SSRG International Journal of Mechanical Engineering
ISSN: 2348-8360/ https://doi.org/10.14445/23488360/IJME-V13I11P103

Volume 13 Issue 11, 25-33, November 2026
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Original Article

Performance Evaluation of Pulsed Eddy Current Testing for Detection and Thickness Estimation of Corrosion under Insulation in Carbon Steel Pipeline Structures

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Received: 10 March 2026 Revised: 30 April 2026 Accepted: 25 November 2026 Published: 27 November 2026

Abstract *- Corrosion under Insulation (CUI) is one of the major degradation problems in insulated pipeline systems because it may occur beneath the insulation layer and remain undetected during routine visual inspection. Conventional inspection often requires partial or complete removal of insulation, which increases sinspection time, cost, and operational interruption. This study evaluates the capability of Pulsed Eddy Current (PEC) testing as a non-destructive technique for detecting thickness variation associated with CUI in carbon steel pipeline structures. Carbon steel specimens with different thicknesses were examined under several insulation conditions, including acrylic, rubber, and wood insulation with thicknesses of 1, 3, and 5 mm. The PEC signal slope was used as the main feature for estimating carbon steel thickness, and the estimated values were compared with actual thickness measurements to determine the percentage error. The results show that PEC signals are affected by carbon steel thickness, insulation material, and insulation thickness. Increasing carbon steel thickness generally reduced the PEC signal response, while insulation material and insulation thickness modified the signal amplitude and slope. The lowest measurement errors were obtained under non-insulated conditions, while higher errors were observed when insulation was applied. These findings indicate that PEC testing has potential for CUI-related thickness estimation without removing insulation; however, signal calibration, insulation effects, and environmental parameters must be carefully considered to improve reliability for field applications. This study also supports SDG 9: Industry, Innovation and Infrastructure by promoting industrial and innovation in non-destructive inspection technologies and improving the reliability and integrity of industrial pipeline infrastructure.*

Keywords *- Carbon steel, Corrosion under Insulation (CUI), Insulation materials, Non-Destructive Testing (NDT), Pulsed Eddy Current (PEC).*

1. Introduction

Pipelines are widely used in oil and gas, chemical processing, petrochemical, and power generation industries for transporting fluids under various operating conditions [1-3]. Many pipeline systems are protected by insulation to maintain process temperature, reduce heat loss, and improve operational efficiency. However, the presence of insulation may also create a hidden environment where moisture, dissolved ions, and contaminants accumulate at the metal-insulation interface.

This condition can initiate Corrosion under Insulation (CUI), which is difficult to detect because the damaged area is not directly visible during routine inspection [4]. CUI is a critical integrity problem because it may lead to wall thinning, leakage, unplanned shutdown, and safety hazards if not detected at an early stage. Conventional inspection of insulated pipelines often requires the removal of insulation to expose the metal surface. Although this method provides direct access to the inspected area, it is time-consuming, labor-intensive, and costly. In industrial facilities, insulation removal may also interrupt plant operation and increase maintenance expenditure [5-7]. Therefore, reliable Non-Destructive Testing (NDT) methods that can assess the condition of insulated pipelines without removing the insulation layer are required.

Several NDT methods have been used for CUI inspection, including ultrasonic testing, radiography, infrared thermography, and eddy current-based techniques. Ultrasonic testing provides accurate wall-thickness measurement but usually requires surface access and proper coupling.

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Radiographic testing can detect internal defects and wall loss, but it involves radiation safety concerns and requires strict field control. Infrared thermography enables rapid and non-contact inspection, but its performance may be affected by surface emissivity, temperature gradients, weather conditions, and insulation properties. Pulsed Eddy Current (PEC) testing has attracted attention because it can inspect conductive materials through non-conductive insulation and coating layers, making it suitable for preliminary screening of insulated pipelines [8-10]. PEC testing works by generating a transient electromagnetic field through an excitation coil.

The induced eddy current response in the conductive specimen produces a secondary magnetic field, which is detected by a sensor. Changes in the measured signal can be related to material thickness, wall loss, or defect conditions. Previous studies have shown that PEC signals are influenced by sample thickness, lift-off distance, probe geometry, insulation material, insulation thickness, and electromagnetic properties of the inspected structure [11-17]. Therefore, understanding the influence of these parameters is important for improving PEC calibration and measurement reliability.

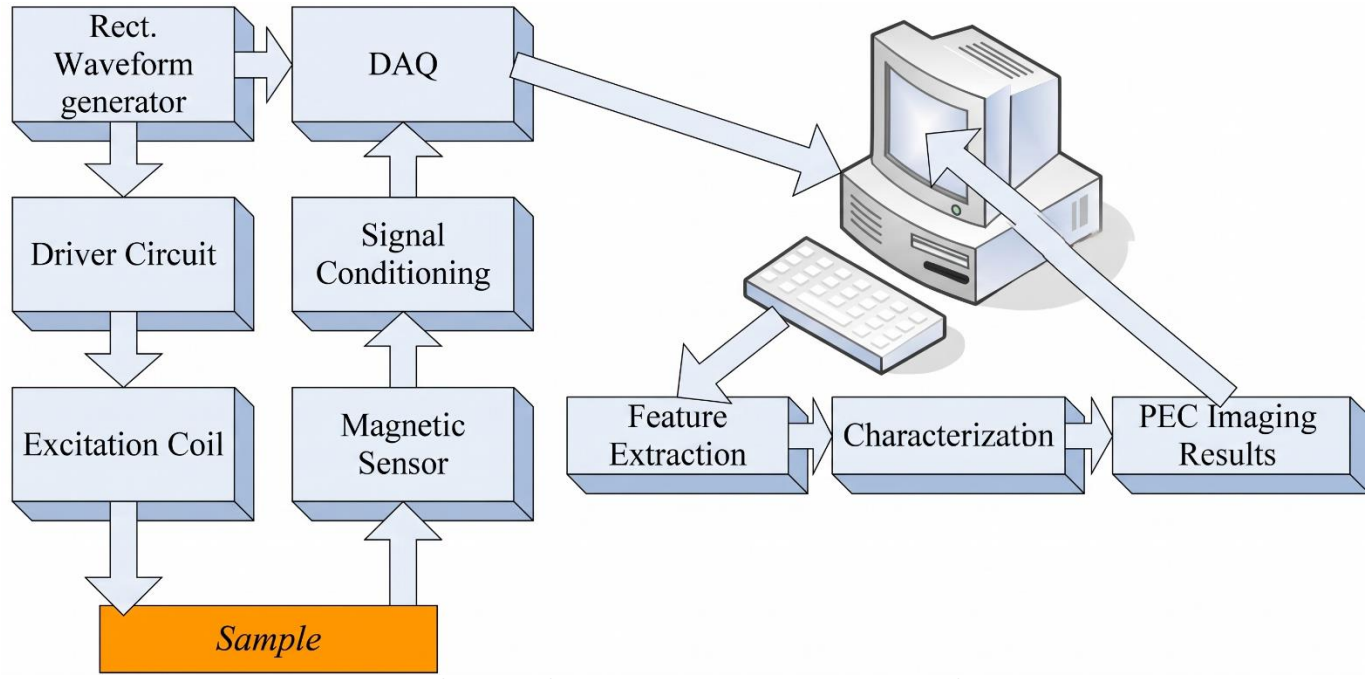


Fig. 1 Schematic configuration of a Pulsed Eddy Current (PEC) NDT system for CUI inspection [15]

Although PEC testing has been widely investigated for metallic defect detection and thickness assessment, further evaluation is still needed for its application in CUI inspection. Many previous studies have focused on general PEC signal behavior, defect detection, or probe development. However, systematic comparison of PEC signal response under different insulation materials and insulation thicknesses remains limited. In addition, quantitative performance evaluation using thickness estimation error is still needed to assess the reliability of PEC-based inspection under insulated conditions.

Therefore, this study evaluates the applicability of PEC testing for detecting thickness variation associated with CUI in carbon steel pipeline structures. The specific objectives are:

- To analyze the effect of carbon steel thickness on PEC signal response,
- To evaluate the influence of different insulation materials and insulation thicknesses on PEC signal behavior,
- To quantify the measurement error of PEC-based thickness estimation compared with actual thickness values.

An alternative to the current technique is to use the non-destructive pulsed eddy current method. Some factors affect the PEC signals, which are sample material thickness, insulation thickness and insulation material. By understanding these factors, a proper PEC system can be created. The relation between the slopes of the PEC signal amplitude and material thickness will subsequently be determined using the regression method. Using this relationship, the experimental material thickness can be calculated and then compared with the actual thickness.

Overall, this non-destructive method has certain factors that affect PEC signals, for example, types of insulation, insulation thickness, and sample material thickness. It will be easier to create PEC systems that function satisfactorily in practical applications if we are aware of the consequences of

these factors [9]. To calculate wall thickness loss in pipework, pulsed eddy current analyses variations in electromagnetic signals. As schematically depicted in the picture below, pulsed eddy current uses magnetic field sensors and coil sensors to find CUI [9, 10]. By creating an eddy current out of an excitation coil inside the area of the chosen objects, a moment magnetic field output can be returned and further gathered by the reception coil. The magnetic field will change if there are any flaws or irregularities.

The effectiveness of using a pulsed eddy current on different cladding materials was investigated using a mathematical simulation. The signal fading coefficient and the loss due to pipe wall thickness have been demonstrated.According to early results, the output signal was stronger whenever the cladding material used had a higher conductivity. The study also showed that larger signals could be detected when aluminium alloy was used as the coating material rather than stainless steel. In the case of an insulated pipe having stainless steel cladding, it was demonstrated that the observed electromagnetic signal amplitude decreased with increasing pipe wall thickness lost [11, 12]. Eddy current technology offers a higher examination efficiency and lower risk of occupational hazards than radiography. The measurement must be carried out by a highly trained operator with the necessary training. Finally, eddy current techniques are insufficient to identify localised corrosion [13-16]. Figure 1 shows schematic system to generate PEC for CUI detection.

1.1. Research Gap and Novel Contribution

Although PEC testing has been widely investigated for metallic defect detection and thickness assessment, several research gaps remain for its application in CUI inspection. First, the effect of different insulation materials on PEC signal response has not been sufficiently compared under the same experimental configuration. Second, many studies emphasize defect detection but provide limited quantitative evaluation of thickness estimation error under insulated conditions. Third, the relationship between PEC signal slope, insulation thickness, and carbon steel thickness requires further clarification for practical calibration.

This study addresses these gaps by experimentally comparing PEC signal response for carbon steel specimens covered with acrylic, rubber, and wood insulation at different insulation thicknesses. The novelty of this work is not only the use of PEC for CUI-related detection, but also the quantitative evaluation of how insulation parameters affect thickness estimation accuracy. The study focuses mainly on detection and thickness characterization, where the PEC signal is used to estimate wall-thickness variation associated with corrosion-related material loss.

1.2. Comparative Analysis of NDT Methods for CUI Inspection

Compared with ultrasonic testing and radiography, PEC testing offers a practical advantage because it can be applied through non-conductive insulation without direct contact with the metal surface. This makes PEC suitable for rapid screening of insulated pipeline systems. However, PEC should not be considered a complete replacement for other NDT methods because its signal interpretation may be affected by insulation thickness, probe lift-off, and electromagnetic noise. Therefore, PEC is more appropriate as a screening and thickness-estimation method, while ultrasonic or radiographic testing may still be required for detailed confirmation.

Table 1. Comparative analysis of NDT methods for CUI inspection

NDT Method	Advantages for CUI Inspection	Limitations and Relevance
Ultrasonic testing	Provides accurate wall-thickness measurement using reflected sound waves.	Usually requires direct surface access and couplant; useful as a reference method for validating PEC thickness estimation.
Radiographic testing	Can detect hidden defects, wall loss, and internal corrosion.	Requires radiation safety control and restricted access; less practical for frequent screening.
Infrared thermography	Fast, non-contact, and suitable for large-area screening based on thermal contrast.	Sensitive to emissivity, temperature gradient, weather, and insulation condition; less reliable for quantitative wall-thickness estimation.
Pulsed eddy current testing	Can inspect conductive materials through non-conductive insulation without direct metal contact.	Affected by lift-off, insulation thickness, probe design, material properties, and noise; main method evaluated in this study.

2. Research Methodology

The experimental work was conducted to evaluate the capability of PEC testing for estimating carbon steel thickness under different insulation conditions. The experimental procedure consisted of four main stages: specimen preparation, insulation configuration, PEC signal acquisition, and data analysis. The PEC system was connected to a data acquisition unit and a computer for signal recording and processing. The measured PEC signal was then analyzed to determine the relationship between signal slope and carbon steel thickness (Figure 2).

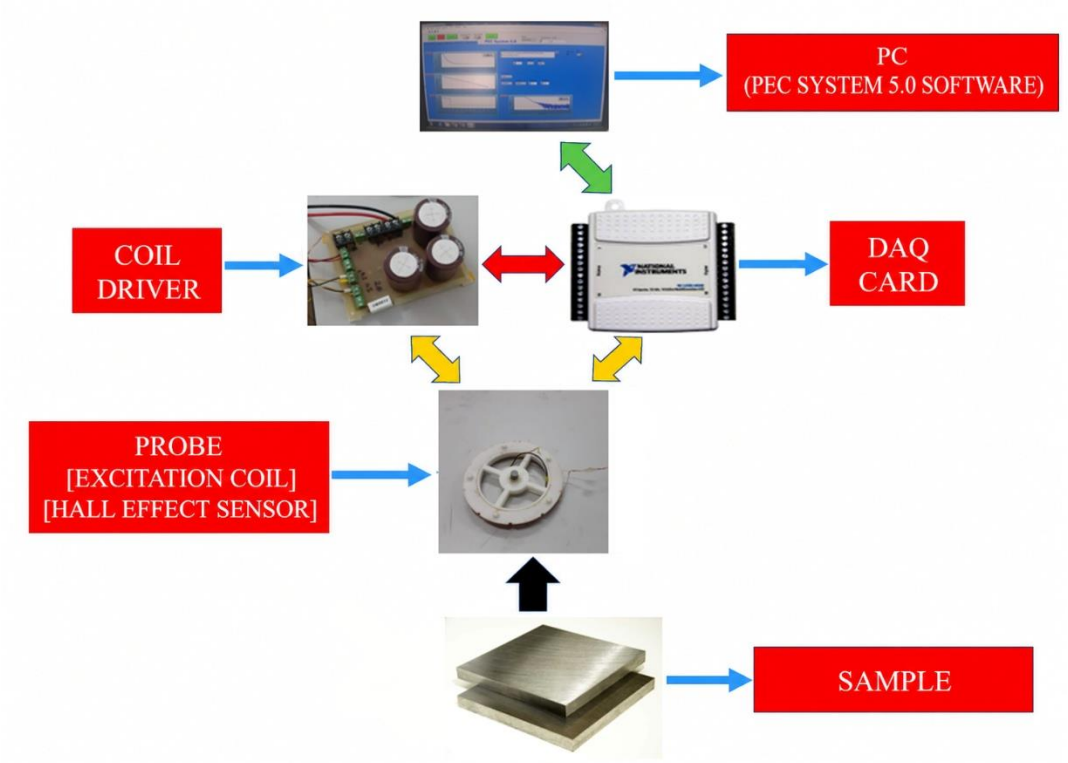


Fig. 2 Experimental PEC data acquisition system used in this study [17]

2.1. Testing Materials

Samples used were carbon steel with thickness will be determined in this experiment. Carbon steel is malleable and ductile. Despite its low tensile strength and being inexpensive and easy to manufacture, mild steel can have its surface hardness increased by carburization [18]. The composition of this mild steel is presented at Table 2. In this experiment, carbon steel specimens with four different thicknesses, namely 6, 7, 8, and 9 mm, were used to evaluate the effect of material thickness on the PEC signal response. Each carbon steel specimen was prepared with a dimension of 400 mm × 400 mm.

Table 2. Composition of samples

Elements	Compositions (%)
Carbon, C	0.14 - 0.2
Iron, Fe	98.81 - 99.26
Manganese, Mn	0.60 - 0.90
Phosphorus, P	≤ 0.040
Sulphur, S	≤ 0.050

2.2. Insulation Materials

Three types of insulation materials were used in this experiment, which are rubber sheet, wood/plywood, and acrylic. Each of these materials was prepared at the size of 400 mm × 400 mm. The rubber sheet known as Ethylene Propylene Diene Monomer (EPDM) is utilized in a wide variety of products. To a certain extent, EPDM can be blended to achieve certain qualities based on the EPDM polymers available, followed by the processing and curing techniques used. Table 3 shows the mechanical properties of the EPDM rubber.

Table 3. Mechanical properties of EPDM rubber insulation

Property	Value
Appearance	-
Hardness, Shore A	30-90
Tensile failure stress, ultimate	17 MPa (500-2500 PSI)
Elongation after fracture in %	≥ 300%
Density	Can be compounded from 0.90 to >2.0 g/cm^3

2.3. PEC System and Data Acquisition

To set up the experiment, some pieces of equipment were used: the probe, DAQ card, coil driver, and a PC with PEC System 5.0 software. Basically, for the identification and evaluation of surface and sub-surface flaws, probes stimulated with single or several frequencies are used. PEC probe will concentrate its strongest magnetic field close to the defect area [19]. Data Acquisition Systems (DAQ) are used to collect data from their immediate environment. Getting data allows for the gathering of specific information about the environment being

studied. Data acquisition devices typically connect to numerous sensors that describe the phenomenon being studied. Different types of transducers that generate analog impulses serve as the source of data for data acquisition systems [20].

These data need to be processed, so an analog-to-digital converter transforms the analog signals into a digital format. Basically, in this experiment, the DAQ card serves in a way where the Hall-effect mechanism detects the signal, which will then be transferred to the PC through a DAQ card and sampled at twenty thousand samples per second [15]. Figure 2 shows the experimental PEC data acquisition system used in this study. Universal computing system called LabView by National Instruments, which has a Graphical User Interface as well as Graphical Program Code, was the software that was used. It was created for data collection, handling, and display programming. This software receives and interprets the signal that was originally detected by the hall effect sensor and then transferred to the PC using the DAQ card.

2.4. PEC Probe Configuration

The PEC probe is main equipment used for testing in this project. PEC is a non-destructive testing method that creates a magnetic field using a probe to cause eddy currents in the material being tested. The eddy current-produced secondary magnetic field is detected by the same instrument. An informational signal about the material's characteristics and the presence of flaws is created by the interplay of the primary and secondary magnetic fields. Under insulation, this PEC can find flaws and corrosion. The probe consists of exciter coils, a ferrite core, and a 90 mV/G-sensitive Hall Effect sensor (DRV5053VA). The magnetic flux is concentrated, and the outgoing signal of the Hall device is amplified using a ferrite core (Figures 3 and 4). The ferrite core is placed above the hall effect sensor, and both the sensor and core are placed at the center of the probe, which will be 50 mm away from the exciter coils. The exciter coils consist of 200 turns with 6 mm thickness. Figure 3 shows a schematic cross-section of the probes used in the thickness detector, Figure 4 illustrates the probes used in PEC, and Figure 5 displays typical data generated from the PEC system.

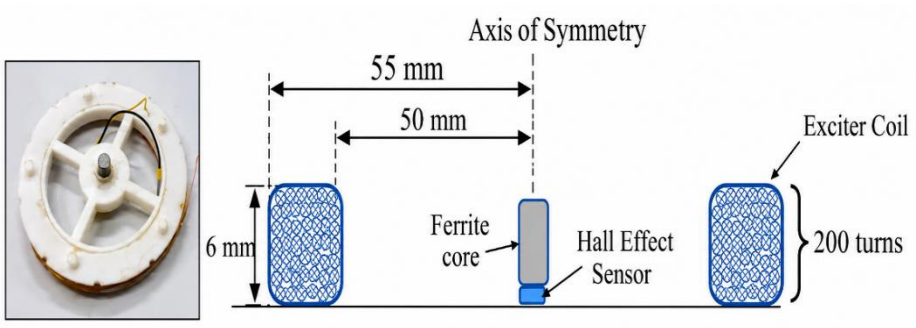


Fig. 3 Cross-Sectional schematic of the PEC probe



Fig. 4 Physical PEC probe used in the experiment

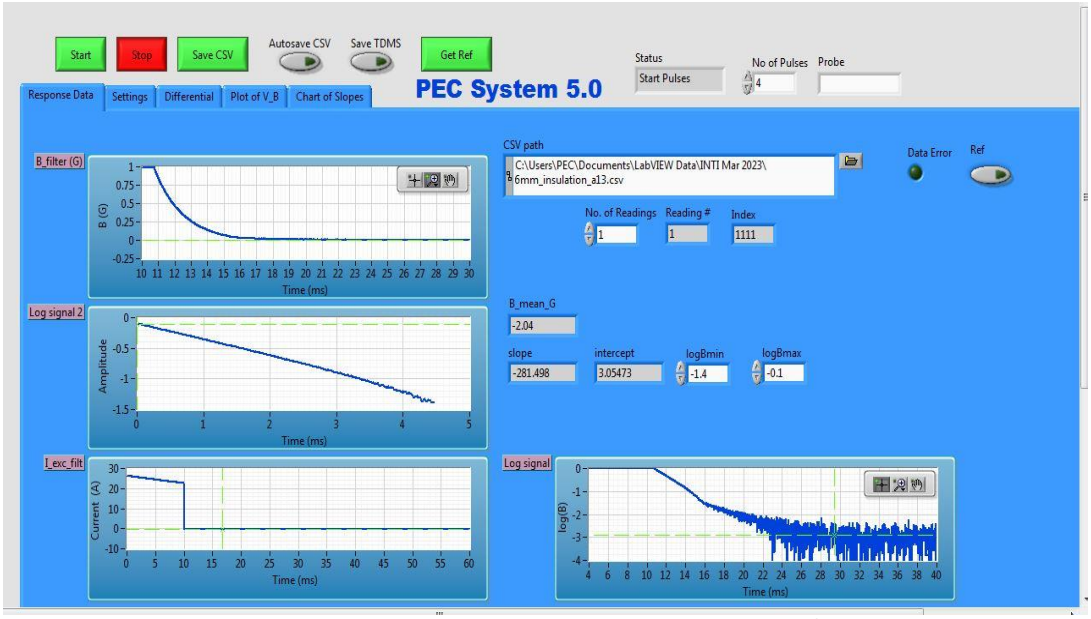


Fig. 5 Typical PEC signal data obtained using PEC System 5.0 software

3. Results and Discussion

Table 4. PEC signal slope under different insulation and carbon steel thickness conditions

Types of samples	Thickness of samples			
Insulation Thickness	**Carbon Steel 6 mm**	**Carbon Steel 7 mm**	**Carbon Steel 8 mm**	**Carbon Steel 9 mm**
Acrylic 1 mm	281.562 mV/ms	275.731 mV/ms	272.657 mV/ms	264.092 mV/ms
Acrylic 3 mm	297.235 mV/ms	292.601 mV/ms	284.356 mV/ms	281.819 mV/ms
Acrylic 5 mm	310.199 mV/ms	310.414 mV/ms	301.119 mV/ms	297.906 mV/ms
Rubber 1 mm	283.116 mV/ms	276.576 mV/ms	267.914 mV/ms	266.389 mV/ms
Rubber 3 mm	291.627 mV/ms	284.307 mV/ms	275.468 mV/ms	272.981 mV/ms
Rubber 5 mm	310.551 mV/ms	304.314 mV/ms	290.873 mV/ms	283.383 mV/ms
Wood1 mm	285.913 mV/ms	278.727 mV/ms	264.722 mV/ms	260.977 mV/ms
Wood3 mm	299.080 mV/ms	297.547 mV/ms	290.413 mV/ms	285.595 mV/ms
Wood5 mm	313.772 mV/ms	307.943 mV/ms	301.97 mV/ms	298.721 mV/ms

Table 4 shows the slope of PEC signal amplitude against the carbon steel thickness without insulation, with acrylic, rubber, and wood insulation. The comparative analysis of insulation thickness and carbon steel thickness shows that both parameters influence the PEC signal response. For all insulation materials, the PEC signal slope generally increased as the insulation thickness increased, with the highest values observed at 5 mm insulation. However, this trend should not be interpreted simply as improved signal transmission through thicker insulation. Instead, the increase in signal response may be associated with changes in electromagnetic coupling, probe-to-specimen distance, and baseline signal behavior caused by the presence of the insulation layer. Therefore, separate calibration for each insulation condition is required before PEC can be applied for quantitative thickness estimation.

The effect of carbon steel thickness shows a clearer trend. As the carbon steel thickness increased from 6 mm to 9 mm, the PEC signal response generally decreased across all insulation types. This indicates that the transient electromagnetic response is sensitive to the amount of conductive material beneath the probe. Thicker carbon steel specimens may produce different eddy current diffusion behavior, resulting in measurable changes in the PEC signal slope.

This confirms that PEC signal features can be correlated with material thickness. However, the presence of insulation introduces additional variability, which may affect the accuracy of thickness estimation. Among the tested insulation materials, wood generally produced the highest signal response, followed by acrylic and rubber. This difference suggests that insulation material properties may affect the PEC signal response under the tested conditions. However, the higher signal response observed for wood should not be directly interpreted as better signal transmission or better insulation performance without further investigation of its electromagnetic and physical properties. Overall, the results indicate that carbon steel thickness, insulation type, and insulation thickness must be considered as correction factors in PEC calibration for CUI-related inspection.

3.1. Percentage Error

From the regression graph of the slope against the testing materials, the equations in relationship to slopes and thickness were able to be found. This equation can be used to determine the thickness of the tested materials with use of the slope, which can be found through this experiment. The thickness which is found through the equation will be a bit different from the actual thickness of the carbon steel (Table 5). The percentage error for this experiment is being calculated to determine how high the error rate is. Equation (1) below shows the formula that was used to calculate the percentage error in this project.

$$\%ERROR = \frac{ER\ theoretical - ER\ analytical}{ER\ theoretical}\ 100\% \qquad (1)$$

Table 5. Comparison between PEC-based thickness estimation and manual measurement

Without Insulation		
Actual Carbon Steel Thickness (mm)	**Experimental Carbon Steel Thickness (mm)**	**Percentage Error (%)**
6	6.0102	0.1700
7	6.9371	0.8986
8	8.1821	2.2763
9	8.8961	1.1544
Acrylic Insulation 1 mm		
Actual Carbon Steel Thickness (mm)	**Experimental Carbon Steel Thickness (mm)**	**Percentage Error (%)**
6	6.0867	1.4450
7	7.1031	1.4729
8	7.6389	4.5138
9	9.1318	1.4644
Acrylic Insulation 3 mm		
Actual Carbon Steel Thickness (mm)	**Experimental Carbon Steel Thickness (mm)**	**Percentage Error (%)**
6	6.0494	0.8233
7	6.8696	1.8629
8	8.3299	4.1238
9	8.7780	2.4667

The results indicate that insulation thickness modifies the PEC signal response. The increase in signal slope observed at higher insulation thicknesses should not be interpreted simply as improved signal transmission, but rather as a change in electromagnetic coupling and baseline response caused by the insulation layer and probe-to-specimen distance. Therefore, calibration for each insulation condition is required before PEC can be used for quantitative thickness estimation.

The reduction in PEC signal response with increasing carbon steel thickness indicates that the transient electromagnetic response is sensitive to the amount of conductive material beneath the probe. Thicker carbon steel specimens produce different eddy current diffusion behavior, resulting in a measurable change in the signal slope. This confirms that PEC signal features can be correlated with material thickness. However, the presence of insulation introduces additional variability, which increases the error of thickness estimation. Therefore, insulation type and insulation thickness must be considered as correction factors in PEC calibration.

3.2. Performance Metrics

The performance of the PEC-based thickness estimation was evaluated using percentage error between the estimated and actual carbon steel thickness. The percentage error was selected as the primary quantitative metric because the study focused on thickness characterization rather than binary defect classification. Lower percentage error indicates better agreement between PEC-based estimation and actual thickness measurement.

In this study, the measurement reliability was assessed by comparing the error trend under non-insulated and insulated conditions. The results indicate that non-insulated specimens produced lower estimation errors, while insulated specimens showed higher deviations due to the additional lift-off and electromagnetic interaction introduced by the insulation layer.

For future binary CUI detection studies, additional performance metrics such as probability of detection, accuracy, false positive rate, false negative rate, and receiver operating characteristic analysis should be included using a larger dataset containing known defective and non-defective samples.

3.3. Signal Processing and Machine Learning Considerations

PEC signal interpretation depends strongly on signal quality and feature extraction. In this study, the slope of the PEC signal was used as the main feature because it represents the transient electromagnetic response associated with material thickness variation. However, PEC signals may be affected by noise, probe lift-off, insulation thickness, and material heterogeneity. Therefore, signal processing techniques such as smoothing, baseline correction, filtering, and normalization are important to improve signal consistency before regression analysis.

Advanced signal processing and machine learning approaches may further improve PEC-based CUI assessment. Features such as peak amplitude, decay rate, time-to-peak, signal slope, and frequency-domain components can be extracted from PEC signals and used as inputs for classification or regression models. Machine learning methods such as support vector machines, random forests, artificial neural networks, and deep learning models can be applied to classify defect conditions or predict wall-thickness loss. Nevertheless, the implementation of machine learning requires a larger dataset, repeated measurements, and independent validation to avoid overfitting. Therefore, future work should combine PEC signal features with machine learning-based analysis for more reliable field-scale CUI detection and characterization.

3.4. Operational and Environmental Effects

The performance of PEC testing is affected by several operational and environmental parameters. Insulation thickness acts as an additional lift-off distance between the probe and the carbon steel surface, which can modify the electromagnetic coupling and influence the measured signal. Different insulation materials may also affect the signal response depending on their electrical, magnetic, and physical properties. Therefore, separate calibration curves may be required for different insulation materials and thicknesses.

Temperature may influence PEC measurement by affecting the electrical conductivity and magnetic permeability of the tested material, as well as the stability of the sensor and electronic components. In field applications, temperature variation may occur due to operating pipelines, solar exposure, or ambient weather conditions. Electromagnetic noise from nearby equipment, cables, motors, and industrial facilities can also interfere with PEC signals. To reduce these effects, proper shielding, repeated measurements, baseline correction, and controlled probe positioning are recommended. These factors indicate that PEC testing should not be interpreted solely based on raw signal amplitude. Instead, calibration under representative insulation, temperature, and environmental conditions is required to improve the reliability of PEC-based CUI inspection.

3.5. Field Validation and Practical Applicability

The present study was conducted under controlled laboratory conditions using carbon steel specimens and selected insulation materials. Although the results demonstrate the potential of PEC testing for thickness estimation under insulated conditions, field validation is required before practical implementation in industrial pipeline systems. In actual field conditions, CUI inspection may be affected by curved pipe geometry, non-uniform insulation

thickness, moisture accumulation, cladding material, surface roughness, temperature variation, and electromagnetic noise.

A recommended field validation procedure should include PEC inspection of insulated pipeline sections with known or suspected CUI, followed by confirmation using reference NDT methods such as ultrasonic testing or radiography after insulation removal at selected locations. The field data should then be compared with laboratory calibration results to evaluate detection reliability, thickness estimation error, and false indication rates. This step is essential to determine whether PEC can be used as a reliable screening method for asset integrity management.

3.6. Application to Asset Management and Digital Twin System

PEC inspection data can support asset management by providing non-destructive information on possible wall-thickness variation beneath insulation. When PEC measurements are collected periodically, the data can be used to monitor changes in signal response over time and identify pipeline sections that require further inspection. This approach can help prioritize maintenance actions and reduce unnecessary insulation removal.

In a digital twin framework, PEC inspection results can be integrated with pipeline information such as material type, insulation condition, operating temperature, maintenance history, and corrosion risk factors. This approach is consistent with recent applications of digital twin models for real-time failure prediction in industrial machinery, where operational data are used to support predictive maintenance and decision-making [21].

Therefore, the integration of PEC data into asset management systems may improve decision-making by enabling risk-based inspection planning and early identification of areas with potential CUI. However, reliable implementation requires standardized data acquisition procedures, calibration models, and validation against reference inspection data.

3.7. Standardization and Best Practices

The practical application of PEC testing for CUI inspection should follow standardized inspection procedures and best practices. Important aspects include probe calibration, verification using reference specimens, control of lift-off distance, documentation of insulation type and thickness, repeated measurements, and comparison with reference NDT methods when possible. Standardized reporting should include specimen information, inspection parameters, signal processing method, calibration equation, estimated thickness, percentage error, and inspection limitations [5, 11, 14].

For industrial application, PEC should be used as part of a risk-based inspection strategy rather than as a standalone method. Areas indicated as potentially degraded by PEC screening should be further evaluated using confirmatory NDT methods or direct inspection after insulation removal. This combined approach can improve inspection reliability and reduce the risk of misinterpretation.

4. Conclusion

This study evaluated the capability of pulsed eddy current testing for estimating carbon steel thickness under different insulation conditions as a preliminary approach for CUI-related inspection. The results show that PEC signal response is influenced by carbon steel thickness, insulation material, and insulation thickness. Increasing carbon steel thickness generally reduced the PEC signal response, indicating that PEC is sensitive to wall-thickness variation. The application of insulation increased measurement complexity and affected the accuracy of thickness estimation, showing that insulation parameters must be included in the calibration process.

The comparison between PEC-estimated thickness and actual thickness confirmed that percentage error can be used as a quantitative indicator of measurement accuracy. Lower errors were observed under non-insulated conditions, while higher deviations occurred when insulation was applied. These findings suggest that PEC has potential as a non-destructive screening method for insulated carbon steel structures, especially for detecting thickness variation associated with CUI. However, the study was limited to laboratory-scale specimens and selected insulation materials. Field validation, larger datasets, repeated measurements, advanced signal processing, and comparison with reference NDT methods are required to improve reliability. Future work should also include probability of detection analysis, false indication assessment, and integration of PEC inspection data into risk-based asset management or digital twin systems.

References

[1] P. Roffey, and E.H. Davies, “The Generation of Corrosion under Insulation and Stress Corrosion Cracking due to Sulphide Stress Cracking in an Austenitic Stainless Steel Hydrocarbon Gas Pipeline,” *Engineering Failure Analysis*, vol. 44, pp. 148-157, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[2] Khan Muhammad Mohsin, Ainul Akmar Mokhtar, and Peter W. Tse, “A Fuzzy Logic Method: Predicting Corrosion under Insulation of Piping Systems with Modelling of CUI 3D Surfaces,” *International Journal of Pressure Vessels and Piping*, vol. 175, pp. 1-14, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[3] Yuan-Hao Tsai et al., "A BIM-based Approach for Predicting Corrosion under Insulation," *Automation in Construction*, vol. 107, pp. 1-14, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[4] TWI Ltd., What is Non-Destructive Testing (NDT)? Methods and Definition, TWI Ltd., 2026. [Online]. Available: https://www.twi-global.com/technical-knowledge/faqs/what-is-non-destructive-testing

[5] Gino De Landtsheer, *Corrosion under Insulation (CUI) Guidelines: Technical Guide for Managing CUI*, 3rd ed., Woodhead Publishing, vol. 55, 2020. [Google Scholar] [Publisher Link]

[6] Neil Wilds, *Corrosion under Insulation*, Trends in Oil and Gas Corrosion Research and Technologies, Woodhead Publishing, pp. 409-429, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[7] Qing Cao et al., "A Review of Corrosion under Insulation: A Critical Issue in the Oil and Gas Industry," *Metals*, vol. 12, no. 4, pp. 1-24, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[8] Ali Sophian, Guiyun Tian, and Mengbao Fan, "Pulsed Eddy Current Non-Destructive Testing and Evaluation: A Review," *Chinese Journal of Mechanical Engineering*, vol. 30, no. 3, pp. 500-514, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[9] C.S. Angani et al., "The Pulsed Eddy Current Differential Probe to Detect a Thickness Variation in an Insulated Stainless Steel," *Journal of Nondestructive Evaluation*, vol. 29, no. 4, pp. 248-252, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[10] Eddyfi Technologies, Corrosion under Insulation: The 7 Inspection Methods you Must Know About, Eddyfi Technologies, 2026. [Online]. Available: https://blog.eddyfi.com/en/corrosion-under-insulation-the-7-inspection-methods-you-must-know-about

[11] American Petroleum Institute, API Recommended Practice 583: Corrosion under Insulation and Fireproofing, 2nd ed., American Petroleum Institute, 2024. [Online]. Available: https://www.api.org/-/media/files/publications/2025-catalog/06_refining_2025.pdf

[12] ASTM International, "Standard Specification for Thermal Insulation for use in Contact with Austenitic Stainless Steel," *ASTM International*, 2023. [CrossRef] [Publisher Link]

[13] Q. Cao et al., "Corrosion of Mild Steel under Insulation-The Effect of Dissolved Metal Ions," *Corrosion Engineering, Science and Technology: The International Journal of Corrosion Processes and Corrosion Control*, vol. 55, no. 4, pp. 322-330, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[14] ASTM International, "Standard Guide for Laboratory Simulation of Corrosion under Insulation," *ASTM International*, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[15] Ali Sophian et al., "A Feature Extraction Technique based on Principal Component Analysis for Pulsed Eddy Current NDT," *NDT and E International*, vol. 36, no. 1, pp. 37-41, 2003. [CrossRef] [Google Scholar] [Publisher Link]

[16] Weiying Cheng, "Pulsed Eddy Current Testing of Carbon Steel Pipes' Wall-Thinning through Insulation and Cladding," *Journal of Nondestructive Evaluation*, vol. 31, no. 3, pp. 215-224, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[17] Zhiyuan Xu et al., "Assessment of Wall Thinning in Insulated Ferromagnetic Pipes using the Time-to-Peak of Differential Pulsed Eddy-Current Testing Signals," *NDT and E International*, vol. 51, pp. 24-29, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[18] Nalika Ulapane et al., "Non-Destructive Evaluation of Ferromagnetic Material Thickness using Pulsed Eddy Current Sensor Detector Coil Voltage Decay Rate," *NDT and E International*, vol. 100, pp. 108-114, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[19] Nalika Ulapane, and Linh Nguyen, "Review of Pulsed-Eddy-Current Signal Feature-Extraction Methods for Conductive Ferromagnetic Material-Thickness Quantification," *Electronics*, vol. 8, no. 5, pp. 1-13, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[20] Sud Sudirman et al., "Pulsed Eddy Current Signal Processing using Wavelet Scattering and Gaussian Process Regression for Fast and Accurate Ferromagnetic Material Thickness Measurement," *Alexandria Engineering Journal*, vol. 61, no. 12, pp. 11239-1125, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[21] Wai Yie Leong, "AI-Driven Predictive Safety Analytics for Accident Prevention in Smart Manufacturing," *Intelligent Manufacturing and Cloud Computing: Proceedings of the 2nd International Conference*, Wuhan, China, pp. 11-20, 2026. [CrossRef] [Google Scholar] [Publisher Link]