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Evaluation of Pipe Wall Thickness Based on Contrast Measurement using Computed Radiography (CR)

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Abstract

Specific properties of imaging plates, like wide dynamic range and greater sensitivity to radiation dose compared to radiographic film, as well as possibility of computer assisted analysis of digital radiographic image make computed radiography (CR) excellent non destructive method for pipe corrosion/erosion monitoring, especially insulated pipes in processing industry. Paper presents methodology for evaluation of pipe wall thickness based on the measurement of achieved radiographic contrast between areas of wall thinning and surrounding material. This technique could be used as complementary technique to usual tangential radiographic technique. Dependence of pixel intensities of digital radiographic image and radiation intensity that reaches imaging plate at three different X-ray energy levels was established. Based on that, optimatization of exposure parameters and selection of X-ray radiation energy (tube voltage) is discussed and the technique based on measurement of radiographic contrast for evaluation of the wall pipe thinning was proposed. This technique was validated by experimental measurement of wall thickness on pipe sample with artificial wall thinning areas. Measurement error was less than 5% for given sample.

Keywords: computed radiography; corrosion monitoring; pipe; radiographic contrast

1. Introduction

Development of appropriate X and gamma radiation sensors for digital radiography enabled it to become a viable alternative to the “classic” film industrial radiography in almost all aspects of industrial radiography applications

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[1]. Due to the simplicity of the implementation of new technology in the existing systems and the similarities in application with film radiography, currently the most common form of digital industrial radiography is - computed radiography (CR). CR system consists of ionizing radiation source (X-ray tube or radioactive isotope), computer unit, CR scanner and phosphor imaging plate (IP). Phosphor IPs used for industrial radiography contain $BaBr:Eu^{2+}$ active layer in which, after radiographic exposure, latent image is formed. Scanning preexposed IP in CR scanner with laser beam enables photo luminance effect and thus transforming latent image into visible light. Emitted visible light is collected by light guides, amplified in photomultiplier tube and transferred into digital image by A/D converter. Possibility of digital radiographic image analysis, unique properties of IPs compared to radiographic film, like wide dynamic range and greater dose radiation sensitivity, CR is particularly suitable for pipe corrosion/erosion mapping and monitoring in process industry. The most common technique for this application is tangential radiographic technique. By using CR instead of film radiography problems like side wall “burn off” and subjectivity of the examiner is avoided and even automated, computer based evaluation can be implemented [2]. The main drawback of this technique is that only the pipe side wall perpendicular to the direction of ionizing radiation can be evaluated. This results in the need for a great number of radiographic exposures if the wall thickness over the entire pipe diameter wants to be inspected and measured. Also, this technique of determining wall thickness is limited to pipes and other cylindrical hollow objects. The relationship between radiation dose and the amount of scanning induced photoluminescence from the exposed imaging plate image plate is proportional [3][4] with radiation intensity that reaches the IP in a wide dose range and therefore CR is suitable for evaluation of wall thickness based on the quantity of X or gamma radiation penetration through matter. This technique can be considered as complementary technique to tangential radiography allowing reduction in necessary exposures for pipe corrosion/erosion monitoring. This is an indirect technique for wall thickness determination and a calibration step in the process is needed. Commonly, reference block is positioned beside the test object during the exposure and is evaluated on the same digital radiogram as the test piece. This setting is not always practical, especially for field testing. For that reason, novel method based on radiographic contrast measurement is proposed where calibration is conducted prior and separately from the testing procedure.

1.1. Theoretical background

When penetrating through matter, radiation photons interact with matter what leads to absorption. Reduction of initial mono energy radiation intensity after penetrating through matter can be expressed by Beer’s absorption law [5]:

$$I = I_0 \ e^{-\mu t} \quad \text{where:} \tag{1}$$

I-intensity of photons transmitted across distance t,
I_0-initial photons intensity,
μ-linear attenuation coefficient,
t-penetrated thickness

As can be seen absorption of radiation depends on material thickness and linear attenuation coefficient. Linear attenuation coefficient for given material is strongly dependent on the photon energy. For industrial radiography applications radiation produced by X-ray tubes and radioactive isotopes (like Ir192,Co60 and Se75) has multi energy radiation spectrum, continues in case of x-rays and discrete in case of radioactive isotopes. For that reason, equation 1 for multi-energetic radiation sources can be written as:

$$I = \int I_0 \ (E) e^{-\mu(E)t} \ dE \tag{2}$$

Linear attenuation coefficient can also be measured for given radiation source – material combination. That way it is possible to establish μ_{eff} for exact testing scenario [6]. Equations (1),(2) are based on the assumption that there is no scattered radiation present in the beam. Because of absorption mechanisms of radiation in the energy range used for industrial radiography, scattered radiation is always present. This leads to a phenomenon that radiation intensity that reaches the sensor after radiation penetrates through the test object is greater than one calculated from the equation 2. For that reason, coefficient known as build-up factor is used. Build-up factor and can be defined as the ratio of total intensity of collided and un-collided photons received by the detector to the intensity of un-collided photons reach to the detector.

The absorption equation can then be written as:

$$I = BI_0\ e^{-\mu_{eff}\ t} \tag{3}$$

Value of the build-up factor depends mostly on radiation energy, material type and material thickness [7][8].

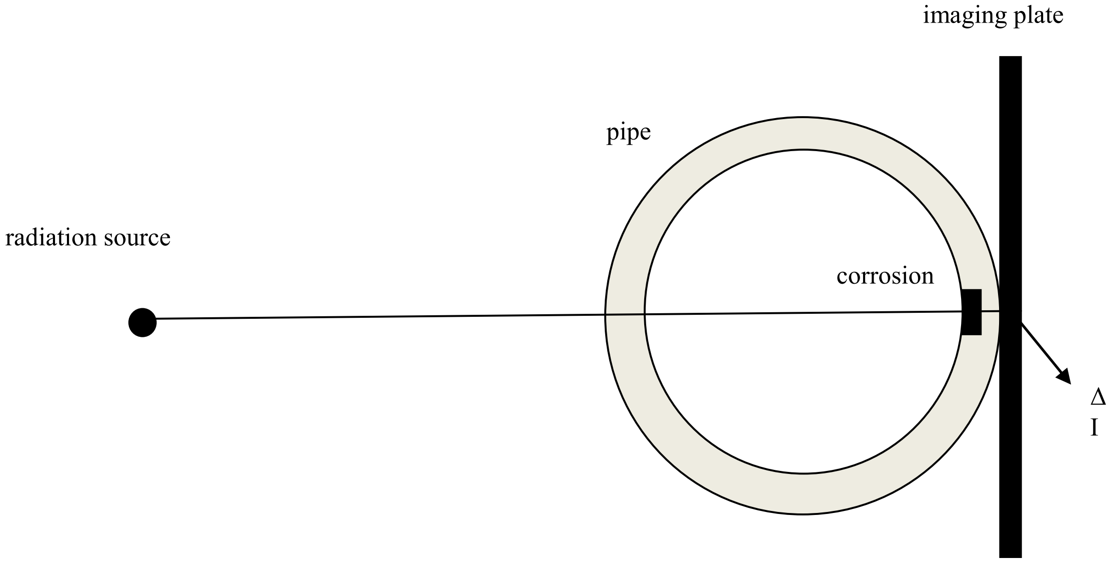

Fig. 1. Setup for pipe wall thickness evaluation based on radiation absorption.

Figure 1 presents test setup for wall thickness determination based on difference of radiation intensity. Due to lesser amount of material that radiation has to penetrate through the wall thinning area, radiation intensity that reaches IP will be higher. By measuring the difference in intensities, assessment of local wall thinning is enabled. Amount of wall thinning can then be calculated using the equation (4) and (5), if the radiation absorbed by the detector is linearly proportional to the intensity of the radiation penetrated and the effective absorption coefficient is determined.

$$I_{\Delta t} = I_{norm}\, e^{-\mu_{eff}\,\Delta t} \tag{4}$$ where:

$I_{\Delta t}$- intensity at double wall thickness + Δt,
I_{norm} - intensity at double wall thickness

$$\Delta t = \frac{\ln\left(\frac{I_{norm}}{I_{\Delta t}}\right)}{\mu_{eff}} \tag{5}$$

Because of some CR scanner output, IP properties, build up factor influence and geometrical setup of the inspection this estimation is not straightforward. For this reason, in order to obtain reliable measurement results, one should first characterize its own CR system.

Instead of determining attenuation coefficient, in this paper relations between radiation dose and pixel intensity values for used CR system were determined experimentaly and wall thickness was estimated indirectly through radiographic contrast measurment.

2. Optimization of parameters

In order to optimize exposure parameters, IP response to a certain dose of X-ray radiation was established experimentally. Steel step wedge samples of known thickness were exposed at three X-ray radiation energy levels: 175 keV(14mAmin), 200keV (8mAmin) and 250 keV (4mAmin). Source detector distance (SDD) was 700mm. Thickness of the sample steps are given in table 1. CR system used, as well as scanning parameters are presented in table 2.

Table 1. Step wedge thickness range

Step No.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.
Thickness [mm]	1	2	3	4	5	6	7	8	9	10	16,4	17,6	18,8	21,2	24	29

Table 2. CR system used

Radiation source	Balteau 300D
CR scanner	VMI CR 5100 M – 16bit
Imaging plate	Kodak Industrex flex GP
Scanning parameters	Resolution 100 µm, Laser power 15 J/m^2 , PMT 5,25 V

Mean values of the pixel intensities were measured at each step and the obtained results are shown by figure 2a. Figure 2b illustrates the response curve of the IP at different doses of x-ray radiation of 175 keV. It is possible to discern three distinctive regions of the curve, of which only region II of the curve can be approximated by a linear function. Part I presents saturation of the IP that occurs when it is exposed to too great dose of radiation, while the nonlinearity of the curve in the III region is caused by scattered radiation (buildup effect). For that reason, it is essential to adjust radiographic exposure in a way that expected pixel intensities of tested object on a digital radiogram are in the linear portion of the curve. This ensures that equal radiographic contrast will be achived between two different areas of penetrated thickness. For CR system used in this research this reagion is between 48000 and 30000 pixel intensity value.

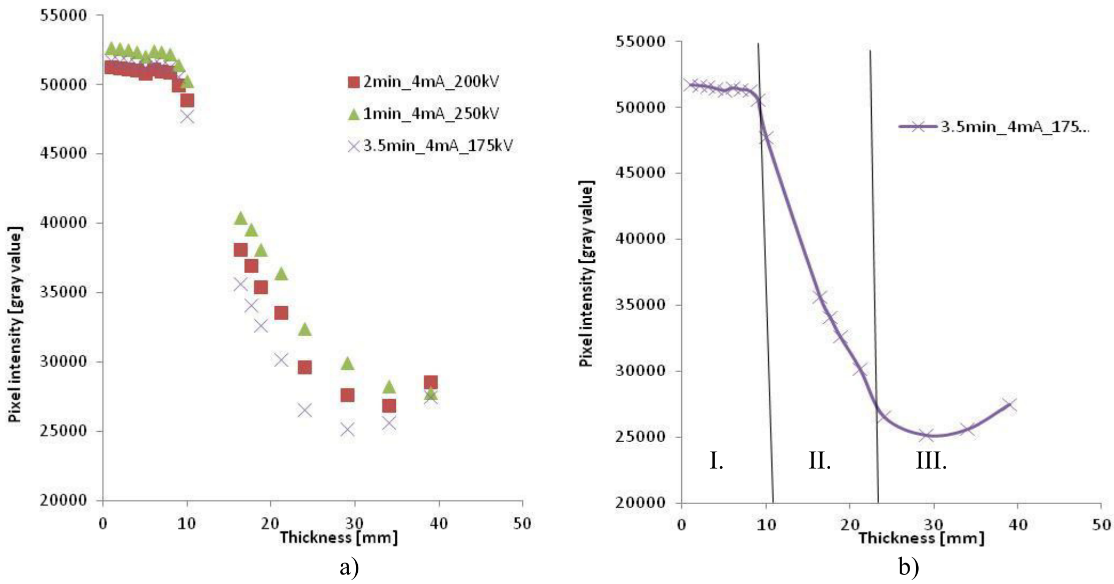

Fig.2. a)results of step wedge exposures;b) dependence od pixel intensity on penatrated steel wedge thickness at tube voltage 175 kV.

Radiation energy influences the shape of the curve (figure 3). When exposing the samples with higher energy radiation less scattered radiation is produced (the II. region is wider) but the gradient of the curve is lesser, resulting in decreased radiographic contrast on the digital radiographic image. For this reason, radiation energy has to be chosen in respect to wall thickness and material of tested object.

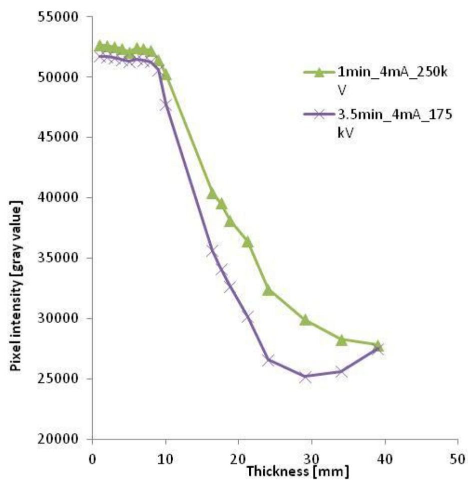

Fig. 3. Influence of radiation energy on radiographic contrast.

3. Technique validation

In order to validate proposed technique, steel pipe sample with artificial wall loss defects of known dimensions was radiographed. Specimen is shown with figure 4. Areas with wall thickness reduction are marked 1. to 4.. Wall thickness of the sample pipe is 8,2mm.

a) b)

Fig. 4. a) pipe sample image; b) digital radiogram of pipe sample.

Dependence of pixel intensity value upon penetrated thickness was obtained by exposing steel step wedge. Thickness range of the step wedges was chosen according to the pipe specimen wall thickness. Also in respect to penetrated material thickness for double wall radiography technique of pipe specimen and in accordance with ISO 17636-2 [9] the tube voltage of 200 kV and exposure of 6mAmin at SDD of 700 mm was chosen. Table 3 presents steps dimensions and measured mean pixel intensities on each step. Graphically results are present by figure 5 with corresponding regression line fitted.

Table 3. Steps dimensions and measured mean pixel intensities

Step No.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
Thickness [mm]	11,2	12,2	13,2	14,2	15,4	16,4	17,4	18,4	19,4	20,4
Pixel intensity	44011	43330	42664	41842	40978	40434	39619	38644	37567	36593

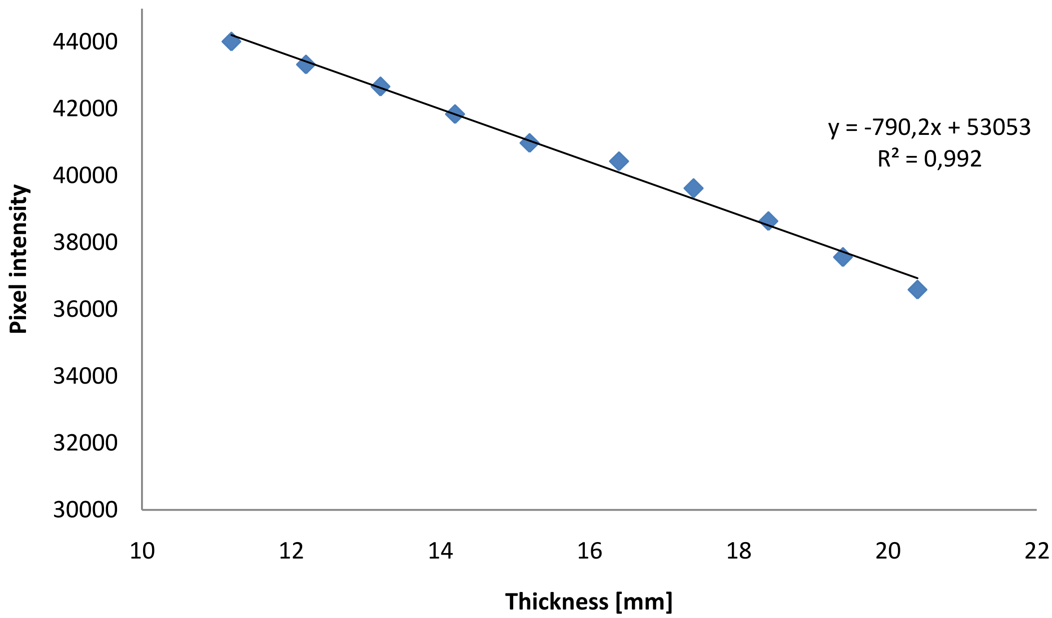

Fig. 5. Dependence of pixel intensity upon steel thickness and corresponded regression line.

From collected data dependence of pixel intensity upon steel thickness for given x-ray radiation and CR system was established as follows:

$$I_{px} = -790{,}21\ t + 53053 \text{ where:} \quad (5)$$

I_{px} – pixel intensity value for penetrated thickness,
t – penetrated thickness.

Pipe sample was exposed using radiographic exposure of 200 kV tube voltage, 6 mAmin at 700 mm SDD. Double-wall penetration single-image radiographic technique was used. Mean pixel intensity values on reagions of interest were measured as shown on figure 6.

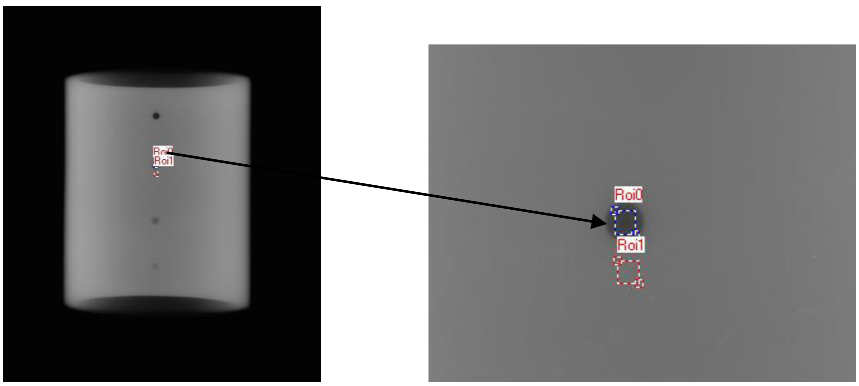

Fig. 6. Example of aquisation of data for radiographic contrast calculation.

The wall thickness was calculated based on the achieved radiographic contrast. Radiographic contrast (C) represents the difference in pixel intensity values of the areas of interest on radiographic image. In this case, it was calculated as difference of mean pixel intensity values at areas of reduced wall thickness and surrounding material (figure 5).

$$C = I_{px\ red} - I_{px\ norm} \text{ where :} \tag{6}$$

$I_{px\ red}$ – mean pixel intensity value at reduced wall thickness area,
$I_{px\ norm}$ - mean pixel intensity value at area without wall degradation.

From equasions 5 i 6 total penetrated material thickness can be calculated as:

$$t_{red} = -\frac{1}{790{,}21}C + t_{norm} \text{ where:} \tag{7}$$

t_{red} – total penetrated thickness at area of reduced wall thickness,
t_{norm} – total penetrated thickness at area without wall degradation.

Results are presented in the table 4.

Table 4. Results of wall thickness estimation of pipe sample

Position	1.		2.		3.		4.	
	I_{red}	I_{norm}	I_{red}	I_{norm}	I_{red}	I_{norm}	I_{red}	I_{norm}
Pixel intensity	49130	43008	46548	42817	44807	41752	41747	43661
Contrast	6122		3731		3055		1914	
Calculated penetrated thickness [mm]	8,253		11,48		12,3		13,77	
Measured penetrated thickness [mm]	8,2		11		12,8		14,4	
Measurement error [%]	0,6		3,6		4,2		4,3	

Measurement error was less than 5%. This level of accuracy is comparable to the results obtained by other authors [2] [6]. It was assumed that geometrical setup (position of test sample in relation to radiation source) influences the measurement accuracy, as well as the X-ray beam uniformity and the scanning process of the IP.

The results confirm the applicability of the method for pipe wall thinning evaluation.

4. Conclusion

Radiography is the only NDT technology that enables thickness wall measurements of pipes under the insulation. Computed radiography is especially suitable for this kind of measurement using tangential technique, because of great dynamic range of phosphor imaging plates, easier analysis of digital radiographic image, reduced exposure ect. Because of the attribute of imaging plates that signal output during scanning is greatly proportional to intensity of radiation reaching the IP, material thickness penetrated by X or gamma radiation can be calculated indirectly by measuring pixel intensity value on the digital radiographic image. The problem with this technique is that results of such measurements are generally less reliable in comparison to the tangential radiographic technique due to effects such as scatted radiation, incorrectly chosen exposure parameters and radiographic testing geometric settings. Also, this technique involves the use of reference block for calibration on the same digital radiogram as the tested object. For that reason, influence of radiographic exposure at 175, 200 and 250 keV X-ray energy levels on IP response was analyzed and optimized in order to prevent IP saturation or excessive amount of scattered radiation. Optimal interval of pixel intensity values between 30000 and 48000 was established. Dependence between pixel intensity and penetrated steel thickness for certain radiation energy and exposure was determined. Based on these findings, wall thickness measurement based on achieved radiographic contrast was enabled with no need of using reference block on the same digital radiogram. To validate proposed method, pipe wall thickness measurement based on radiographic contrast was conducted on the pipe sample containing artificial wall thinning defects. Measurement error was within 5%. Further improvement of the presented method will be conducted through determining the influence of geometric settings of the test arrangement (relative position of defect to the radiation source) on the measurement accuracy.

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