to be failure and fell down until one out of six pipes was broken and obstructed by nozzle. Results clearly indicated the capability of developed technique to distinguish between normal situation case and abnormal situation cases.

1. Introduction

In 1972, Godfrey Hounsfield developed the technique to compute the cross-section image from measurement of X-ray data [1]. He demonstrated that, it is possible to compute high quality image with high accuracy using reconstruction algorithm. His research played important roles in the medical field which is known as Medical Computed Tomography (CT). The advantages of CT become challenged to the industrial application filed when the problem occurs inside the large object such as distillation column or vessel and the problem propagated until production processes becomes malfunction. Industrial Computed Tomography (ICT) has been developed to accommodate the technology in inspection during manufacturing, in-services and even problem shooting [2]. Advantage of using ICT is the capability to demonstrate result in image format either in 2 dimensions or 3 dimensions. The quality of reconstructed image from projection is defined by resolution of image, definitely, high resolution is preferable, but high resolution image comes with expensive equipment. Most of the system costs are bearing on the cost of detection system, data acquisition instrument and mechanical driving system. In many cases, resolution can be compromised depending on the size of interesting defects. For example, if the size of defects inside weldment is considered, a scale of millimeters resolution would be satisfied. On the other hand, if the size of interesting defect is the integrity of nozzle inside vessel, a scale of centimeters would be satisfied which is an interesting issue in this paper.

A broken nozzle inside the vessels may occur when plant is operating under abnormal condition or even under a normal operating condition. This problem is somewhat difficult to be inspected since non-destructive testing technique such as radiographic testing has limitation when dealing with large scale of test piece such as vessels or distillation column. Gamma scanning is another option of inspection methods to identify location of problems inside large vessel. The scanning is simple by using one radiation source and one radiation detector to scan and plot a density changed inside medium along each elevation. Nevertheless, gamma scanning results are difficult to be interpret since the results are presenting in form of x-y graph (radiation count vs. elevation) which required experience persons to understand [3,4]. Many industrial inspection researchers have tried to apply ICT to

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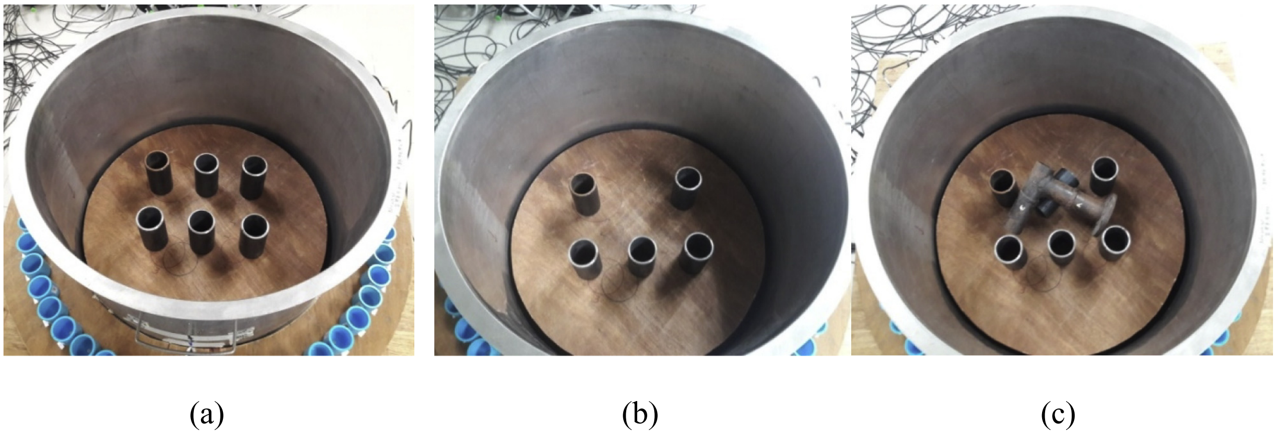

Fig. 1. Model of six metal pipes with diameter of 76.2 mm (3"), installed in two rows and three column array-like 2 × 3 (row x column) (a) six riser pipes were installed in their position, (b) one riser pipe was missing from its position and (c) assumed nozzle was broken and damaged one riser pipe.

the petroleum and petrochemical industries [5,6]. The simulation software, Monte Carlo for N-Particle (MCNP), was used to simulate a transmission of gamma rays through the interested objects and reconstructed image [7]. The designed system composed of detectors and radiation source arranged until the pattern were recognized in form of 3rd and 4th generation CT projection system. Together with simulation, experiment in laboratory scale was also presented. The image reconstructed results showed good agreement between simulation and experiment [8]. These results implied that, there is a possibility to apply ICT algorithm in inspection of any medium when the scanning system is applicable. This paper, we proposed an inspection technique to determine integrity of nozzle pipe inside vessel using gamma scanning coupled with industrial computed tomographic technique and represent the results by reconstructed image in 2 dimensions. The experiment was done through laboratory scale model as illustrated in Fig. 1. The model is a top opened tank with diameter of 800 mm. The scenario was assumed that six metal pipes diameter of 76.2 mm (3") were installed in two rows and three column array-like 2 × 3 (row x column) to represent the gas riser inside vessels. One uncollimated radiation source, Cesium-137 (Cs-137), 10 mCi and uncollimated radiation detectors sodium iodine (NaI) was installed at distance about 100 mm from surface of tank. The 11 radiation detectors used in this experiment were connected to radiation counter and transferred measured data to computer. Since the number of detectors were not sufficient to project all area of interesting, thus acquisition technique was needed complete a projections of 21 detectors [9].

2. Equipment and methodology

2.1. Equipment

This experiment used 12 channels radiation counter system to measure the transmitted radiation from gamma radiation source. The counter was connected to computer through serial communication (RS-232) with baud rate of 19200, 8 data bit, no parity, 1 stop bit as specified in user's manual. Data of all detectors was generated as a package once a second which synchronize plotting in developed software in unit of count per second. An uncollimated gamma radiation source Cs-137 with activity of 10 mCi, was used for gamma-ray emission. On the other hand, receiver side, uncollimated Sodium Iodine (NaI) radiation detectors size of 25.4 mm × 25.4 mm (1" × 1") were installed against the radiation source to receive transmitted radiation that remained after absorbed by medium. The detectors were well equipped with the photo multiplier tube (PMT) and contained inside the aluminum cylindrical container. Normally, high voltage for the detectors was set to 800 V. However, the efficiency of each detector could be different and the system calibration was required (will be discussed in section 3.1). Both radiation source and radiation detectors were arranged to meet fan beam configuration as shown in Fig. 2.

2.2. Experiment phantom

The phantom used in this experiment was opened tank made up of stainless steel with diameter of 800 mm and 1200 mm height, the tank was surrounded by PVC blocks to hold detectors in a fixed position, such that the center of tank could be regarded as a center of system rotation. Each PVC block installed at angular pitch of 7.5°. Detectors and source were aligned until the scanning area of fan beam covered all pipes inside the tank.

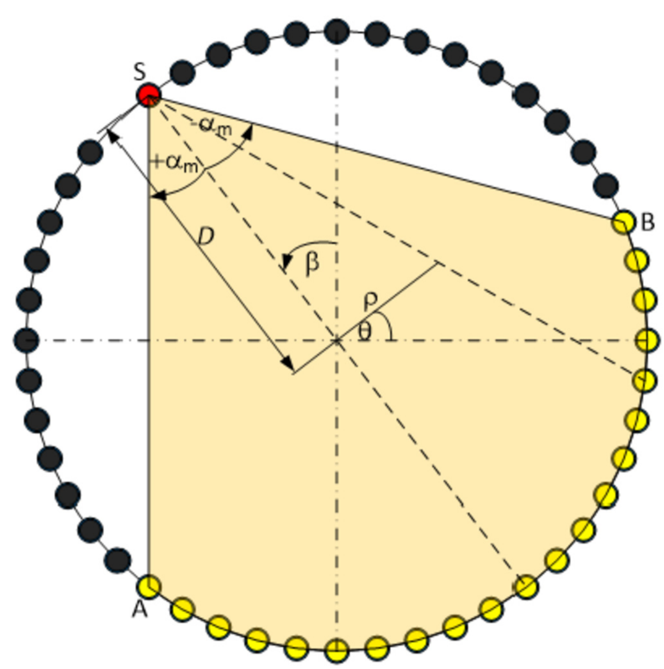

Fig. 2. Fan beam projection system.

2.3. Methodology

The system composed of gamma radiation source and detectors. They were setting until the gamma radiation can be regarded as fan beam projection. Hence, the fan beam image reconstruction algorithm can be used in this study, regardless the scattering radiation.

The image reconstruction for fan beam can be considered by the transformation from Cartesian coordinate into the polar coordinates [9]. Fig. 2 shows configuration of fan beam scanning technique. Let the shape $A\widehat{S}B$ in Fig. 2 represents the fan beam rays from the radioactive source (S) which is installed at distance D measured from center of rotation of the system. The interested information will be acquired from the detectors installed between arcs AB with the equiangular distribution of α_m (this is regarded as detector pitch). Assume that the main beam line represents the reference angle from y-axis when source is rotated by the angle of β. It can be shown that

$$\theta = \beta + \alpha \tag{1}$$

$$\rho = D \sin \alpha \tag{2}$$

By converting from Cartesian coordinate to polar coordinate,

$$\rho = x \cos \theta + y \sin \theta \tag{3}$$

Apply (2) and (3) to obtain the function that represents the individual ray sum when angle of interest of detectors are bounded by $-\alpha_m$ to $+\alpha_m$, $f(x\,,\,y)$ can be obtained and apply in Radon transform by

$$f(x,y) = \frac{1}{2}\int_0^{2\pi}\int_{-\alpha_m}^{\alpha_m} g(D\sin\alpha,\quad \beta+\alpha)\delta(r\cos(\beta+\alpha-\theta) - D\sin\alpha)\, D\cos\alpha\, d\alpha\, d\theta \tag{4}$$

In this experiment, the number of detectors was 21 and each detector pitch, α_m, was 7.5°. Thus equations (2)–(4) reconstructed the function $f\,(x,y)$ using Filtered Back Projection algorithm (FBP) would be a function of image. Ram-Lak filter function, $h(k)$ in (5) was used in this study [10].

$$h(k) = \begin{cases} \dfrac{1}{4\tau^2} & for \quad k = 0 \\ 0 & for \quad k = even \\ -\dfrac{1}{k^2\pi^2\tau^2} & for \quad k = odd \end{cases} \tag{5}$$

$\tau = 1,\ k = -(N-1)/2, \ldots, -2, -1, 0, 1, 2 \ldots (N-1)/2$

Applying filter (5) into (4), we obtained (6) filtered back projection for image reconstruction

$$f(x,y) = \frac{1}{2}\int_0^{2\pi}\int_{-\alpha_m}^{\alpha_m} g(D\sin\alpha,\quad \beta+\alpha) * h(k)\, \delta(r\cos(\beta+\alpha-\theta) - D\sin\alpha)\, D\cos\alpha\, d\alpha\, d\theta \tag{6}$$

As indicated in Figs. 2 and 21 detectors generated a signal corresponding to the attenuation between radiation source and detectors. The radiation source and detectors rotated counter clockwise from one position to another position and record generated signal (one projection). The rotation continues until it reaches to 360° (in this study, since the pitch was 7.5° therefore 48 projections were done for single scan). In each projection, there was a gap of information between each detector such that the back projected image resolution was too low. Linear interpolation algorithm was incorporated in the computation process in order to increase the data point between projected lines; in this experiment, 25 interpolation points were calculated.

The smallest object inside the fan beam that expected to be scanned is depending on the pitch between detectors which can be calculated by (7).

$$\boldsymbol{pitch} = 2\boldsymbol{D}\sin\boldsymbol{\alpha_m} \tag{7}$$

2.4. Data acquisition technique for small number of detectors

As an algorithm of generation 3 computed tomography, it required rotational system of both radiation source and detectors, simultaneously. In a case of small phantom, it is possible to invent the rotational system and install them at the interesting phantom to be inspected. However, to inspect the large vessel on-site the rotational system is too complicate to install all such equipment surrounding the object since the external structure may obstruct the scanning. Thus, manually acquisition technique is required to avoid the external structure and try to keep the equipment as simple as possible to ensure that handling of equipment would not be an issue for scanning operation. The idea of scanning is to use the small number of detectors and move them from the top of vessel to the proper position as required by fan beam algorithm.

The equipment composed of 11 radiation detectors and one gamma radiation source. In order to increase a resolution as well as increasing an area of interested, 21 detectors were preferred. The technique to fulfill the projection of 21 detectors was to separate the data collection into two halves or two projection sets. The first set of projection represented first half of fan beam, i.e. detector number 1 to 11while second half of projection completed full

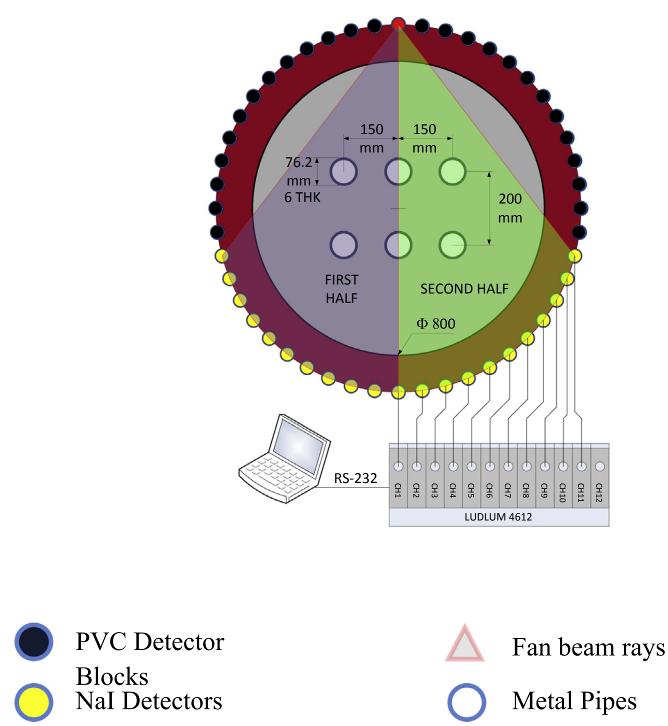

Fig. 3. Measurement system setting up and configuration of radiation equipment in fan beam pattern.

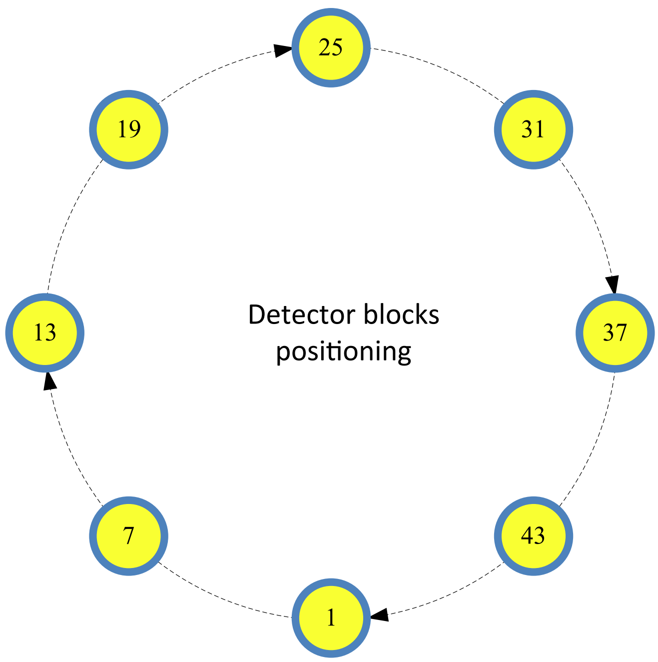

Fig. 4. Sequential of detectors blocking.

projection, i.e. detector number 12–21 as indicated in Fig. 3.

As mention, complicate system might not be applicable when working on-site since it is too difficult to be installed and to be operated, thus manually operating system shall be used to make the position of source and detectors until the data collection fits to the CT-fan beam algorithm. In order to explain the manual operation, the system was designed with 48 positions of PVC blocks and placed around the tank 360°. These PVC blocks were used to hold the radiation source and detectors at their position. They were numbering in the sequences as indicates in Fig. 4. Since the detectors used in the experiment were 11 detectors but the projection required 21 data for 1 projection. Thus the algorithm for scanning is required. Fig. 5 shows the data collection algorithm. Following steps explain the operation of Fig. 5 (a) to Fig. 5 (d).

In Fig. 5 (a), it generates the first half of projection #25 and second half of projection #35. As indicated in purple shading and green shading color in Fig. 5 (a), radiation source is placing in position 25 while all detectors are placed in position 1 to 11, respectively. This represents the first half of projection #25. For the second half of projection #35, radiation source is moved from position 25 to position 35.

In Fig. 5 (b), it generates the first half of projection #24 and second half of projection #34. As indicated in purple shading and green shading color in Fig. 5 (b), radiation source is placing in position 24. In this case, detector number 11 was moved from position 11 to position 48. This represents the first half of projection #24. For the second half of projection #34, radiation source is moved from position 25 to position 35.

In Fig. 5 (c) and Fig. 5 (d), they generate the first half and second half of consequence projections. The operation processes continued until they cover the 48 projections (360° scanning). In total, the radiation source moved 96 times while the detectors were moved 48 times. With this invented algorithm, radiation source and detectors were freely to be located to the assigned position.

As results of scanning, the data composed of 96 sets of with the pre-defined arrangement. It is important to re-shuffle all data into the patterned that fold the data to suit with the filtered back projection algorithm. Regarding to section 2.3 Methodology, the value of β is 7.5° and obviously the value of α_m is 3.75° where m is varied from 1 to 21 as the number of detectors. The parameter D is a half of distance between radiation source and detector at the center line of fan beam. In this experiment, there are 48 projections which is a function of $g(D \sin\alpha, \ \beta+\alpha)$ in (6). Each projection composed of 21 rays-sums from angle $-\alpha_1$ to α_{21}. The size of object to be inspected is depending on the pitch between detectors as indicated in (7). In this experiment the smallest size of object that expected to be scanned is 58.87 mm in diameter.

3. Experiment

3.1. System calibration

The calibration was done by adjusting allowed parameters, i.e. High Voltage (HV), Lower Level Discrimination (LLD) and Upper Level Discrimination (ULD). The LLD was setting until the measured signal had overcome the background radiation (noise and Compton scattering). Setting up ULD was opened since the radiation of higher energy played less dominant influence to the measurement data. Lowest count from one detector was selected as a reference detector and adjusted others detector's HV until the radiation count became closed to reference detector. This is the most important process since all detectors must be able to measure as a compatible to each other. If the system was not well calibrated, mess up reconstructed image would come.

The main idea of system calibration, in this case, is to adjust the parameter until all measured information from 11 detectors is representing as the same as using only one detector in the corresponding positions.

(a) Before calibration

The evaluation of detector's efficiency was done by first select one detector to measure the transmitted radiation at the location where all 21 positions are required, see Fig. 6. At the center, place

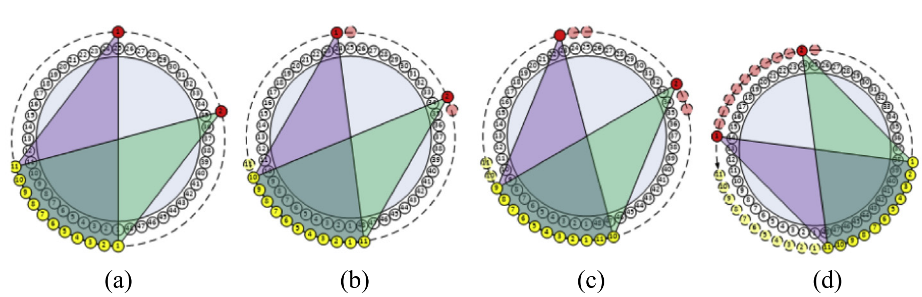

Fig. 5. Projection pattern proposed to scan in laboratory model. The purple shading represent scanning of first half while green shading represent scanning of second half.

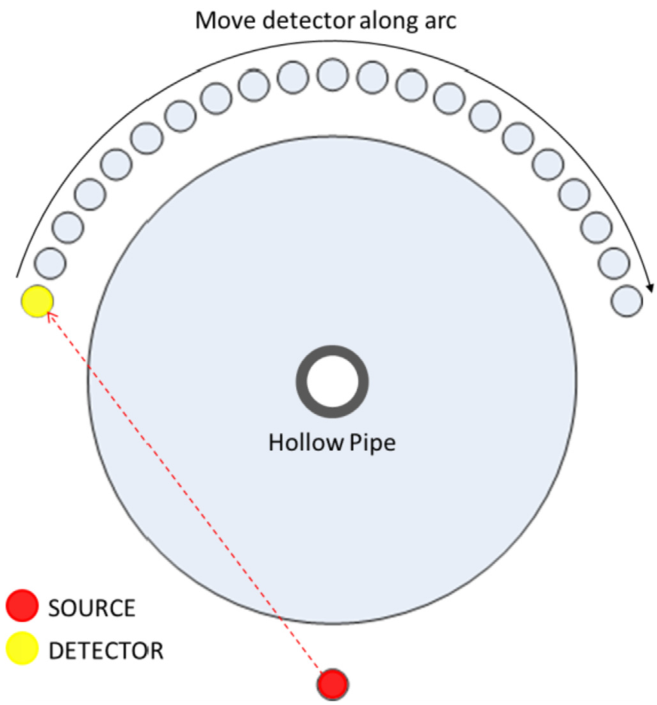

Fig. 6. Make a profile using one detector.

the 101.6 mm hollow pipe in order to obtain scanning profile which represents a pipe. The profile from one detector measurement is regarded as "reference profile". The measurement was done step by step at position by position until complete the 21 position, as indicates in Fig. 6. Plot the measured radiation count against the positions.

Second step, place all 11 detectors in their positions and measured transmitted gamma radiation for first and second half set

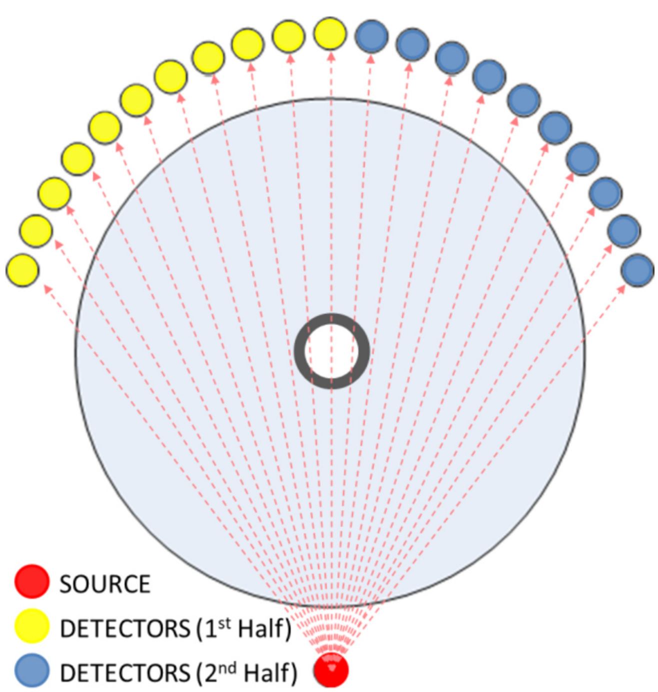

Fig. 7. Make a profile using 11 detectors for 21 positions.

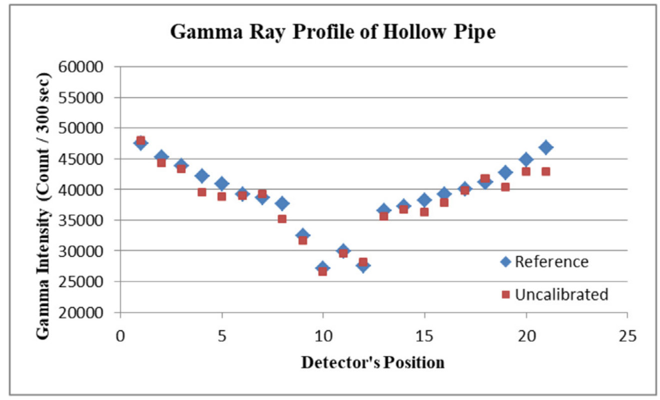

Fig. 8. Profile comparison before calibration.

as indicates in Fig. 7. Plots both sets in one graph and compare with reference profile as indicates in Fig. 8. Obviously, the uncalibrated detectors produced a difference profile compared to the reference. The goal of calibration was intend to tune up all detectors to measure the radiation as the same.

(b) After calibration

The system calibration experiment is quite tedious but important since it required several measurement and judgement on the measured data as described in 3.1 (a). The "high voltage", "upper limit discriminator" and "lower limit discriminator" were the allowed parameters to tune up. Measurement processes as indicated in Fig. 7 were again required and compare to the plotting of reference profile and showed in Fig. 9. A calibrated profile was accepted as almost closed to the reference profile.

3.2. Experiments and results

The experiments aimed to determine cross-section pictures in two dimensions (2D) of interested plane using simplest equipment by considering the possibility of operation in field works. Three studied cases were done as follow: (a) all six riser pipes were well installed inside the vessels at their position, (b) assumed that one riser pipes were broken and missed from its installed position and (c) assume there was a fallen down broken nozzle inside vessel damaged one riser pipe.

Studied case 1, well installed six riser pipes. Fig. 10 (a) shows reconstructed image projected onto 21 detectors. The

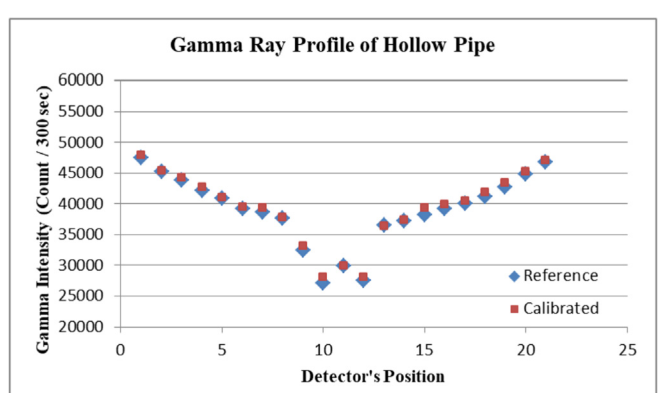

Fig. 9. Profile comparison after calibration.

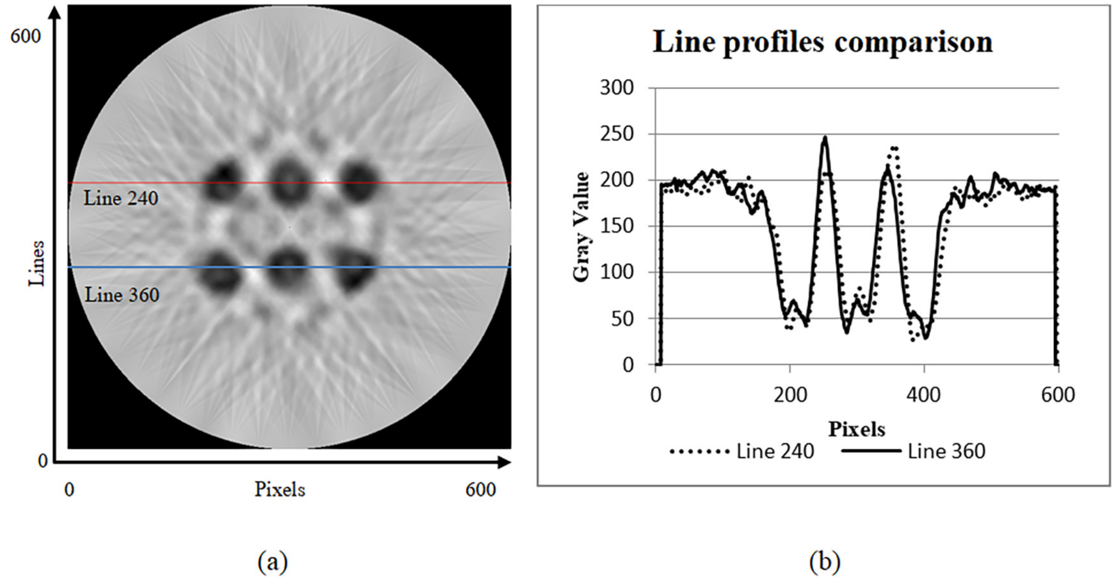

Fig. 10. (a) Reconstructed image of normal installed pipes and (b) plotting profiles at pixel line #240 compared to pixel line #360.

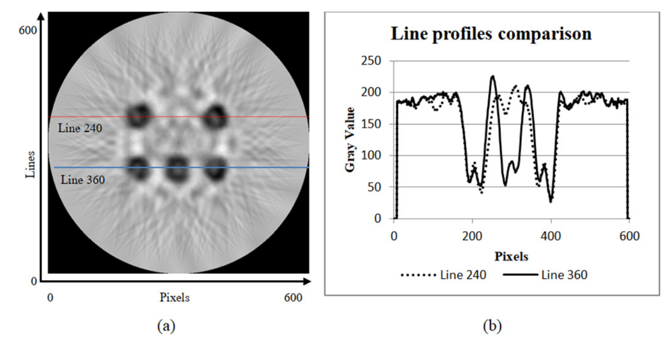

Fig. 11. (a) Reconstructed image of one missed pipes and (b) plotting profiles at pixel line #240 compared to pixel line #360 of studied case 2.

reconstructed image was clearly showed the position of six riser pipes when it was normally installed. Fig. 10 (b) shows the comparison between pixel profile line #240 and pixel profile line #360. Though a distortion of image through the pixel profile was observed since both plotting were not completely superimposed onto each other, their trends provided good agreement to each other.

Studied case 2, one riser pipes was damaged and missed from position. Fig. 11 (a) shows reconstructed image of one missed pipe case. The image was clearly showed the location where pipe was missing from position. Fig. 11 (b) shows the comparison between pixel profile line #240 and pixel profile line #360. Profiles also clearly showed that one pipe was missing from its position.

Studied case 3, broken nozzle fell down and damaged one riser pipe. This case assumed that a nozzle with pipe flange was broken and fell down to damage one of riser pipe and obstruct in between the riser pipes. Fig. 12 (a) shows reconstructed image of case 3. The

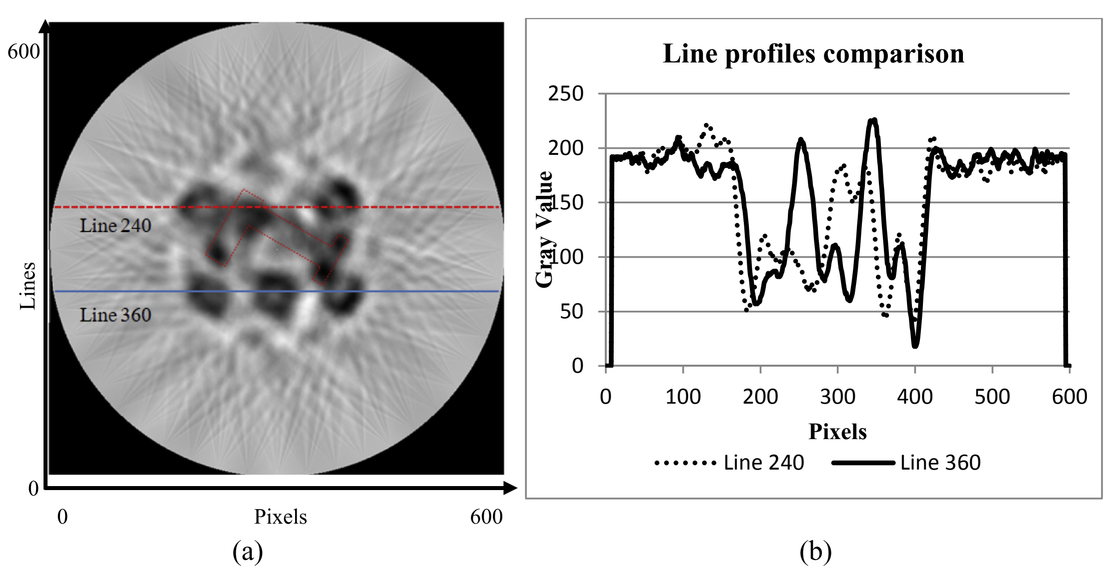

Fig. 12. (a) Reconstructed image of one missed pipes and (b) plotting profiles at pixel line #240 compared to pixel line #360 of studied case 3.

image was not clear to show the damaged nozzle pipe with flange since inside the nozzle was empty, thus gamma ray absorption in that area was low, however it clearly showed the abnormality occurred in the area of pipe riser. Fig. 12 (b) shows the comparison between pixel profile line #240 and pixel profile line #360. Profiles also clearly showed the problem occurred at location of riser pipe in the middle of top row compared to Fig. 10 which normal riser pipes were installed. To be slightly bias, drawing of broken nozzle on reconstructed image is illustrated as a red shape in Fig. 12 (a).

4. Conclusion

This experiment shows the capabilities of developed data acquisition technique for gamma radiation scanning couple with computed tomography technique in order to identify the problem inside vessels without complicate rotational mechanic system. The flexibility of equipment in system allowed the scanning in many patterns such as proposed pattern, but not limited to. The movement of all equipment showed the possibility to install equipment from accessible location provided that the equipment must be well install in their position. The demonstration results showed that computed tomography technique could be manually performed if the back projected image resolution met the minimum detectability requirement. In this studied cases, only 11 detectors were used in measurement system to detect the riser pipes with diameter of 76.2 mm. Though the resolution was not fine enough to see the thickness of pipes, it could identify the location of pipes in both normal situation and abnormal situations. Studied case 1 and case 2, back projected images were easily to be interpreted and identify the location of riser pipes in case of normal and abnormal situation, respectively. If problem is limited to only pipe rupture or pipe missing location, detection of problem would not be complicated but as showed in studied case 3, the reconstructed image was fuzzy and difficult to be interpreted. Without prior knowing the problem's shape, identification of problem in this case would be difficult to know that it was a broken nozzle. One reason of fuzzy reconstructed image in case 3 was that a broken nozzle in the model filled with air; hence detection was also difficult to identify only the periphery of nozzle by their coarse resolution. The selection of proper elevation to scan could improve the image, but not enough for single layer scanning. This further leads to multiple layers scanning technique by means of collect the data and reconstructed them in each elevation, change elevation and repeat the operation again until satisfactory elevation was done. All reconstructed image are stacking as layers and render them into three dimension images. Even though, the model used in this study was small size compared to real vessel used in petroleum and petrochemical industries, the ideas and techniques from this study can be applied to the larger diameter but pitch of detectors must be properly assign to assure that all information are good enough for interpretation. It is also important to note that scanning of normal situation is very important to record the system when it is operating under normal condition and can be regarded as a fingerprint of the system. In case of problem occur, it can be used to compare the results and clearly identify the location of problem.

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