Learning gamma-ray scanning technique through an educational simulation rig

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Abstract. Gamma-ray scanning is non-destructive testing (NDT) technique to inspect problems in distillation columns of industrial plant. In order to familiarize with the problems’ identification and data interpretation, an attempt has been made by constructing an educational rig for simulation of gamma-ray scanning technique in a laboratory scale. The rig is made of cylindrical transparent acrylic material with a diameter and a height of 0.3 m and 2.4 m, respectively. The rig consists of artificial trays and packed bed structures designed in such a way that it represents a duplicate of the distillation unit but in a miniature size. The rig is also equipped with a submerged water pump and water tank which both are located at the bottom part of the rig. Water from the tank are circulated by a water pump through a pvc tube to a distributor at the upper part of the rig. In the rig, water is flowing downward gravitically for passing through packed bed and trays structures until terminated at the tank. The gamma-ray scanning experiment was carried out by moving the radiation detector and Cs-37 gamma-ray source simultaneously from top to bottom for every 5 cm moving step. Artificial problems such as flooding, tray positions, collapsed trays are clearly identified. The lesson learned from this experiment concludes that simulation of gamma ray scanning is very suitable for troubleshooting and diagnosing malfunctions of the internal structure of the distillation column.

1. Introduction
For plant engineers, big five classes of conventional non-destructive testing (NDT) consist of radiography, liquid penetrant, magnetic particles, ultrasonic and eddy current techniques. They are well known as they are frequently used for routine inspection in industrial process plant [1,2]. The inspection is usually carried out when the plant is shut down. The plant components should be inspected thoroughly to find any discontinuities, mostly welding defects, in them. The time required for inspection of one unit of plant using conventional NDT techniques is in the range of 2 – 3 weeks in average.

Although it is not so similar in the inspection way, a nuclear-based technology called gamma-ray scanning technique is a completely non-destructive method [3]. It offers a non-invasive, straightforward measurement, shorter inspection time, and is un-ambiguous in providing essential scanning data [4,5]. It is also cost-effective and safe [5]. The gamma scanning technique uses one gamma radiation source and one radiation detector. The strength of gamma sources used in the gamma scanning is commonly in the range of 0.4 – 40 GBq, which is 100 - 1000 times lower than those usually used in industrial radiography [6]. From a radiological point of view, gamma-ray scanning is safer compared to industrial
radiography. The high energy of gamma-ray is capable of penetrating any materials it passes, making an online inspection mode could be conducted and the operation of the inspected processing plant is not necessarily be stopped. With these capabilities, the gamma scanning technique is superior and shows its state of the art of nuclear techniques for an online application to industrial plants [3, 6–8].

The gamma scanning technique is usually used for scanning distillation units in petroleum and petrochemical refineries. The terms that are commonly used in gamma-ray scanning are troubleshooting, diagnosing and malfunctioning of plant internal structures. The term of malfunction may have similar connotation with the terms of defects or indications in conventional NDT techniques. Typical malfunctions that can be identified using the gamma-ray scanning technique are damaged or missing trays in trayed column type, damage or missing supports in packed bed column type, flooding, blockage, and liquid levels. Other problems that are more difficult to be examined are entrainment and weeping due to these problems absorbing small part of radiation intensity [9].

Distillation or fractionating tower is essentially a cylindrical pressurized steel vessel with a typical height is about 120 feet [10]. There are two types of distillation unit that is tray type and packed ones [3, 5, 8, 11–14]. The primary function of the distillation unit is to perform the initial separation of crude oil into intermediate products, which will undergo further processing in a downstream unit to become ready-to-use products for consumers [15]. Doing gamma-ray scanning inspection in petroleum or petrochemical plant is not an easy task. Skillful and experience in handling radiation or radioactive material is required. This article aims to introduce a gamma-ray scanning technique as applied to a laboratory simulation rig to study the mechanism of internal process in a distillation column. The rig is made of transparent acrylic material make that artificial malfunctions could be seen during the experiment. This simple experiment is dedicated to educational purposes that may be useful for undergraduate students in physics and engineering.

2. Theory of gamma-ray scanning

Implementation of gamma scanning technique for internal inspection of process materials in distillation column is carried out by moving concurrently in vertical direction a sealed gamma radiation source and scintillation detector, (NaI(Tl)), along the exterior side of the column. The background theory of the gamma scanning techniques is based on the interaction of gamma radiation with the material its passed in the mode of transmission. During the period of investigation, the radiation source is encapsulated and placed permanently in a specially designed housing and makes no contact with a radiation detector or with the process materials in the column. A source holder with an appropriate panoramic collimator is designed to expose the column. A scintillation detector on the other side of the column is employed to record the radiation intensity emitted by the radiation source. Interaction of the gamma radiation with a medium of interest in the column will produce a change in the beam's radiation intensity, which correlates to the properties of the material in the column [3–5].

The theory of gamma scanning technique is based on fundamental relation [7, 11, 12]

\[ I = B I_0 \exp\left( -\sum_i^N \mu_i \rho_i x_i \right) \]  

(1)

where, \( I \) and \( I_0 \) are radiation intensity after and before interacting with material or transmitted and incident radiation intensities respectively, in count per second (cps). \( \mu_i \) is mass absorption coefficient of \( i^{th} \) material in \( \text{m}^2/\text{kg} \), \( \rho_i \) is density of \( i^{th} \) material in \( \text{kg}/\text{m}^3 \) and \( x_i \) is the thickness of the \( i^{th} \) material, in cm. \( B \) is the buildup factor (dimensionless). In practical application, each medium in the column is assumed to be linear and isotropic. By using collimated beam, it is also assumed that intensity contribution form scattering radiation is considered none, therefore the buildup factor is set equal to one. Based on these assumptions, it is safe to state that Eq. (1) can be simplified as

\[ I = I_0 \exp\left( -\mu x \right) \]  

(2)
where \( \mu_l \) is linear constant and apply for each medium. It is worth noting that gamma radiation for column investigation should be capable of penetrating the wall thickness of the column and all materials inside the column.

3. Experiment
Gamma-ray scanning has been demonstrated experimentally to a simulation rig made of cylindrical acrylic material. The rig dimension is 0.3 m in diameter and 2.4 m in height. The rig consists of trays and packed bed structures designed in such a way that it represents a simplified duplicate of the real industrial distillation column, but in a miniature size. The rig is also equipped with a submerged water pump and water tank which both are constructed at the bottom part of the rig. Water in the tank is circulated into the rig by the pump through a PVC tube. At the upper part of the rig water fall gravitically which undergo for further passing through packed bed, tray structures until terminated in the tank. Cesium-137 gamma source with activity around 10 mCi placed in panoramic collimator is used to scan the rig. Panoramically collimated scintillation detector (NaI(Tl)) and 9302 ratemeter (both are produced by Minekin Inc) are used as the data acquisition system. The experiment is carried out for full scan from top to bottom of the rig. Both radiation source and detector are concurrently moved downward for every 5 cm moving step. The moving mechanism is controlled by software applied to the electro-mechanic system. During the experiment, all the radiation intensity is counted by the radiation detector and recorded in a laptop computer for subsequent analysis. Schematic diagram of experiment is shown in Fig.1.

![Figure 1. Schematic diagram of gamma-ray scanning experiment](image_url)

4. Result and discussion
Before going to further detailed discussion, let us consider the following guidance to have a meaningful conclusion. It is not easy to interpret the scanning data if it solely based on the scan data. One has to learn the corresponding mechanical drawing of the scanned column thoroughly before doing the measurement [3,16,17]. Any useful hydraulic information such as the position of tray, packed bed, inlet-outlet flow and manhole are usually described in the drawing. One has also to consider the position of the mechanical obstacles at the exterior of the column. When a continuous full scan is carried out, the scan data of the obstacles can be a source of false information, leading to misinterpretation [17].
Mechanical drawing is essential information for the determination of scan orientation [3,16,17]. Scan orientation is a strategic plan in the placement of radiation source and radiation detector outside wall of the scanned column. It is worth understanding that although the source and detector collimators are designed in panoramic shape, the data obtained from measurement is just the counted radiation intensity where the detector is placed. Therefore, each scan orientation essentially produces information about the hydraulic condition of the material in the column only in scan direction [17]. In most industrial applications, the scan is directed to detect the critical components of the internal structure, such as trays and packed bed. Although it is also critical in intensifying chemical processing, the scan orientation to detect downcomer is sometimes not necessarily be carried out [16].

Scanning data obtained from radiation intensity measurement on the simulation rig is presented in Fig. 2. In principle, interpretation of scanning data is an implementation of Equation (1) for idealized conditions. Equation (1) states that radiation intensity measured by a detector is exponentially proportional to the density of the material that exists between the source and the detector. The dimensionless quantity, \( \mu_i \rho_i x_i \), is the most important term because it is related to the formation of scan profile generated from the measurement. \( \mu_i \) is constant for a given gamma-ray energy and material composition. In this situation, increasing material density and material thickness will reduce the radiation intensity recorded by a detector and vice versa.

![Figure 2](image-url)  
*Figure 2. Gamma-ray scanning experiment shows scan profile generated from interaction of gamma radiation with materials in the simulation rig. Scan data is recorded when the experiment is being performed.*

When the Equation. (1) is applied to interpret the density profiles of materials in the trayed column, there would be three main mechanisms of interaction processes to occur:

- When gamma radiation interacts with space containing air or vapor phase of liquid, a small amount of incident radiation is absorbed and most of the radiation is transmitted. The scan profile produced from this interaction shows a scan profile with the highest (maximum) radiation intensity. In some publications, such scan profile is termed as a baseline [9,14,16].
- When gamma radiation goes through the liquid on the tray, incident radiation is partly absorbed by liquid. The recorded radiation intensity shows an appreciable medium-strength scan profile.
• When gamma radiation interacts with tray or packed bed, the incident radiation is strongly absorbed by these materials, and the transmitted radiation intensity shows weak scan profiles.

As can be seen from Fig. 2, variation of scan profiles are caused by the interaction of gamma-ray with different sizes and orientations of the internal components of the column. Strong absorption of gamma-ray by packing bed results in low transmitted radiation intensity, which produces a low scan profile. A similar result is also indicated by strong absorption of gamma-ray by a material of trays, as indicated by trays 1,3, 5, 7-9, 11, and 12. They show similar scan profiles and also their corresponding adjacent spaced distances. Here, these materials are in their position and are functioning properly.

Figure 2 also shows simulated problems on artificial trays. As can be seen, simulated flooding occurred on the tray 2. Trays 4 and 6 show almost similar scan profile, because these trays are doubled like a superimposed tray to another. Scan profile for a joint spot in the space between trays 6 and 7 is also clearly observed as indicated by broadened scan profile along the joint in a vertical direction. Tray 10 collapsed and fell down to the tray 9 is also observed from its corresponding scan profile. The position of the collapsed tray is not perfectly superimposed on tray nine but there is a bit of space gap; therefore the scan profile of the collapsed tray is not the same to the situation on double trays.

To sum up, the gamma-ray scanning method has become a non-destructive method that is routinely applied to industry. The establishment of a simulation rig is an attempt to familiarize the usage of the gamma-ray scanning method on a laboratory scale. We believe that this method is valuable for undergraduate physics and engineering undergraduate students to study the complex structure of petroleum and petrochemical processing units.

5. Conclusion
This experiment demonstrates that gamma-ray scanning is an effective method for studying internal processes and material integrity in a visible simulation rig consisting of artificial packed bed and trays. The process is stimulated mechanically by circulating water from and to the water tank. The tray position and artificial malfunction such as flooding and tray misplace or collapsed trays are clearly observed during the experiment. The experiment also shows that online measurement using high penetrating gamma energy of radioactive material even in low-level radioactivity shows its superiority in providing valuable information about internal structure materials in the column.

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Authors’ statement
All authors have the same contribution and there are no conflict of interest.

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