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Gamma Tomography as A Complementary Technique for Pipe Scale Inspection: Field Experiment at Petrochemical Plant

Tomografi Gama sebagai Teknik Pelengkap untuk Inspeksi Kerak Pipa: Eksperimen Lapangan di Pabrik Petrokimia

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ABSTRACT

Crack gas flowing from furnace to gasoline fraction tower through BA-106 pipeline. The pipeline has not been inspected for 30 years of operation and it is suspected that there is pipe scale in it. The scaling reduces the inner diameter of the pipe which disrupt the pipeline flow rate that might cause a fatal accident. The scale particles also became impurities in the subsequent process. The information on scale conditions inside the pipeline is needed to determine further action to ensure safety and maintain the productivity of the plant. The gamma scanning technique was conducted at 18 points to diagnose the scaling profile inside the pipe. A collimated 2.96 GBq ^{137}Cs radiation source emits a pencil beam of gamma photons to penetrate the pipe. A NaI(Tl) scintillation detector was placed opposite the gamma source to detect the photons. They were moving in parallel vertically and horizontally for every 10 mm step to get the attenuation profile of the pipe. Furthermore, a tomography scan was performed at selected points with 32 projections data. So far previous experiments were performed in the laboratory and the objects were smaller (less than 500 mm), however, the current experiment was performed in real industrial plants and the object diameter was about 1500 mm. The reconstructed image has been successful in showing the cross-sectional of the pipe that consists of scale inside it. The image was analyzed to get the percentage of the remaining fluid area due to scaling. The remaining fluid area was 56.15% of normal pipe without scale. It was proved that the gamma tomography technique is suitable for pipe scale measurement to get the cross-section visualization of the pipe.

Keywords: Field experiment, gamma tomography, industry, petrochemical plant, pipe scale.

ABSTRAK

Crack gas mengalir dari tungku ke tower fraksi bensin melalui jalur pipa BA-106. Jalur pipa tersebut tidak pernah diperiksa selama 30 tahun beroperasi dan dicurigai terdapat kerak pipa di dalamnya. Pengerakan mengurangi diameter dalam dari pipa yang mengganggu laju aliran jalur pipa yang dapat menyebabkan kecelakaan fatal. Partikel-partikel kerak juga menjadi pengotor pada proses berikutnya. Informasi kondisi kerak di dalam jalur pipa sangat dibutuhkan untuk menentukan tindakan selanjutnya untuk menjamin keselamatan dan menjaga produktivitas pabrik. Teknik pemindaian gamma telah dilakukan di 18 titik untuk mendiagnosa profil pengerakan di dalam pipa. Sumber radiasi 2,96 GBq ^{137}Cs terkolimasi memancarkan berkas pensil foton gamma untuk menembus pipa. Sebuah detektor sintilasi NaI(Tl) diposisikan berlawanan dengan sumber radiasi untuk mendeteksi foton. Mereka bergerak secara parallel secara vertical dan horizontal setiap 10 mm untuk mendapatkan profil atenuasi pipa. Selanjutnya, pemindaian tomografi dilakukan pada titik yang dipilih dengan 32 data proyeksi. Selama ini eksperimen sebelumnya dilakukan di laboratorium dan objeknya lebih kecil (diameter kurang dari 500 mm), namun eksperimen kali ini dilakukan di lapangan industri dan diameter objeknya 1500 mm. Citra hasil rekonstruksi berhasil dalam menunjukkan penampang lintang pipa yang mengandung kerak di dalamnya. Citra dianalisis untuk mendapatkan persentase area fluida tersisa yang diakibatkan oleh pengerakan. Area fluida yang tersisa adalah 56,15% dari pipa normal tanpa kerak. Ini membuktikan bahwa teknik tomografi gamma cocok untuk pengukuran kerak pipa untuk mendapatkan visual penampang lintang pipanya.

Kata kunci: Eksperimen lapangan, tomografi gama, industri, pabrik petrokimia, kerak pipa.

INTRODUCTION

The furnace produces crack gas to be flown to the gasoline fraction tower at the olefins plant in the largest petrochemical industry located in Banten province-Indonesia. Particle residue of the gas cracking process was found in the BA-106 pipeline. The BA-106 has a diameter of 1219.2 mm, a wall thickness of 12.7 mm, and a length of 20 m. Its position is about 15 m above earth level. The temperature of the gas flowing within it was 150 ºC, so the pipe was encased in insulation and a jacket with 150 mm of thickness. This pipeline has not been inspected after 30 years of operation and is suspected to consist of scale inside it.

Scale is the deposition of inorganic minerals inside the pipeline [1]. The scaling inside the pipeline will reduce the gas flow rate due to the inside diameter of the pipeline becoming smaller. The residual particles also become impurities in the next process. The worst case of pipe scaling problems can cause damage to the pipeline, other process units, and equipment, and may end with a fatality accident [2]. Inspection of pipe scaling is needed to determine further actions to prevent the failure of production equipment, emergency shutdown, increased maintenance cost, decrease in production efficiency, and fatal operational accident. Gamma scanning and gamma tomography techniques were selected to diagnose the inner pipeline condition.

Gamma-ray has been widely used for industrial applications in diagnosing and measuring systems such as radioisotope tracer techniques, fluid density measurement, column scanning, etc [3], [4]. The advantages of using gamma sources are that they have high energy that can penetrate high-density material and it's simple because does not need a radiation generator.

Gamma pipe scanning is one of the major radioisotope sealed source techniques. The gamma source is placed opposite to the detector and conducts translational moves to get the attenuation profile of the object. Vertical and horizontal scans were conducted at 18 positions on the pipeline to predict the scale profiles inside it and have been reported by Wibisono et al. [5]. A gamma tomography technique was needed to complete the pipe inspection. It was performed at a selected position to get the cross-sectional visualization of the pipe.

Tomography is an advanced technique that has been continuously developed and used for diagnostic purposes throughout the last 40 years in medicine, industry, biology, and civil engineering [6]. Tomography started with the theoretical justification of the possibility of reconstructing the distribution of a certain parameter across a planar section of an object from its projections [7]. By non-invasively in providing high-contrast human anatomic information, X-ray tomography has become an important tool in radiological examination since its introduction in the 1970s [8]. While for medical tomography, the patient goes to the computed tomography system, for industrial applications the tomography system should be transported to the object (pipe or column) and mechanically adapted to the object setting [9]. For industrial purposes, gamma tomography is preferred over X-ray tomography due to two main advantages: 1) high detection efficiency of high-density or thick materials and 2) the use of a radioisotope that does not require a high-voltage power supply system [10].

There were several gamma tomography experiments for the inspection of process columns, heat exchanger units, multiphase flow in pipelines, etc. [11]–[15], but they were performed on lab-scale. There were also several simulation studies on the development of the gamma tomography technique [16]–[18]. There is very limited literature about gamma tomography experiments in the real field. Kim et al. developed a gamma tomography scanning system and performed it in the field in 2011 [19]. In 2014, Schafer et al. also conducted gamma tomography in real field conditions to analyze holdup distributions of gas in centrifugal pumps [20]. While their object dimensions are relatively small (diameter less than 500 mm), our object diameter is about 1500 mm. The challenges were the object dimension, object elevation (15 m above earth level), and how to collect data without disrupting the object itself.

THEORY

The principle of gamma pipe scanning is to move the gamma source and detector in parallel (translational scan) by flanking the pipe to be scanned. They move on a gantry to maintain the same distance. The source was encapsulated and placed in a lead collimator during the inspection. A collimated scintillation detector on the other side of the pipe counts the radiation emitted by the radiation source. Gamma source collimator aims to make gamma rays into a narrow beam for radiation safety purposes, whereas the detector collimator blocks scattered radiation detected by the detector. Interaction of gamma radiation with the medium of interest in the pipe will produce a change intensity of the beam which correlates to the properties of the medium [21]. The number of gamma photons that are detected at the detector after passing through an absorber with variable thickness will follow the Beer-Lambert law:

$$\frac{I}{I_0} = e^{-\mu t} \qquad (1)$$

Where I is the intensity of radiation transmitted through the absorber. I_0 is the intensity of initial radiation. μ is linear attenuation coefficient and t is the thickness of the absorber.

Gamma tomography parallel beam scanning system is the gamma pipe scanning system added by rotational movement ability. The rotational movement aims to obtain number of projections of the pipe being scanned. The projections data reconstructed to image by using filtered back projection (FBP) algorithm. The projective applied for parallel beam scanning as shown in Fig. 1. The projection can be expressed as a radon transform of the object to be reconstructed. The radon transform is expressed as follows [6]:

$$P_\theta(t_1) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)\delta(x.\cos\theta + y.\sin\theta - t_1)dx.dy \qquad (2)$$

Where

$$t = x.\cos\theta + y.\sin\theta \qquad (3)$$

$$s = -x.\sin\theta + y.\cos\theta \qquad (4)$$

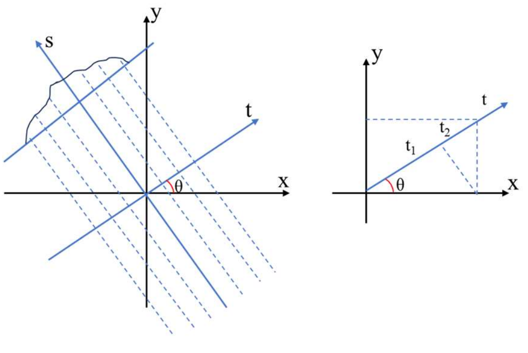


Figure 1. Parallel beam geometry [6].

The reconstructed image is analyzed by tracing the exterior boundaries of the object in the image. The first step is to convert the image to a binary image where the non-zero pixels values belong to an object and zero-pixel values constitute the background (air). Furthermore, the fluid area of the scaled pipe (0 pixels values inside the non-zero pixels values) can be calculated based on the number of pixels.

EXPERIMENTAL METHOD

The BA-106 position is about 15 m above ground level, therefore scaffolding was needed to conduct the experiment. There was no preparation for the pipeline itself. No insulation needed to be removed and there was no contact between the scanning system with the pipeline during the inspection. It was important to do the experiment without disrupting the unit because it was conducted when the unit was in the production stage.

The portable parallel beam gamma tomography scanning system was built by Azmi et al. in 2017 as shown in Fig. 2 [22]. The system was used in this experiment to conduct a gamma tomography scan. The system needs to be modified to cover the pipe size (diameter of 1500 mm including the insulation). The gantry size was about 200 x 200 cm which made it the biggest gamma tomography system that has been applied in the industrial field.

^{137}Cs with an activity of 2.96 GBq was used as a transmitter. ^{137}Cs are commonly used in nuclear gauging applications in industries because it has a long half-life, do not scatter interference of photons of other energies, and emit a single clear photo peak [23]. It has a half-life of 30.23 years and decays by pure β- decay, producing ^{137}Ba, which creates all the γ-ray emissions with an energy peak of 662 keV [24]. It was collimated with lead material that has a 5 mm diameter of slit. On the other side of the pipe, a collimated scintillation detector was set up to measure the radiation intensity after through the pipe.

Ludlum Model 44-2 Gamma Scintillator (NaI(Tl)) Detector was used in this experiment. Ludlum Model 2200 Scaler Ratemeter supplies high voltage and counts pulse from the detector. The scanning process was automatically performed by using a parallel beam gamma tomography scanning and data acquisition system [22].

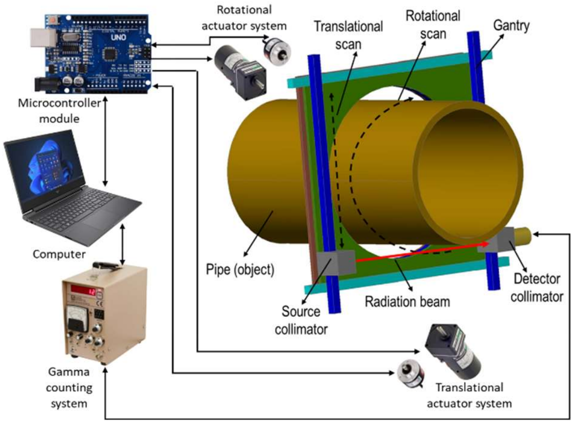


Figure 2. Gamma tomography scanning and data acquisition system schematic [22].

Gamma pipe scanning was conducted at 18 positions as shown in Fig. 3 and Tabel 1. The vertical and horizontal scan was done at 18 positions codes A to R with a 10 mm scanning step interval and 5 s counting time each step. The scanning was performed by using a parallel beam gamma tomography scanning system but only at 0º positions as a horizontal scan and at 90º positions as a vertical scan. The vertical and horizontal scanning data were used to predict the scale profile inside the pipe. Wibisono et al. have reported the gamma pipe scanning results [5]. The results were the prediction based on just two (vertical and horizontal) scanning data at each position. Hence, the gamma tomography technique was needed to complete the inspection.

Gamma tomography was performed at point Q. The point was selected by considering the gantry access to perform the rotational move. There were many obstacles around the pipeline to do tomography scans. Point Q was the most likely position for a tomographic scan over the other points. Translation scanning parameters were 10 mm intervals at each step and 5 s for radiation counting.

Table 1. Positions of gamma pipe scanning and tomography

No	Code	Position (cm)	No	Code	Position (cm)
1	A	200	10	J	7600
2	B	700	11	K	8450
3	C	1100	12	L	9500
4	D	1800	13	M	10500
5	E	2600	14	N	11100
6	F	3600	15	O	11450
7	G	4300	16	P	12500
8	H	5450	17	Q	13500
9	I	6600	18	R	14500

The gantry did a rotational move after the first translation scan was done. The rotational move performed a semi-circle (180º) rotation to the cross-sectional of the pipe. It was rotated 5.625º after a translational scan set was done. It started from 0º to 174.375º position to get 32 sets of translational scans (projections). The number of projections data was chosen by considering the scanning time. It took about 48 minutes to accomplish 1 projection scan. It took about 4 days to get the 32 projections data added 1 day for installation and dismantling of the scanning system from the pipeline.

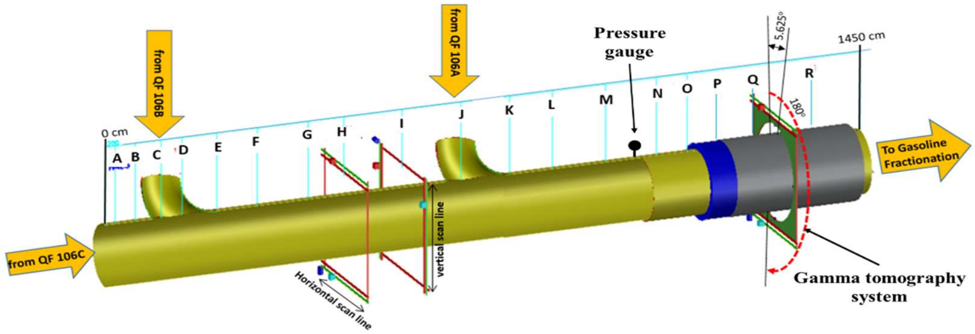


Figure 3. Gamma pipe scanning and tomography positions.

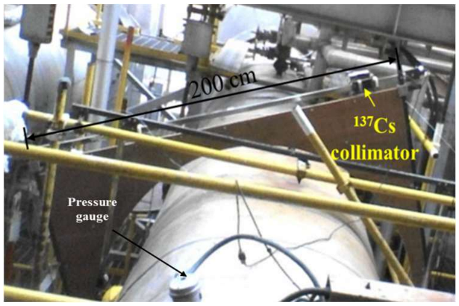


Figure 4. Gamma tomography scanning system set up in the field.

It was necessary to get the air-transmitted intensity as the empty (lowest density) at the image reconstruction process. After the air intensity is known, the scanning process can be conducted only at the interest region (object) to reduce total scanning time without reducing the resolution [25].

The scanning and data acquisition process was conducted automatically [22]. The gantry dimension is 200 × 200 cm as shown in Fig. 4. The gantry is attached to scaffolding during translational and rotational scans. The 32 projections data were built into an image using the FBP method.

The reconstructed image was analyzed using an image analysis algorithm built in Matlab. The purpose of this analysis was to calculate the area of the object in pixel units [26]. The first step was converting the image into a binary image where nonzero pixels belong to an object and zero pixels constitute the background. Boundary recognition was traced to the exterior boundary of objects as well as the boundary of holes inside these objects. The object (cross-sectional pipe area) and the hole (fluid area) were calculated in pixels. After compensating for pipe wall thickness, the remaining fluid area due to the scale was obtained.

RESULTS AND DISCUSSION

The cross-sectional BA-106 scale profiles at 18 points were studied by gamma pipe scanning technique and have been reported by Wibisono et al. [5]. Vertically and horizontally scanning data was plotted to predict the scale profile inside the pipe. Scale profile prediction at point Q (tomography scan point) as shown in Fig. 5. The vertical and horizontal scan profiles at point Q were not symmetrical with the simulated normal pipe scan profiles (black dash lines). The vertical scan profile has indicated that there was a lot of absorption of radiation in the middle and bottom of the pipe when compared to the normal pipe scan profile. Furthermore, the horizontal scan profile indicated most of the absorber location was in quadrants I and IV.

Fig. 6 shows the 3-dimensional scale prediction along the pipeline built from 18 scan positions [5]. The prediction showed there were several deposits of scale at several positions. The first was before the input from QF-106B. It might be caused by the particles contained in QF-106C and the pressure from QF-106B. Then at the pressure gauge, it might be caused by the probe (intrusive) itself that made the particles stick and accumulate to it. The last was at the bottom of the pressure, it might be caused by the particles from input QF-106A. Based on the scale prediction, crack gas from QF-106C and QF-106A were contaminated by particles, while the crack gas from QF-106B was relatively clean. As mentioned before, it came from a 2-dimensional prediction. So, it needs to be confirmed by another technique called tomography.

The cross-sectional reconstructed tomography image of the BA-106 pipeline at point Q is shown in Fig 7. The result was able to recognize the pipe wall, scale, and fluid area (gas area). A tomography scan was performed by a parallel scanning method at 10 mm (1 cm) intervals per step. That means each pixel in the reconstructed image represents 1 cm^2 of the actual condition. The color difference in the image shows the difference in the density of the scanned object. The lowest density (air) was represented by the blue color and the highest density (pipe wall) was represented by the red color.

There were some artifacts in the image. This may be due to the relatively small amount of data (projections) in this tomographic inspection. As mentioned before, the number of 32 projections was determined based on consideration of data collecting duration in the field. The artifacts can also be caused by the stability of the scanning system. The mechanical system dimension and conditions in the field made the scanning process not ideal condition. The dimension of the mechanical scanning system made it to be harder to control. Scaffolding stability as the support of a mechanical system is a disturbing factor in the scanning process. Because of the pipeline was under operation during the scanning, its vibration also caused the artifacts in the reconstructed image.

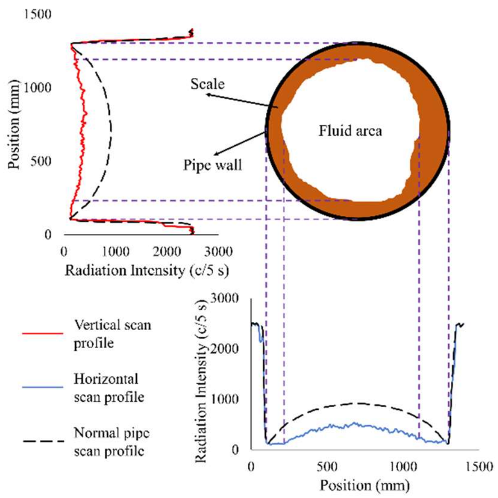


Figure 5. Scale profile prediction at point Q.

Based on the reconstructed image, the scale density in the pipe varies. Scale that is adhered directly to the pipe wall has higher density represented by the yellow color than the scale further away from the pipe wall represented by the green to light blue color. Scale prediction using vertical and horizontal scan data at point Q was confirmed by the tomographic image. The results were almost identical. While the gamma scan prediction results were subjective, gamma tomography data will produce the same result. It does not depend on the personnel.

To complete the inspection, the reconstructed image was analyzed. The purpose of this analysis was to calculate the area of the object in pixel units. In this case, the algorithm traces the exterior boundary of the object (pipe and scale), as well as the boundary of a hole inside these objects (fluid area) as shown in Fig. 8 (a). The red lines are the boundaries of the outer pipe wall and the scale. The dark blue color are the area of the pipe wall and the scale. Whereas the light blue color was the fluid area.

One of the information obtained from the boundary recognition algorithm was the area of the object including its hole as shown in Fig. 8 (b). The white color was the object with 12002 pixels. As mentioned before, 1 pixel in the reconstructed image represents 1 cm^2 of the actual condition, then 12002 pixels equal to 12002 cm^2 (A_c). The actual pipe area is:

$$
\begin{aligned}
A_a &= \frac{\pi}{4} D^2 \\
&= \frac{3.14}{4} 121.92^2 \\
&= 11668.62 \cong 11669 cm^2
\end{aligned}
$$

Where A_a is the actual area of the pipe. The calculation area (A_c) was 12002 cm^2. There was a discrepancy in the calculation pipe area (12002 cm^2) with the actual pipe area (11669 cm^2). There was a difference of 333 cm^2 from both values. It was 2.85% bigger than its actual area. It could be caused by the quality of the picture was not good enough due to the amount of data and measurement conditions in the field and caused by the pixel dimension being relatively big (low resolution).

Fig. 8 (c) shows the area contained a pipe wall and scale which represented by white color. The calculation area was 5541 cm^2. The fluid area can be calculated by subtracting the whole pipe area from the pipe wall and scale area. It found the fluid area was 6461 cm^2.

The percentage of the fluid area was calculated by comparing the fluid area with the entire pipe area after being compensated with the thickness of the pipe wall as shown in Fig. 8 (d). It was 56.15% of the normal fluid area or 0.5615 × 11187 cm^2= 6282 cm^2.

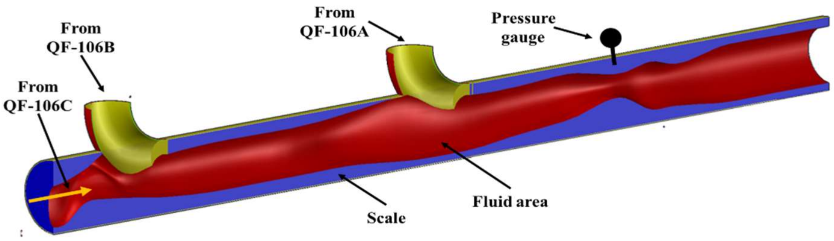


Figure 6. Three-dimenssional scale profile prediction along BA-106 pipeline.

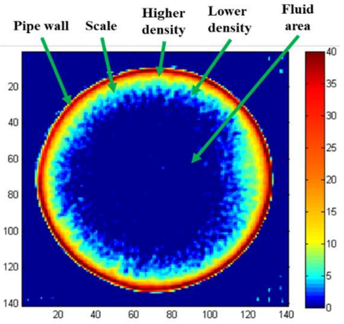
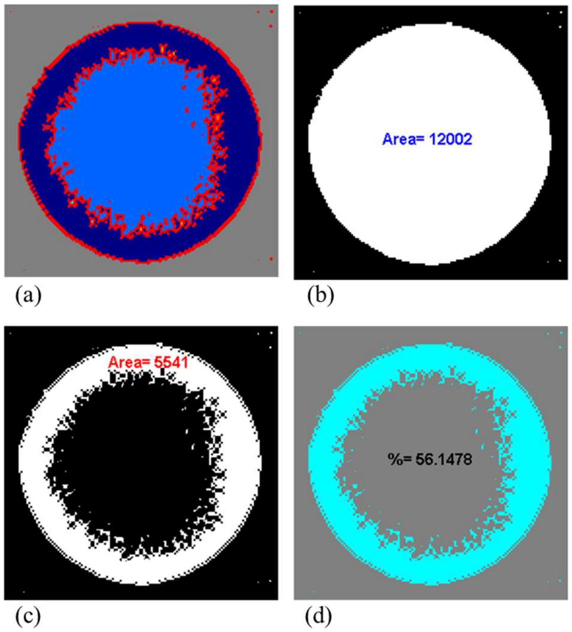


Figure 7. Tomography reconstructed image.

Based on the dimensions of objects and conditions in the field, the gamma tomography system was successful in providing the pipe cross-sectional image. The challenge was how to adapt the tomography system to the field conditions. The stability of the mechanical system also needs to be improved to get better data. The duration of scanning was also a limitation of this technique. Therefore, this system needs to be developed into a fan beam method that uses multi-detector. The use of a multi-detector will shorten the scan time. Finally, the gamma tomography technique with image analysis can be used to estimate the remaining fluid area due to the scale in the pipe.



(a) (b) (c) (d)

Figure 8. Image analysis. (a) boundary recognition, (b) whole pipe area calculation, (c) pipe wall and scale area calculation, and (d) fluid area percentage calculation.

CONCLUSION

Scale profiles in the pipeline can be predicted using the gamma pipe scanning technique. Gamma tomography is important as a complementary technique to get the cross-section visualization of scale profile inside the pipeline. The reconstructed image showed scale that adhered directly to the pipe wall has a higher density than the scale further away from the pipe wall. Gamma tomography technique with image analysis can be used to estimate the remaining fluid area due to the scale in the pipe. The remaining fluid area is approximately 56.15% of normal pipe without scale.

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