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EXPERIMENTAL STUDY ON THE EFFICACY OF ULTRASOUND IN IN-SITU DETECTION OF CORROSION IN PALM OIL REFINING EQUIPMENT

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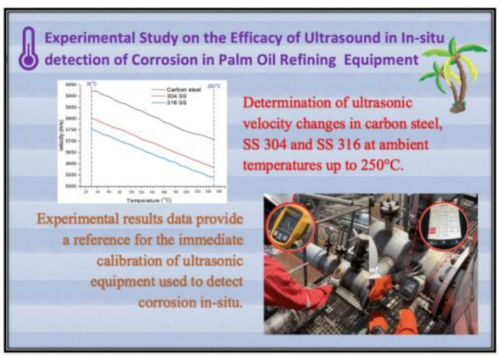
Graphical abstract



Abstract

Palm oil is an important agricultural product for many countries. Stainless steel refining equipment faces corrosion challenges due to the corrosive nature of palm oil, which gradually deteriorates the equipment over time. Ultrasonic testing (UT) can detect corrosion, usually performed during palm mill downtime due to temperature constrain. The study aims to optimize UT at temperatures up to 250°C. The experimental outcomes serve as a foundation for broadening the application of phased array corrosion mapping (PACM) into elevated temperatures. The results offer intricate insights into velocity fluctuations within specific materials, correlating with temperature elevation. In summary, the suite of UT methods demonstrates their aptitude for employment during palm oil refinery operations up to 250°C involving carbon steel as well as 304 and 316 stainless steels. It allows further UT application during the palm mill's operation and achieves the study's objective of allowing palm mill owners to detect and monitor corrosion growths without stopping production.

Keywords: Phased array ultrasonic testing (PAUT), non-destructive Testing (NDT), ultrasonic thickness gauge (UTG), elevated temperature, pitting

Abstrak

Minyak kelapa sawit merupakan produk pertanian penting bagi banyak negara. Peralatan penyulingan keluli tahan karat menghadapi cabaran karat disebabkan sifat korosif minyak kelapa sawit, yang secara beransur-ansur merosakkan peralatan tersebut sepanjang masa. Ujian ultrasonik (UT) dapat mengesan karat, biasanya dilakukan semasa waktu rehat kilang kelapa sawit disebabkan oleh had suhu. Kajian ini bertujuan untuk mengoptimumkan UT pada suhu sehingga 250°C. Hasil eksperimen ini bertindak sebagai asas untuk meluaskan penggunaan pemetaan korosi laras bersusun (PACM) ke dalam suhu yang lebih tinggi. Keputusan menawarkan wawasan yang rumit terhadap fluktuasi halaju dalam bahan tertentu, berkorelasi dengan peningkatan suhu. Secara keseluruhan, rangkaian kaedah UT menunjukkan kebolehan mereka untuk digunakan semasa operasi penapisan minyak kelapa sawit sehingga 250°C melibatkan keluli karbon serta keluli tahan karat 304 dan 316. Ini membolehkan penggunaan UT yang lebih lanjut semasa operasi kilang kelapa sawit dan mencapai objektif kajian untuk membolehkan pemilik kilang kelapa sawit mengesan dan memantau pertumbuhan karat tanpa menghentikan pengeluaran.

Kata kunci: Ujian ultrasonik laras bersusun (PAUT), Ujian Tanpa Merusak (NDT), alat pengukur ketebalan ultrasonik (UTG), suhu tinggi, piting

1.0 INTRODUCTION

Palm oil is one of Malaysia's essential agricultural products. According to the Malaysian Palm Oil Board (MPOB), which is the government agency that oversees Malaysia's palm oil industry, in 2022, 18.45 million tonnes of palm oil was produced in Malaysia [1,2]. Palm oil refining consists of several pieces of equipment such as sterilizers, steam injection digesters, clarifiers, storage tanks for crude palm oil, boilers and piping systems [3].

The piping system transports palm oil and other liquids from one piece of equipment to another during processing. It typically consists of pipes, their connections usually in the form of multi-bolted joints [4], as well as pumps and valve components made of materials compatible with the palm oil characteristics, such as stainless steel (SS) or plastic. SS is used in these components due to its resistance to corrosion, heat and chemical damage [5], making it well-suited for food processing and handling equipment.

The operating temperature of the piping system in a palm oil processing plant will depend on the specific being carried out and the type of palm oil being processed. In general, the temperature of the piping system is kept between 55°C to 140°C to allow for efficient processing and to prevent the formation of solid deposits in the pipes [6]. Deodorization is an indispensable process in the refining of palm oil. The deodorization stage can be described as comprising several different processes such as pre-stripping, deodorizer and vacuum scrubber. Palm oil deodorizers generally operate at temperatures of 240°C to 260°C and pressures of 0.1 kPa to 0.3 kPa [7]. Sterilization is a critical process to eliminate or inactivate various microorganisms in a product carried out at 131°C with steam pressure [8].

Corrosion is a common problem in the palm oil processing industry, as the acidity of palm oil can cause damage to stainless steel equipment over some time. Monitoring the growth of corrosion is essential to ensure the longevity and efficiency of processing equipment [9].

Corrosion can be classified into two categories, which are localized corrosion and general corrosion, also known as uniform corrosion, which results in gradual loss of material thickness [10,11]. Localized corrosion result in more concentration with small and shallow pits but penetrate deeply [12–14]. Furthermore, stress corrosion cracking is a dangerous form of localized corrosion influenced by environmental stress that could lead to a sudden and catastrophic failure that requires regular inspection and monitoring [15–17].

Ultrasonic testing (UT) is a widely used nondestructive testing method to detect corrosion [18]. The advantages and disadvantages of UT, the comparison with other testing methods, and the development of ultrasonic and various novel application techniques over the years have been studied by many researchers [19–21]. The UT technique, i.e. phased array corrosion mapping (PACM), has recently gained popularity. It has several advantages, such as faster scan coverage of an area which is not only for spot detection [22]. Instead of drawing grid lines to get point-by-point ultrasonic thickness gauging readings of the entire area, PACM can cover a single scan with approximately 30 mm width [23]. The significant advantage of PACM is the ability to detect localized corrosion compared to other ultrasonic techniques [24–26] and the result presentation of PACM with 3D information to indicate detected detects precisely in size and location [27].

One of the UT limitations is that the testing material surface is not recommended to be higher than 52°C [28]. Hence, the common practice is to perform UT during equipment off-production at ambient temperature. Therefore, PACM is also the most challenging detection technique due to the relatively large contact area while assessing the palm mill's operation.

The above literature review shows that corrosion is a potential hazard in the palm oil refining industry, not only for carbon steel but also for stainless steel. PACM is a suitable ultrasonic inspection technique to detect corrosion effectively, especially localized corrosion, but it is mainly applied at ambient temperatures [29].

In-situ inspection can be carried out without stopping production for inspections and repairs so that profitability is not affected [30]. Given that the machinery throughout the plant is not at risk from corrosion, especially as the operating temperature of the sterilization equipment exceeds 100°C and the temperature of the deodorization process is around

250°C, further proof that the inspection process can cope with high temperature is needed.

This study aims to explore the effective use of ultrasound on different temperatures from 30°C to 250°C, determine the parameters of ultrasound change with the increase in temperature and also with different materials through practical experiments. A significant innovation is the study of the relationship of ultrasonic velocity with temperature change in stainless steel, which was not included in previous research. This study can overcome the temperature limitation of the ultrasonic test to 52°C [28]. One of the practical implications of this research is to eliminate the need to stop production lines waiting for ambient temperatures to perform corrosion detection and monitoring. Our method can be used in a variety of temperature conditions, ensuring production continuity while protecting against corrosion issues. The outcome of the experiments serves as a reference to further apply PACM in high temperatures. It lets palm mill owners detect and monitor corrosion growth without stopping production. Furthermore, with the proposed method, the current pipeline condition monitoring plan can be extended by including additional pipes that were previously excluded from the assessment, as this would have required a production shutdown.

Previous studies have done similar experiments on carbon steel and found that the velocity will decrease and the attenuation will increase as the temperature rises [31,32]. So far, few similar experiments have been found on stainless steel except experimental in ambient temperature [33]. Moreover, no articles comparing different materials have been found.

It is necessary to increase the decibel (dB) to maintain the quality of the ultrasonic wave when the temperature rises. Stainless steel has a higher attenuation than carbon steel due to the relationship of coarse grain [34,35]. With the increase in temperature, it can be predicted that there will be higher attenuation.

The method of this study used a known thickness test specimen to measure the ultrasonic propagation speed at two points. The test specimen was placed on the heater to simulate the actual temperature on site to achieve the purpose of this study. The test temperature was raised from 30°C to 250°C, with a temperature difference of 10°C each time, and three data were collected for each set temperature, and the average value was taken. The parameters of the different materials were then compared.

The experiment results provide the detail of velocity change in particular material along with temperature rise and indicate that dB is not a significant obstruction. In conclusion, the UT methods, including conventional UT, ultrasonic thickness gauging and phased array ultrasonic testing or corrosion mapping, are suitable to use during palm oil refinery operations up to 250°C in carbon steel, SS 304 and SS 316.

It allows further UT application during the palm mill's operation. It achieves the study objective of allowing palm mill owners to detect and monitor corrosion growths without stopping production.

2.0 METHODOLOGY

In order to monitor the corrosion of SS equipment in palm oil processing plants, several methods can be used, including visual inspection and UT methods [36]. Visual inspection provides a quick and simple assessment of the surface condition of the equipment. However, it is limited in terms of the ability to detect corrosion occurring beneath the surface [37]. UT can provide a more comprehensive equipment assessment using sound waves to penetrate the surface and detect internal corrosion [38].

This study used the phased array ultrasonic equipment to determine ultrasonic longitudinal velocity and attenuation change from temperature 30°C to 250°C on three different materials: carbon steel, SS 304 and SS 316. The selected experiment temperature range is based on the common operating temperature in palm oil processing plant. The mean value of three (3) data sets in each temperature was recorded for further comparison. The results of the experiments were used to furnish the PACM equipment calibration and setting to be applied during palm mill operation.

2.1 Material

A phased array ultrasonic equipment, a 5 MHz 64 elements phased array probe mounted with a high-temperature resistance wedge and a non-water base couplant [39] was used for the experiment. A heating pad powered by a transformer was used to simulate the experiment temperature from 30°C to 250°C. The test specimen selected in this study are carbon steel, SS 304 and SS 316 for comparison. These materials were chosen due to their extensive utilization in the field. Despite stainless steel's superior resistance to corrosion, heat, and chemical damage in comparison to carbon steel, the latter is typically favored in situations where cost considerations are paramount. The comparative relationship of these materials will be helpful for future research and can also support the entire inspection activities.

2.2 Method

The experiment's first step was to determine the longitudinal velocity using pulse-echo A-Scan to capture round trip back wall echoes at ambient temperature [40]. This method allows for the bi-directional determination of both material thickness and ultrasonic velocity. The ultrasonic velocity can be determined by measuring the time it takes for the ultrasonic wave to pass through the thickness of the material. Three sets of velocity data were collected at the same temperature to minimize human error, and the mean velocity value was calculated [41].

Next, the test specimen was gradually heated in 10°C increments [42]. The mean velocity value was recorded and documented at each temperature step from 30°C to 250°C for further analysis and comparison. A handheld thermometer and thermocouples were affixed to the test specimen to ensure accurate temperature measurements to monitor and maintain the specific test temperature.

As the temperature increased, the amplitude of the echo decreased. The baseline was established at ambient temperature using the 80% full-screen height (FSH) dB of the experimental test to track these changes. Subsequently, during each following test, as the temperature rose, the dB was manually adjusted to restore it to 80% FSH and recorded for reference [43]. This manual adjustment served as the standard procedure for determining ultrasonic attenuation.

The velocity's round trip back wall echoes and the attenuation obtained through the experiment was used to adjust the second echo to 80% FSH for each temperature. The adjustment process is depicted in Figure 1, showcasing the variations in echo amplitudes with changing temperatures.

The same experiment method was applied to carbon steel, SS 304 and SS 316. Detailed analysis and comparison once collected all of the material's data have been discussed in the next section.

Figure 1 Phased array equipment in A-scan display

3.0 RESULTS AND DISCUSSION

The speed of sound passing through a material can vary depending on microstructure and temperature [44,45]. In a study of three materials, carbon steel was found to have the highest velocity, with a mean velocity of 5925 m/s at 30°C, dropping to 5707.4 m/s at 250°C.

The three sets of experimental data and the mean value of carbon steel velocity are shown in Figure 2. As can be seen from the graph, the data of the three groups of experiments do not differ much from each other and are consistent with the average value. The possibility of human error can be ruled out, thus increasing the credibility of the graph.

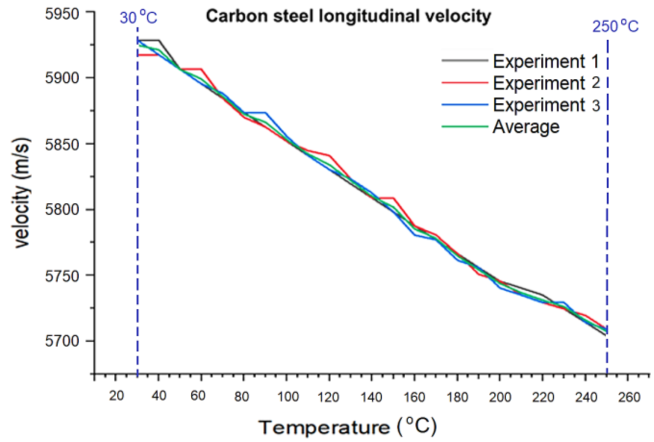


Figure 2 Ultrasonic longitudinal velocity of carbon steel between 30°C and 250°C

Figure 3 similarly recorded three sets of the experiment as well as the mean velocity of SS 304, which has a mean velocity of 5802.3 m/s at 30°C, dropping to 5584.3 m/s at 250°C, while SS 316 has the lowest mean velocity of 5752 m/s at 30°C and 250°C at 5538.4 m/s shown in Figure 4. The two sets of data for SS are also similar to those for carbon steel, and the data for the different experiments at the same temperature are not too far apart. The only difference is that the velocity at the beginning and end of the experiment is different for the different materials.

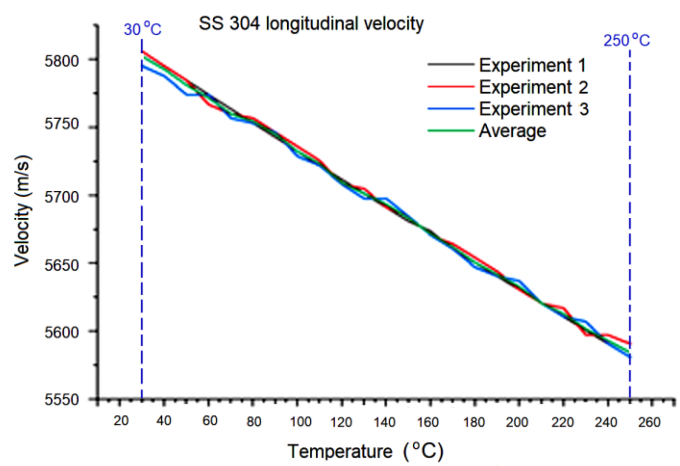


Figure 3 Ultrasonic longitudinal velocity of stainless steel SS 304 between 30°C and 250°C

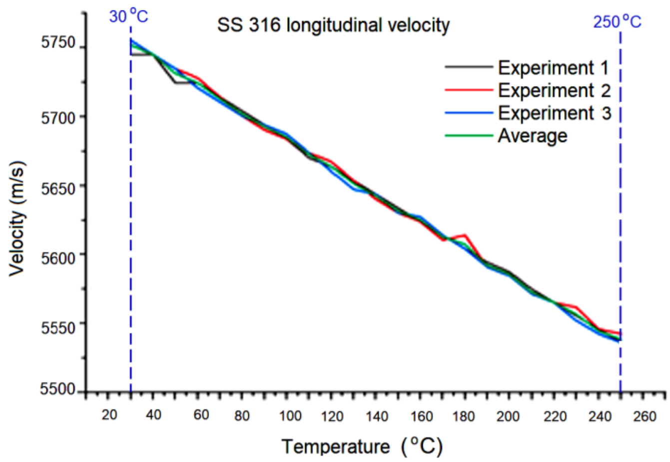


Figure 4 Ultrasonic longitudinal velocity of stainless steel SS 316 between 30°C and 250°C

This difference in velocity between materials highlights the effect of microstructure on ultrasonic velocity and demonstrates the proportional relationship between velocity and temperature.

Figure 5 provides the summary velocity among the carbon steel, SS 304 and SS 316 for better comparison, and Table 1 gives the detailed mean velocity of three materials in different temperatures.

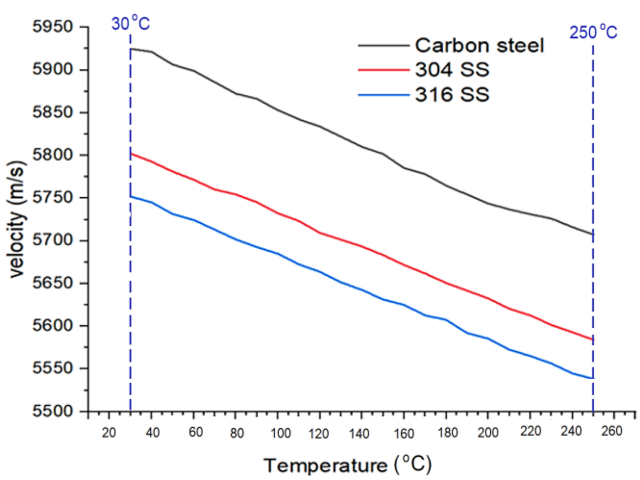


Figure 5 Comparison ultrasonic longitudinal velocity for carbon steel, SS 304 and SS 316

The velocity data listed in Table 1 are essential in detecting corrosion. While it is clear that velocity is linked to temperature change, it is also linked to the thickness of the detected object.

Previously, for materials of known thickness, round-trip back wall echoes were used to measure velocity. On the other hand, for inspections where the material's thickness is unknown, it is necessary to calibrate the UT machine with velocity to get the correct thickness. For example, to check an SS 304 pipe at 150°C without knowing the effect of temperature on velocity, the calibrate UT machine would inadvertently detect the wrong depth by blindly entering a consistent 5802.3 m/s instead of 5683.4 m/s as shown in Table 1.

Table 1 Experimentally derived average ultrasonic longitudinal velocity for carbon steel, SS 304 and SS 316

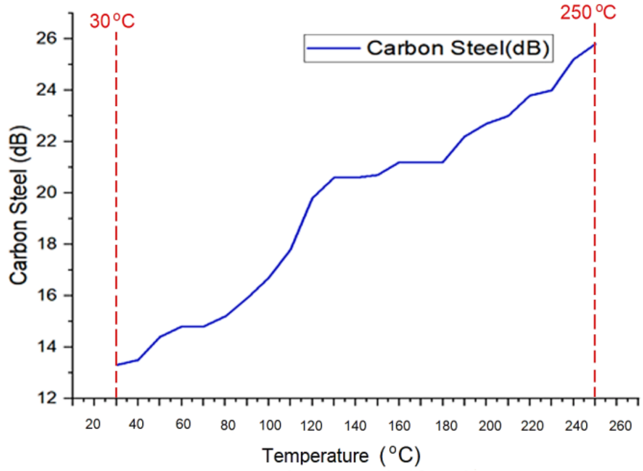
Temperature	CS (m/s)	SS 304 (m/s)	SS 316 (m/s)
30°C	5925.0	5802.3	5752.0
40°C	5921.3	5792.8	5745.1
50°C	5906.5	5781.2	5731.4
60°C	5899.2	5771.7	5724.5
70°C	5885.8	5760.1	5713.1
80°C	5872.4	5754.4	5701.7
90°C	5866.3	5745.2	5692.8
100°C	5853.1	5732.4	5685.0
110°C	5842.2	5723.2	5672.6
120°C	5833.9	5709.3	5663.7
130°C	5822.0	5701.4	5651.6
140°C	5810.0	5693.4	5642.5
150°C	5801.7	5683.4	5631.5
160°C	5785.2	5671.8	5625.1
170°C	5778.2	5661.9	5612.8
180°C	5764.8	5650.6	5607.5
190°C	5754.2	5641.8	5592.1
200°C	5743.8	5632.7	5585.5
210°C	5736.8	5620.6	5572.6
220°C	5731.2	5612.7	5565.2
230°C	5726.2	5601.7	5556.5
240°C	5716.0	5592.9	5544.8
250°C	5707.4	5584.3	5538.4

Using Table 1, a novel approach to monitoring and detecting corrosion in high-temperature pipelines can be applied, particularly for PACM, which requires the machine to be calibrated at a specific speed value before inspection. For example, when performing PACM on SS 316 pipe at 200°C, a velocity of 5585.5 m/s should be used for calibration to obtain an accurate corrosion thickness reading.

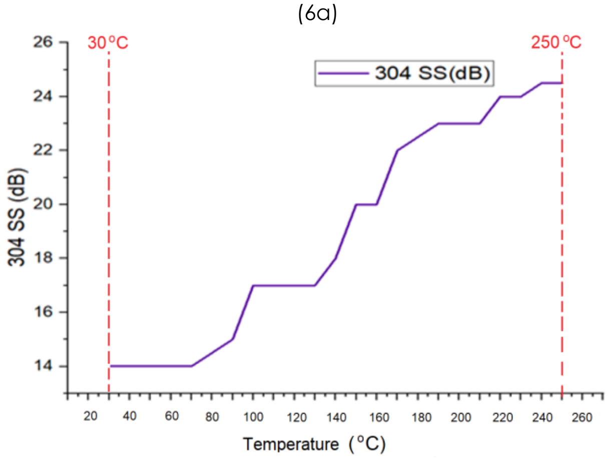
This article further investigates the impact of attenuation in three different types of materials at various temperatures [46]. The results reveal that the attenuation in carbon steel significantly increases with rising temperature. At 30°C, the dB value is measured at 13.3 dB, and as the temperature reaches 250°C, the attenuation gradually rises to 25.8 dB, as illustrated in Figure 6a.

In the case of SS 304, the initial attenuation is relatively higher, measuring at 14 dB at 30°C. Throughout the temperature range, the attenuation remains notably consistent, reaching a value of 24.5 dB at 250°C, as depicted in Figure 6b.

Similarly, the SS 316 material starts with an attenuation value of 13 dB at 30°C, shown in Figure 6c. As the temperature increases, the attenuation gradually rises, reaching 25.5 dB at 250°C.



(6a)



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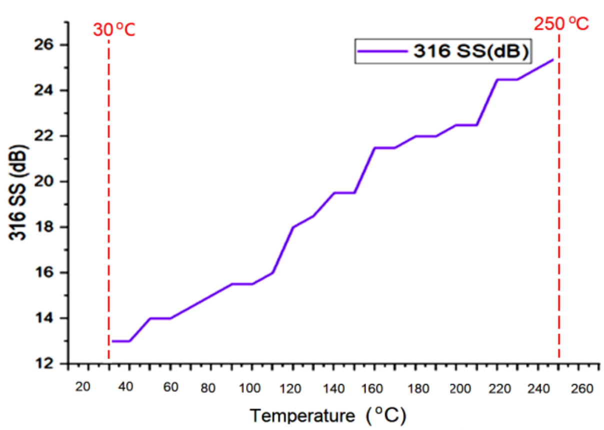

(6c)

Figure 6 Ultrasonic attenuation between 30°C and 250°C varies for: a) carbon steel, b) SS 304, c) SS 316

It can be observed that there is not much attenuation difference among the three materials because the specimens are 15 mm low in thickness. Material thickness is one of the reasons to contribute to sound attenuation. This occurrence also indicates that the dB changes from 30°C to 250°C is around 12 dB, which will not obstruct the implementation of this testing technique since it does not affect the overall data quality.

3.1 Validation

The next step is to perform validation. Figure 7 shows two V1 blocks made of carbon steel and SS 316 materials. V1 block has the standard design dimension used for UT calibration, the function of the V1 block includes determining the beam index, probe angle, resolution and sensitivity, etc. [47].

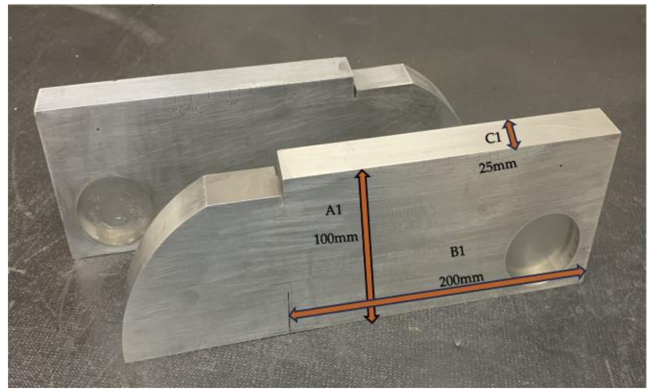

Figure 7 V1 Ultrasonic calibration block

A comprehensive validation process was carried out to verify the accuracy of UT for detecting corrosion on carbon steel and SS 316 at different temperatures. The distances of reference points A1 (100 mm), B1 (200 mm) and C1 (25 mm) were used as measurement references. An initial calibration of the UT machine was carried out at 30°C using the velocity data in Table 1 with values of 5925 m/s for carbon steel and 5752 m/s for SS 316. During the initial calibration, the detection depths of A1, B1 and C1 matched their respective design thicknesses. This calibration established a baseline for subsequent validation.

Subsequently, the UT device was calibrated to 50°C using the corresponding velocity data in Table 1 (5906.5 m/s for carbon steel and 5731.4 m/s for SS316) and the same points (A1, B1, and C1) were re-inspected with detection depths of 96 mm and 94 mm for A1, 196 mm and 197 mm for B1, and 24 mm and 23 mm for C1 respectively. The recorded measurements are shown in Table 2.

The validation process was then repeated at higher temperatures, including 100°C, 150°C, 200°C, and 250°C. A1, B1 and C1 measurements were then recorded and compared to their respective design thicknesses.

Table 2 shows the complete validation results for both materials and indicates the relationship between velocity calibration and depth of detection. Again showing the longer velocity travelling distance has a larger variation. Thus, the same phenomenon occurs when the material is at high temperatures, and incorrect calibration will not result in a correct and valid material depth.

Table 2 Depth validation

Temperature	Carbon Steel				316 Stainless Steel			
	Velocity (m/s)	A1 (mm)	B1 (mm)	C1 (mm)	Velocity (m/s)	A1 (mm)	B1 (mm)	C1 (mm)
30°C	5925.0	100.3	200.6	25	5752.0	99.75	201.8	25.01
50°C	5906.5	100.03	200.35	24.9	5731.4	98.9	201	24.88
100°C	5853.1	99.0	198.5	24.7	5685.0	98.12	199.5	24.72
150°C	5801.7	98.2	196.8	24.45	5631.5	97.2	197.6	24.5
200°C	5743.8	97.3	197.75	24.3	5585.5	96.4	195.75	24.3
250°C	5707.4	96.5	193.6	24.08	5538.4	95.5	194	24.1

3.2 On-site Validation

The validation process was further expanded to conduct on-site testing, with the cooperation of an owner's engineer who preferred to keep the specific details confidential. During this on-site investigation, the author verified and corroborated the experiment's results in a real-world setting.

Figure 8 depicts the utilization of a handheld thermometer to accurately determine the operating temperature of a 12-inch schedule 10s stainless steel pipe, which was measured at 90°C. The pipe in question was then subjected to a Positive Material Identification (PMI) test using X-ray Fluorescence (XRF) technology to confirm that the material matched the fabrication record, indicating it was SS 316.

The subsequent step in the investigation involved ultrasonic inspection. Initially, the UT machine was calibrated based on the velocity of SS 316 at the operating temperature of 90°C, which was determined to be 5692.8 m/s, as presented in Table 1.

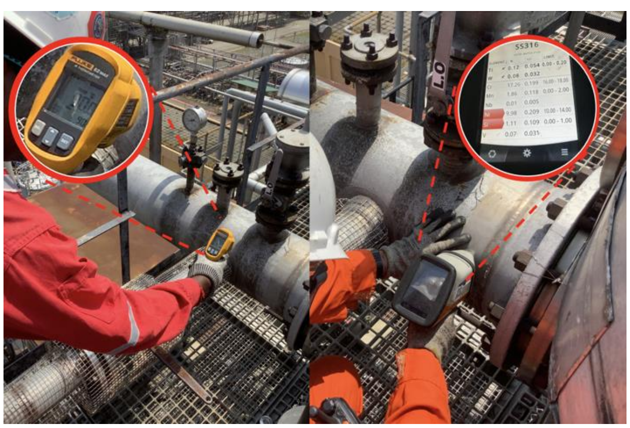

Figure 8 Temperature and material verification on the operating steam pipeline

Upon conducting the ultrasonic inspection, the detected wall thickness of the SS pipe was measured and found to be 4.04 mm. This measurement indicated a wall loss of 0.53 mm compared to the original thickness of 4.57 mm. These results are illustrated in Figure 9.

The data obtained from the ultrasonic inspection provides valuable insights into the condition of the SS pipe after 15 years of operation.

Figure 9 Ultrasonic inspection to detect the material thickness

This validates the feasibility of previous experiments and provides a simple method for effectively calibrating a machine to detect corrosion on carbon and stainless steel. Next, by following the velocity of Table 1 for different materials and temperatures, it is possible to avoid erroneous detections due to incorrect calibration.

4.0 CONCLUSION

One of the limitations of PACM or PAUT is that it requires pre-equipment calibration and setting as per the same testing condition is going to test, such as material grade as well as temperature, since the ultrasound's velocity varies.

Velocity data from ultrasonic tests can significantly impact corrosion detection and must be accurately calibrated if reliable thickness measurements are to be obtained. Temperature-induced changes in velocity must be carefully considered, especially if the material thickness is unknown. Correct calibration ensures that material thickness is correctly assessed, improving the overall efficiency of corrosion detection in critical applications.

This study provides insight into velocity and dB levels in different materials and temperatures, allowing for rapid equipment calibration and setting in the field. By using a PMI machine to determine the material grade and a handheld thermometer to measure the temperature, corrosion can be quickly detected accurately, reducing on-site time and increasing the widespread use of the testing technique. The experiment also includes a visual representation of data to show the velocity differences in different materials and temperatures.

The experiment results indicate that the velocities change due to temperature rise and that the dB is not the major effect. In conclusion, the UT methods, including conventional UT, ultrasonic thickness gauging, and phased array ultrasonic testing or corrosion mapping, can detect corrosion effectively on palm oil refinery's equipment made by carbon steel and SS during In-situ inspection.

The extension of In-situ inspection coverage to equipment and piping systems that were previously excluded from shutdown assessments due to time constraints enables the early detection of potential issues, thus reducing the risk of disasters.

Next, future experiments are planned to be conducted at higher temperatures to cover equipment with higher operating temperatures. Furthermore, the applicability of the same methodology to pressurized piping systems will be determined.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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