Effect of projections number on the image quality of industrial parallel beam gamma tomography

Bayu Azmi and Megy Stefanus

Center for Isotopes and Radiation Application, Badan Tenaga Nuklir Nasional (BATAN), Jl. Lebak Bulus Raya No. 49 Jakarta 12440, Indonesia
E-mail: bayuazmi@batan.go.id

Abstract. Gamma tomography technique can provide cross-sectional visualization of an object that needed for investigating pipe scale in geothermal power plants. Parallel beam tomography has advantages such as a simple system so that it is easier to apply in the field, but the scanning duration is relatively long. This paper discusses the effect of projections number on the reconstructed images quality and proposes the number of most effective projections for pipe scale investigation. Geothermal pipe sample (OD= 275 mm, t= 10 mm) with scale has been scanned with a parallel beam gamma tomography system. The system consists of a gamma radiation source (137Cs, 80 mCi), scintillation detector, motorized gantry, control module, data acquisition, and computer. The images were reconstructed with six different projections: 128, 64, 32, 16, 8, and 4 projections and the scanning duration: 530.8, 258.9, 127.9, 63.5, 31.7, and 15.8 minutes, respectively. Visually, the 128 projections data produces the smoothest image, whereas 64 and 32 projections images look almost the same. The 16 and 8 projections images are still able to distinguish between the pipe wall, scale, and void even though the 8 projections image looks very blurry. Then, the 4 projections image is not able to visualize the shape of the object. The gaps between the average pipe wall and void gray-scale pixels value of 128, 64, 32, 16, 8 and 8 projections images are 175, 174, 167, 153, 106, and 45, respectively. Based on the scanning duration, visualization, and the gray contrast, then the number of most effective projections is 32.

1. Introduction

Pipelines are an essential part of the industrial process such as petrochemical, oil and gas, power plant, and so on. Pipes serve to transport the fluid for both production and distribution purposes. During the process, precipitation may occur, which results in a scale in the pipeline. The scale is the deposition of inorganic minerals inside the pipeline [1]. It is occurring in the oil-gas pipeline system reduces the effective flow area, increases the flow resistance and reduces the transportation ability of pipe, and even leads to a potential blockage [2], [3], [4].

In a geothermal power plant, fluid is transported to the power plant through the well, minerals with low solubility begin to precipitate in an uncontrollable manner on the equipment [5]. Typical problems associated with scaling include clogging of pipes and wells, reduced efficiency of pumps and heat exchangers, reduced reinjection capacity as well as accumulation of hazardous materials (e.g., Pb- and Ra-bearing scales) that require costly disposal [6], [7], [8]. It also reduces the harvesting of energy from brines [9].

Gamma tomography system has been developed to visualize the internal condition of industrial units including geothermal pipeline [10]. It is a parallel beam tomographic system using a couple of transmitter and receiver called the first-generation tomography system. Gamma tomography is an
efficient and reliable method for cross-sectional imaging of industrial processes and equipment. In the beginning, in the early 1970s, CT was used solely in the medical field, but early 1980s adaptations from medical CT technology started to appear for industrial non-destructive evaluation (NDE) [11]. While for medical tomography, the patient goes to the computed tomography system (CT), for industrial applications, the CT system should be transported up to the object (pipe or column) and, mechanically, adapted to the object setting [12].

Based on our experiences, the parallel beam gamma tomography is good enough to be applied in the field because of its simple components and simple measurement systems. The less electronic and mechanical components make it more resistant to extreme conditions in the industrial field. However, the parallel beam method has a limitation that is the relatively long data collection duration. The duration of data collection depends on the object dimension, the amount of data in one projection (translational scan step), and the number of projections.

The speed and the image quality are interrelated and affect the cost of the tomography system [13] as shown in Figure 1. Spatial resolution is the number of pixels in the image depending on the translation scanning step. The smaller the distance between the translational steps, the smaller the pixel size, which means higher image resolution. Whereas, contrast is the ability of the tomographic system to distinguish object density values distribution.

![Figure 1](image)

**Figure 1.** The tomography system cost is proportional to the area of the triangle [13].

In this paper, a portable parallel beam gamma tomography system has used to scan a geothermal pipe sample. The scans were conducted in a vary of projections number. The images were reconstructed using filtered back projection (FBP) algorithm. Furthermore, the pixels of the image were analyzed to study the effect of projections number to the image quality.

2. **Materials and methods**

2.1. **Object**

A sample of a geothermal pipe was used as the object as shown in Figure 2. The sample was taken from a geothermal power plant company in Central Java. The outer diameter is 275 mm with 10 mm of wall thickness. There is a scale inside the pipe with an average thickness of around 90 mm.
2.2. Tomographic system

The industrial gamma tomographic scan method is a class of tomography that was derived from medical applications [14]. Modern medical CT has 3rd or 4th generation gantry with an X-ray source of ~130 keV [15]. Figure 3 shows the development of tomography geometry from the 1st to the 4th generation. The 1st generation turns the translation and rotation of a source and a detector. The 2nd generation has multi-detectors, but it cannot cover an object entirely and has to translate to cover an object fully. In 3rd and 4th generation, the beam angle can cover the object entirely, rotational one is sufficient to generate the projection.

The portable 1st generation of gamma tomography system was used in this research. The system uses a single gamma source and a single detector as shown in Figure 4. The slit's diameters of the collimators are 5 mm, the system can cover an object with a diameter up to 550 mm.

The 137Cs (80 mCi) was used as the gamma source. It is commonly used in nuclear gauging applications in industries because it has a long half-life, it does not scatter interference of photons of other energies and emits a single clear photo peak [16]. The 137Cs have a half-life of 30.23 years and
decays by pure $\beta$- decay, producing $^{137}\text{Ba}$, which creates all the gamma-ray emissions with an energy peak of 662 keV [17]. The gamma sensor was the NaI(Tl) scintillation detector.

**Figure 4.** Parallel beam gamma tomography system.

In this research, the translational scan was every 5 mm, which is mean the resulting image pixel size is $5 \times 5$ mm$^2$. As mentioned above, the rotational scans varied from 4 to 128 projections. The measurement parameters, as shown in Table 1. Figure 5 shows the measurement setup.

**Table 1.** Measurement parameters.

| Scans          | Condition                        |
|----------------|----------------------------------|
| Translational scan | 5 mm per step                    |
| Rotational scan  | • 4 projections (45$^\circ$ per step) |
|                 | • 8 projections (22.5$^\circ$ per step) |
|                 | • 16 projections (11.25$^\circ$ per step) |
|                 | • 32 projections (5.62$^\circ$ per step) |
|                 | • 64 projections (2.81$^\circ$ per step) |
|                 | • 128 projections (1.41$^\circ$ per step) |

**Figure 5.** Measurement setup.
2.3. Image reconstruction and analysis
There are two categories for image reconstruction algorithms, the analytical algorithm and the iterative algorithm. Analytical algorithms have a single step filtering process and back-projection process, while iterative algorithms repeat the process for projection and back-projection [14]. In this research, a filtered back projection (FPB) algorithm was used to reconstruct the images. It is an analytical algorithm. The filtered back-projection algorithm is a well-known classical technique, if the fast Fourier algorithm is used, then the data should be obtained in 2n parallel rays and use of the radon transformation [13]. The radon transform is defined as [18]:

\[ R(f) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) \delta(x \cos \theta + y \sin \theta - t) \, dx \, dy \]  

(1)

where \( x, y \) are the coordinates and \( t \) is the distance between translational steps. Image obtained by restoring the value of radon to the \( x, y \)-axis by using the inverse radon (iradon):

\[ \mu(x, y) = \int_{0}^{2\pi} P(t) \int_{0}^{\infty} \delta(x \cos \theta + y \sin \theta - t) \, dt \, d\theta \]  

(2)

where \( \mu \) is the pixel value.

The filter used was a Hann filter. Hann filter is better at recognizing object density distribution than other filters such as Ramp, Shepp-Logan, Hamming, and Cosine filters [19]. The filter is designed directly in the frequency domain and then multiplied by the Fast Fourier Transform (FFT) of the projections. The projections are zero-padded to a power of 2 before filtering to prevent spatial domain aliasing and to speed up the FFT.

Image analysis was done by calculating the pixels value. The images were reconstructed to 8-bit grayscale pixel value with 0 is the darkest color (black) and 255 is the brightest color (white). Images analysis was aimed to study the contrast of the images. It is to calculate the ability of reconstructed images to recognize the density distribution of the object.

3. Results and discussion
Measurements have been carried out using the industrial parallel beam gamma tomography system. The sinograms of projections data as shown in Figure 6. Based on the sinograms, the data has been collected properly. There is no data shift and there is no noticeable intensity in the data set. The more projections number then the sinograms become smoother.

The reddish color indicates a high intensity, which in this case is air. The dark blue color is low-intensity data (pipe wall dan scale). There is a bright blue color in the middle of the sinograms, which is the void of the pipe (the air between the pipe scale). The reason why the void area in the middle of the pipe is not red color (high intensity) is that the gamma radiation passes through the pipe wall and the scale is not like the air area of the beyond of pipe, while the air outside the pipe is not obstructed by any material.

The parallel beam tomography system limitation is the measurement duration. In this research, it took about 530 minutes to complete the 128 projections of a pipe with a diameter of 275 mm (translational scan was per 5 mm). The complete measurement duration as shown in Table 2.

It is a major issue when it takes almost 9 hours to collect cross-sectional data of a relatively small pipe. It makes the measurement system ineffective for industrial applications. The image is reconstructed from various numbers of projections as shown in Figure 7. It aims to study the effectiveness of the number of projections on the reconstructed image.

As mentioned above, since speed (measurement duration) and image quality are interrelated and affect the cost of the tomography system, then it is necessary to make a compromise between speed, contrast and spatial resolution. It means, if the image quality (spatial resolution and contrast) is expected to be high, then the speed will be low. When the spatial resolution was fixed by translational scan step (5 mm), then we need to compromise with the image contrast.
Figure 6. Sinograms of data.

Table 2. Measurement duration at each projection.

| Projections number | Duration (minutes) |
|--------------------|--------------------|
| 4                  | 15.8               |
| 8                  | 31.7               |
| 16                 | 63.5               |
| 32                 | 127.9              |
| 64                 | 258.9              |
| 128                | 530.8              |

Figure 7. Reconstructed images.
Figure 7 shows the reconstructed images from various numbers of projections. Based on visual observation, the image reconstructed with 4 projections data is failed to visualize the object geometry. That is due to the lack of projections data to be reconstructed into an image. The image from the 8 projections data looks better than the image from the 4 projections data. The shape of the pipe can be identified. The scale and voids in the middle of the pipe can also be visualized. However, there is a lot of noise in the air area outside the pipe, pipe wall, scale, and in the void area in the middle of the pipe. The contrast between void and scale pixel values is not very good. The next is 16 projections image. The image can visualize the pipe, scale, and void clearly. The contrast between void and scale is better than the 8 projections image.

The last three images (32, 64, and 128 projections) are much better than the previous three images. The 128 projections image looks very smooth. The 32 projections and 64 projections images look the same, but the 64 projections image looks smoother than the 32 projections image.

Figure 8 shows the pixel value plotting profiles of all projections reconstructed images and a model of the ideal pixel value of the object. Based on the profiles, the 128, 64, and 32 projections reconstructed images show relatively the same, while the 16 projections reconstructed image shows a little bit near to them but less contrast between the void and the scale. The pipe wall intensity also looks asymmetrical. Figure 9 shows the plotting profiles of 128, 64, 32, and 16 projections images to provide clearer observations. The gaps between the average of pipe wall pixel values and the void pixel value as shown in Table 3. The bigger number of the gap indicates the contrast of the image is high.

Figure 8. (a) Pixel value line of 128 projections reconstructed image and (b) all projections pixel value line plotting profiles.

| Projections number | Gap (8-bit pixels value) |
|--------------------|--------------------------|
| 4                  | 45                       |
| 8                  | 106                      |
| 16                 | 153                      |
| 32                 | 167                      |
| 64                 | 174                      |
| 128                | 175                      |

Table 3. Gaps between average pixel value of pipe walls and voids.
Figure 9. Plotting profiles of 128, 64, 32, and 16 projections reconstructed images.

The image from 16 projections data shows a quite good result. If the purpose of the investigation is limited to study the internal structure of the object qualitatively, then the 16 projections can be used with consideration of less measurement duration compared to the more projections number. But if the objective is to study the object quantitatively, then 32 projections number 32 can be considered related to the measurement time is much shorter than 64 or 128 projections number.

The 8 projections can be used if the measurement objective is to study the structure of an object without expecting good geometric accuracy. While the number 4 projection is not recommended for use because it fails to visualize the object being measured.

4. Conclusion
This research proves that the number of projections affects the quality of the image. The number of projections is directly proportional to the contrast of the reconstructed image. The higher the number of projections, the higher the image contrast will be. However, more projections will increase the duration of the measurement. Based on the analysis results of the reconstructed images, the 32 projection images have almost the same quality compared to 64 and 128 projections reconstructed images. Due to the consideration of measurement duration, the 32 projections number is recommended for use in the industrial field. The 16 projections number can be used if the measurement is not oriented towards the quantitative analysis of the object. Based on this research, it is also found that the minimum number of projections so that the reconstructed image can visualize the geometry of the measured object is 16 projections.

Acknowledgment
The authors would like to acknowledge Center for Isotopes and Radiation Application-National Nuclear Energy Agency (BATAN) for supporting this research. We also thank to Mr. Wibisono and Mr. Adhi Harmoko Saputro for their help in this research.

References
[1] Jing G, Tang S, Li X and Wang H 2017 The analysis of scaling mechanism for water-injection pipe columns in the Daqing Oilfield Arab. J. Chem. 10 S1235–9
[2] Quan Q, Gong J, Wang W and Gao G 2015 Study on the aging and critical carbon number of wax deposition with temperature for crude oils J. Pet. Sci. Eng. 130 1–5
[3] Haj-shafiei S, Serafini D and Mehrotra A K 2014 A steady-state heat-transfer model for solids deposition from waxy mixtures in a pipeline FUEL 137 346–59
[4] Duan J, Deng S, Xu S, Liu H, Chen M and Gong J 2018 The effect of gas flow rate on the wax deposition in oil-gas stratified pipe flow 162 539–47
[5] Demir M M, Baba A and Atilla V 2014 Types of the scaling in hyper saline geothermal system in northwest 50 1–9
[6] Basin M, Germany S, Wanner C, Eichinger F, Jahrfeld T and Diamond L W 2017 Causes of abundant calcite scaling in geothermal wells in the Bavarian Geothermics 70 324–38
[7] Bozau E, Häußler S and Berk W Van 2015 Hydrogeochemical modelling of corrosion effects and barite scaling in deep geothermal wells of the North German Basin using PHREEQC and PHAST Geothermics 53 540–7
[8] García A V, Thomsen K and Stenby E H 2006 Prediction of mineral scale formation in geothermal and oilfield operations using the Extended UNIQUAC model Part II. Carbonate-scaling minerals Geothermics 35 239–84
[9] Topcu G, Çelik A, Kandemir A, Baba A, Sahin H and Demir M M 2019 Increasing solubility of metal silicates by mixed polymeric antiscalants 77 106–14
[10] Azmi B, Wibisono and Saputro A H 2017 Portable Gamma Ray Tomography System for Investigation of Geothermal Power Plant Pipe Scaling 15th Intl. Conf. QiR Intl. Symp. Elec. Com. Eng 159–63
[11] Villarraga-Gómez H, Herazo E L and Smith S T 2019 Progression of X-ray computed tomography from medical imaging to current status in dimensional metrology Precis. Eng. 58 1–50
[12] Velo A F, Hamada M M, Carvalho D V S, Martins J F T and Mesquita C H 2017 A portable tomography system with seventy detectors and five gamma-ray sources in fan beam geometry simulated by Monte Carlo method Flow Meas. Instrum. 53 89–94
[13] Anon 2008 Industrial Process Gamma Tomography IAEA-Tedoc-1589
[14] Kim J, Jung S, Moon J and Cho G 2011 Industrial gamma-ray tomographic scan method for large scale industrial plants Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 640 139–50
[15] Seibert J A and Boone J M 2005 X-Ray Imaging Physics for Nuclear Medicine Technologists. Part 2: X-Ray Interactions and Image Formation * J. Nucl. Med. Technol. 33 3–18
[16] Al-Juwaya T, Ali N and Al-Dahhan M 2017 Investigation of cross-sectional gas-solid distributions in spouted beds using advanced non-invasive gamma-ray computed tomography (CT) Exp. Therm. Fluid Sci. 86 37–53
[17] Al Mesfer M K, Sultan A J and Al-Dahhan M H 2016 Impacts of dense heat exchanging internals on gas holdup cross-sectional distributions and profiles of bubble column using gamma ray Computed Tomography (CT) for FT synthesis Chem. Eng. J. 300 317–33
[18] The Duy D N, Quang N H, Dao P Van, Duy B T and Chuan N Van 2015 A Third Generation Gamma-ray Industrial Computed Tomography Systems for Pipeline Inspection J. Teknol. 17 49–53
[19] Azmi B, Wibisono, Darman and Sugiharto 2019 Effect of Filter on Image Reconstruction using Filtered Back Projection Algorithm for Industrial Gamma-Ray Tomography Technique A Sci. J. Appl. Isot. Radiat. 15 57–67