NUCL SCI TECH (2018) 29:109
https://doi.org/10.1007/s41365-018-0447-4

Determination of thickness of wax deposition in oil pipelines using gamma-ray transmission method

Can Cheng[1] · Wen-Bao Jia[2,3] · Da-Qian Hei[2] · Shu-Qun Geng[2] · Hong-Tao Wang[2] · Li-Teng Xing[4]

Received: 3 July 2017 / Revised: 20 November 2017 / Accepted: 4 December 2017 / Published online: 3 July 2018

Abstract Wax deposition in pipelines is a crucial problem in the oil industry. An approach that combines the gamma-ray transmission method with scanning technology is proposed to detect the thickness of wax deposition. The performance of the method is validated through simulations with MCNP code. An experiment is also carried out with a 300 mCi ^{137}Cs source and a $LaBr_3$ detector. A good correspondence is observed between the simulation and experimental results. The results indicate that the approach is efficient for detecting the thickness of wax deposition in oil pipelines.

Keywords Gamma-ray transmission · Scanning technique · Wax deposition

This work was supported by the National Natural Science Foundation of China (Nos. 11505097 and 11775113), the Priority Academic Program Development of Jiangsu Higher Education Institutions, and the Postgraduate Research and Practice Innovation Program of Jiangsu Province (No. KYCX17_0286).

✉ Da-Qian Hei
heidq@nuaa.edu.cn

1 College of Astronautics, Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China

2 College of Materials Science and Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China

3 Collaborative Innovation Center of Radiation Medicine of Jiangsu Higher Education Institutions, Suzhou 215000, China

4 Jiangsu Institute of Metrology, Nanjing 210023, China

1 Introduction

Crude oil is a very important resource for industrial production. Chinese crude oil usually contains high wax content. One of the many problems faced while transporting this type of crude oil is the wax deposition on the inner surface of pipelines. Wax deposition can often lead to negative consequences such as decrease in production efficiency, emergency shutdown, and safety risk under certain scenarios [1, 2]. Therefore, pipelines that have been under operation for long durations require cleaning of the wax deposits, and the determination of wax thickness is important for the pipeline cleaning process. Many theoretical models for wax deposition under different conditions have been studied [3–5]. However, these models are often calculated with several assumptions, and they need to be validated by considering the deviation from practical results. Therefore, the approaches for measuring and monitoring the thickness of wax deposition in pipelines are very important.

Among the different types of detection approaches, the nondestructive detection is the most efficient and powerful approach. Nuclear analysis technique, which is a rapid and nondestructive measurement method, is widely used in industrial production [6, 7]. Some methods based on X-ray and gamma-ray transmissions have been applied for the detection of wax accumulation in pipelines. The common methods involve tangential X-ray and gamma-ray radiography, and useful information is saved in the form of photographs or digital images [8, 9]. However, these methods are usually based on the calculation of the transmission rate of rays. A crucial problem often faced in these techniques is the collection of information about the deposition such as the intensity and elemental components, which are different for different oil fields [10]. Another problem is that these methods are time-consuming. These problems limit the application of these methods.

To validate the performance of the model for wax deposition in oil pipelines, a large amount of experimental data is required. In practice, only the average thickness of the wax deposition is compared with the predicted values. An approach based on the gamma-ray transmission method and scanning technology is proposed to detect the thickness of wax deposition. The performance of the approach is evaluated with MCNP code. In addition, some experiments are carried out to validate the approach.

2 Experimental section

2.1 Methodology

For a narrow gamma-ray beam, the intensity of a transmitted gamma-ray beam follows Lambert–Beer's law [11]:

$$I = I_0 \exp(-\mu l), \tag{1}$$

where I_0 is the initial intensity of the gamma ray and I is the transmitted intensity of the gamma ray through a sample with length l; μ is the linear attenuation coefficient of the material. For a uniform wax deposition, when a gamma-ray beam is incident upon the sample, the gamma ray reacts with the sample and follows Eq. (1). When a pipeline is scanned using a gamma ray, the transmitted intensity of the gamma ray changes due to the different passing thicknesses, and information about the wax deposition can be obtained. A schematic illustration of wax thickness acquisition is shown in Fig. 1.

The penetrated length in the pipeline and wax can be calculated by using Eq. (2). D is the penetrated length in the wax deposition, R_1 and R_2 are the outer and inner radiuses of the pipeline, respectively, R_3 is the inside radius of the wax deposition, and x is the distance from the starting point, which is at the top of the pipeline. The minimum intensity of the transmitted gamma ray is at the scanning node, where the value of x is equal to R_1–R_3, which is the thickness of the pipeline and wax deposition. If the thickness of the pipeline is known, the thickness of the deposition can be calculated.

$$D = \begin{cases} 2\sqrt{R_2^2 - (R_1 - x)^2}, & R_1 - R_2 \le x \le R_1 - R_3 \\ 2\sqrt{R_2^2 - (R_1 - x)^2} - 2\sqrt{R_3^2 - (R_1 - x)^2}, & R_1 - R_3 \le x \le R_1 \end{cases}. \tag{2}$$

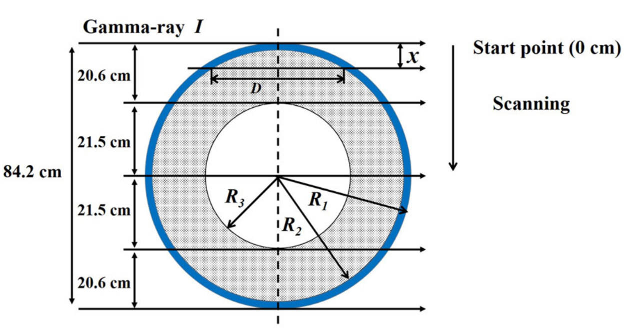

Fig. 1 Schematic diagram of the approach based on the gamma-ray transmission method

2.2 Detection system and sample preparation

The sample was measured at the ionizing radiation laboratory, located at the Jiangsu Institute of Metrology. The gamma-ray source was a 300 mCi ^{137}Cs source, which was placed in a lead container. As shown in Fig. 2, the source was controlled by the pneumatic switch valve with a diameter of 8 cm. The diameter and length of the cavity were 16 cm and 10 cm, respectively. The lead was placed in the cavity to collimate the gamma ray. The detector was $LaBr_3$: Ce detector (Saint-Gobain; the energy resolution is 3% at 0.662 MeV; crystal size: 3 inch diameter by 3 inch height). The distance between the source and the detector was 300 cm. Both the gamma-ray source and the detector were collimated by using a lead with dimensions of $10 \times 10 \times 10$ cm^3. The collimators were squared with an area of 2×2 cm^2.

The components of the wax deposition of crude oil include wax and some minerals with the major elements being carbon and hydrogen. In this work, the accumulation was replaced by uniform polyethylene, set as a regular shape. A hollow cylindrical polyethylene with a thickness of 20 cm was taken as the grease stain and placed snugly inside a stainless steel pipeline with a diameter of 84.2 cm

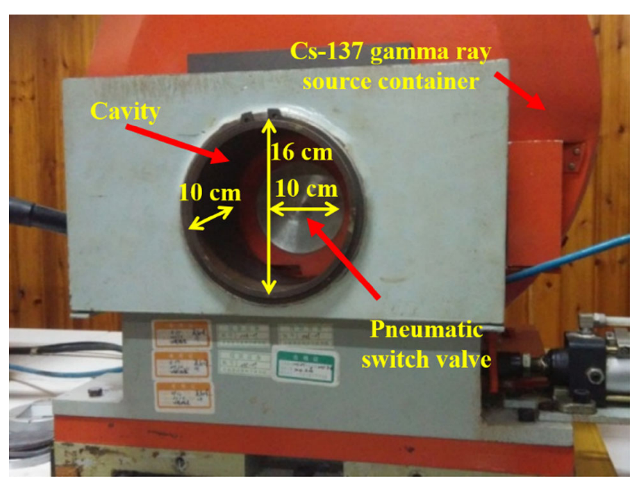

Fig. 2 (Color online) Picture of the gamma-ray source container

and thickness of 0.6 cm. The schematic and dimensions of the detection system are shown in Fig. 3.

2.3 MCNP simulation and measurement

To validate the proposed approach, a simulation was performed using the Monte Carlo code MCNP4C by simplifying the practical system. The 3D MCNP model of the detection system and sample are shown in Fig. 4. In this study, only the relative intensity of the gamma ray need to be known and F1 tally can provide this information. The tally type 1 was used to count the gamma ray at the detector surface. The gamma-ray beam was moved with 2 cm increments. The particle number was set to 10^8, and the statistical uncertainty of the results was less than 3%.

For convenience of measurement, the scanning was performed in steps of 2 cm by moving the pipeline, with no overlapping between the scanning nodes. The detector was connected with a Lanbase model multi-channel analyzer with 4096 channels. Each scanning node was measured twice, and both the acquisition times were 100 s with live time. The spectrum was acquired by using the software eMorpho. Then, detection was performed without the gamma-ray source, and the results were considered as the background.

3 Results and discussion

In the process of scanning, only half of the pipeline was measured due to the symmetry. During the movement (with step size of 2 cm) from the top to the horizontal central line of the pipeline, different gamma-ray spectra were collected. Figure 5 shows the spectra collected from the $LaBr_3$ detector at the scanning nodes 7, 21, and 31 cm. The full energy peak of 0.662 MeV can be observed clearly along with the intensity changes for different scanning nodes.

Because the intensity of the initial gamma ray I_0 was too large, to compare the simulated and experimental results clearly, the intensities of the transmitted gamma rays were used. Each transmitted gamma-ray intensity was normalized to the maximum value, for which the scanning node was 41 cm, to get the relative intensity. For different scanning nodes, the relative intensities of the full energy peak were different and were plotted against the distance x. Figure 6 shows the simulated and experimental results of the relative intensity as a function of x. The theoretical results were also calculated with Eqs. (1) and (2). The attenuation of both iron and wax was taken into consideration. The linear attenuation coefficient for iron and wax was calculated by using XCOM [12]. The solid line represents the theoretical calculation. The sphere and square symbols indicate the experimental and simulated results, respectively.

It can be observed that these results agree quite well. As shown in Fig. 6, the intensity of the full energy peak decreases with increase in the scanning distance x until it reaches 19 cm, which is the thickness of the pipeline and wax deposition, and then increases with increase in x till the horizontal central line. As mentioned above, the thickness of the pipe is 0.6 cm. Then, the thickness of the wax deposition is 18.4 cm. One point that should be noted is that the precision of this method is affected by the width of the beam and the scanning step size. For a narrow beam with a small scanning node, the measured results will be more accurate. In the present study, the width of the beam and step size is 2 cm, and the difference between the measured result and the actual thickness is about 8%.

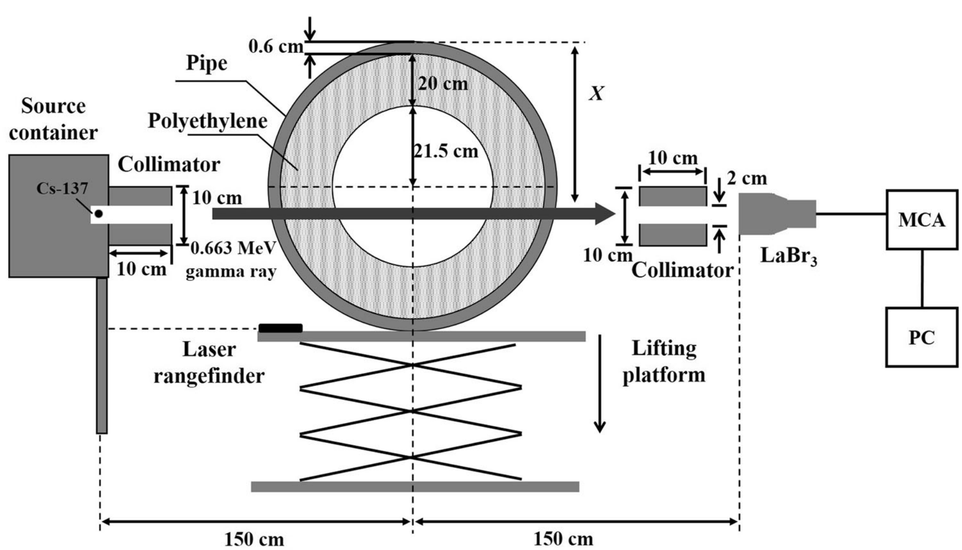

Fig. 3 Schematic diagram of the detection system

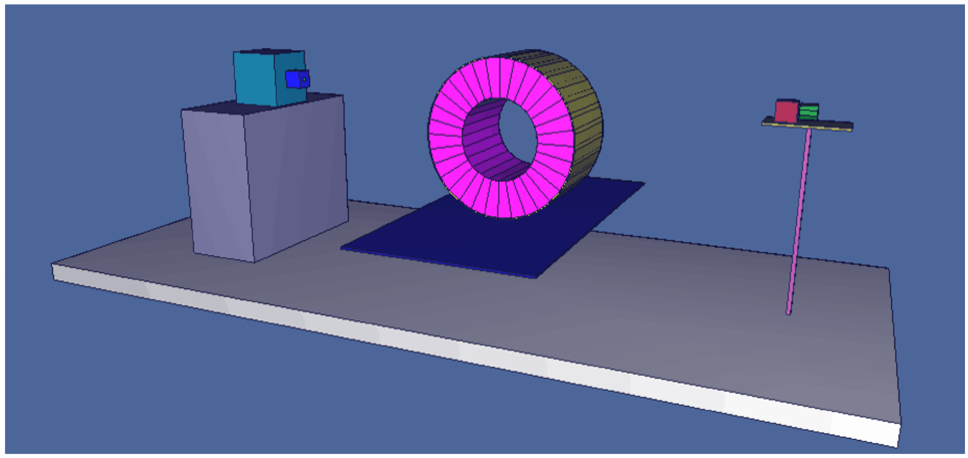

Fig. 4 (Color online) 3D MCNP model of the detection system and sample

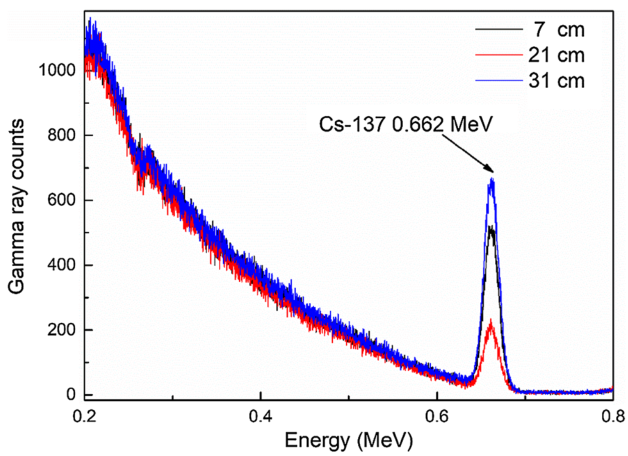

Fig. 5 (Color online) Gamma-ray spectra with different scanning nodes

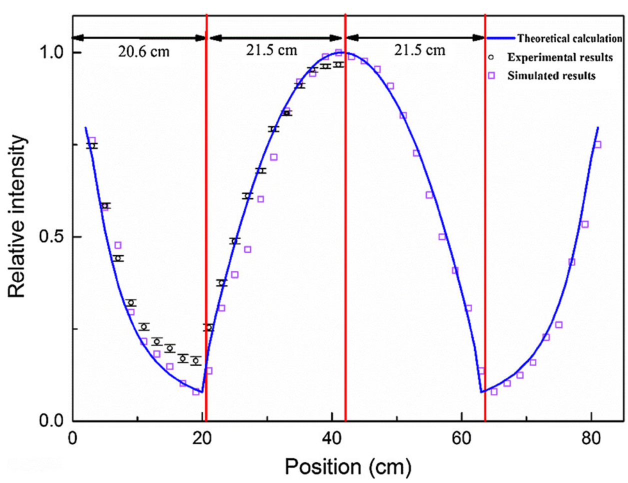

Fig. 6 (Color online) Theoretical calculation, simulation, and experimental results of the scanning node

However, the precision is sufficient to detect the wax deposition inside the pipeline in this application.

4 Conclusion

An approach that combines the gamma-ray transmission method with scanning technology was used to detect the thickness of wax deposition. By measuring the transmitted intensity of the gamma ray at each scanning node, the thickness of wax deposition can be obtained. MCNP calculations were used to validate this method. The experiment was carried out with a 300 mCi ^{137}Cs source and a $LaBr_3$ detector. Both the results indicate that this method is efficient for detecting the thickness of wax deposition in oil pipelines. Unlike the traditional nuclear analysis methods, the method proposed in this study can be applied for in situ measurement with an unknown sample.

Acknowledgements The authors would like to thank the Jiangsu Institute of Metrology for providing the gamma-ray source.

References

1. J. Gong, Y. Zhang, L. Liao et al., Wax deposition in the oil/gas two-phase flow for a horizontal pipe. Energy Fuels **25**, 1624–1632 (2011). https://doi.org/10.1021/ef101682u
2. Y. Zhang, J. Gong, H. Wu, An experimental study on wax deposition of water in waxy crude oil emulsions. Pet. Sci. Technol. **28**, 1653–1664 (2010). https://doi.org/10.1080/10916460903096822
3. H. Shasha, H. Qiyu, Research on wax deposition in the pipeline without pigging for a long time. Pet. Sci. Technol. **32**, 316–323 (2014). https://doi.org/10.1080/10916466.2011.578090
4. N.V.B. And, A.K. Mehrotra, Modeling of deposit formation from "Waxy" mixtures via moving boundary formulation: radial heat transfer under static and laminar flow conditions. Ind. Eng. Chem. Res. **44**, 6948–6962 (2005). https://doi.org/10.1021/ie050149p
5. S. Correra, A. Fasano, L. Fusi et al., Modelling wax diffusion in crude oils: The cold finger device. Appl. Math. Modell. **31**, 2286–2298 (2007). https://doi.org/10.1016/j.apm.2006.09.007
6. Y. Ren, P. He, H.L. Wang et al., Compressed sensing and Otsu's method based binary CT image reconstruction technique in non-destructive detection. Nucl. Sci. Tech. **5**, 63–68 (2015). https://doi.org/10.13538/j.1001-8042/nst.26.050403

7. B.L. Macdonald, J. Vanderstelt, J. O'Meara et al., Non-destructive investigation of a time capsule using neutron radiography and X-ray fluorescence. Nucl. Instrum. Methods Phys. Res., Sect. B **367**, 46–52 (2016). https://doi.org/10.1016/j.nimb.2015.11.019
8. D.F. Oliveira, J.R. Nascimento, C.A. Marinho et al., Gamma transmission system for detection of scale in oil exploration pipelines. Nucl. Instrum. Methods Phys. Res., Sect. A **784**, 616–620 (2015). https://doi.org/10.1016/j.nima.2014.11.030
9. H.S. Cho, J.E. Oh, S.I. Choi et al., Performance evaluation of a gamma-ray imaging system for nondestructive testing of welded pipes. Nucl. Instrum. Methods Phys. Res., Sect. A **652**, 650–653 (2011). https://doi.org/10.1016/j.nima.2010.08.045
10. A.M. Al-Bahi, A.Y.A. Soliman, A. Alzahrani et al., Concept design of a PGNAA system for optimizing the performance of gravity separators. J. Radioanal. Nucl. Chem. **304**, 925–931 (2015). https://doi.org/10.1007/s10967-014-3869-4
11. E.E. Ermis, F.B. Pilicer, E. Pilicer et al., A comprehensive study for mass attenuation coefficients of different parts of the human body through Monte Carlo methods. Nucl. Sci. Tech. **27**, 54–62 (2016). https://doi.org/10.1007/s41365-016-0053-2
12. M.J. Berger, J.H. Hubbell, Photon Cross section on a Personal Computer (XCOM). NBSIR87-3597 (National Institute of Standards and Technology, Gaithersburg, 1987)