COMPUTATIONAL FLUID DYNAMICS (CFD) ANALYSIS OF EXTERNAL CORROSION IN NIGERIAN OIL AND GAS PIPELINES

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ABSTRACT

External corrosion remains a major threat to the integrity, safety, and reliability of buried oil and gas pipelines in Nigeria, largely due to complex interactions between soil chemistry, moisture, and climatic conditions. The aim of this study is to investigate the external corrosion behavior of the Ajaokuta–Kaduna–Kano (AKK) gas pipeline and quantify the influence of key environmental parameters on corrosion rate distribution along the pipeline corridor. A Computational Fluid Dynamics (CFD)–based electrochemical modeling approach was adopted, incorporating soil pH, moisture content, temperature, and humidity data obtained from five representative locations: Ajaokuta, Lokoja, Abaji, Kaduna, and Kano. Transient CFD simulations were performed using ANSYS Fluent, with corrosion kinetics implemented through the Butler–Volmer equation and corrosion rates computed via Faraday's law. The results revealed that corrosion rates varied significantly with location, ranging from a minimum of 0.0114 mm/year in Kano, characterized by arid conditions and near-neutral soil pH, to a maximum of 0.1143 mm/year in Abaji, associated with higher humidity and more aggressive soil conditions. Soil pH values ranged between 5.0 and 8.5, while operating temperatures were within 305–310 K. Higher moisture content, elevated humidity, and lower soil pH were identified as the dominant factors accelerating external corrosion. It is recommended that location-specific corrosion mitigation strategies, including optimized cathodic protection, improved coating management, and continuous environmental monitoring, be implemented along the AKK pipeline to enhance long-term pipeline integrity and operational safety.

Keywords: External Corrosion, CFD Simulation, Pipeline Integrity, Soil pH, Moisture Content, Corrosion Rate.

1 INTRODUCTION

Corrosion remains a major challenge in the oil and gas industry, leading to significant economic losses, safety hazards, and environmental pollution [1]. Among the various types of corrosion affecting pipelines, external corrosion is particularly critical because it results from direct exposure of buried pipelines to surrounding environmental conditions such as soil composition, moisture content, and stray electrical currents [2]. In Nigeria, the combination of a humid tropical climate, variable soil chemistry, and industrial emissions further exacerbates external pipeline degradation [3]. External corrosion occurs through complex interactions between the pipeline surface and its environment. Several parameters, including soil resistivity, temperature variations, oxygen concentration, and microbial activity**,** govern this process [4]. Low soil pH and high moisture levels accelerate the deterioration of protective coatings and expose the underlying metal to electrochemical reactions that lead to material loss. Furthermore, stray currents from nearby industrial or power infrastructure often initiate localized pitting and stress corrosion cracking [5]. These corrosion mechanisms collectively compromise pipeline integrity, increasing the likelihood of leaks, product loss, and catastrophic failures. Although cathodic protection systems, protective coatings, and periodic maintenance are commonly employed to mitigate external corrosion, their effectiveness largely depends on environmental factors such as soil pH, aeration, and moisture balance [2]. Recent research emphasizes the integration of real-time monitoring and predictive modeling to enhance corrosion control and maintenance planning [3]. Advanced computational tools, such as Computational Fluid Dynamics (CFD) and machine learning-based models**,** enable the simulation of corrosion processes under varying soil and environmental conditions, allowing for better prediction and prevention strategies [6]. This study focuses on analyzing the external corrosion mechanisms affecting the Ajaokuta–Kaduna–Kano (AKK) gas pipeline in Nigeria using CFD simulations. The work examines how environmental factors, including soil pH, temperature, and moisture content, influence corrosion severity at different pipeline locations. By integrating simulation outputs with predictive corrosion modeling concepts, this research provides insight into site-specific degradation patterns and contributes to the development of an integrated corrosion management framework aimed at extending the operational life and safety of Nigeria's oil and gas pipeline infrastructure.

2 LITERATURE REVIEW

Obaseki and Elijah developed an artificial neural network (ANN) model to predict corrosion rates in acidic environments, achieving a prediction accuracy exceeding 95%. Their study revealed that multi-factor interactions, including pipeline age, environmental pH, and temperature, significantly influence corrosion rates [6]. Similarly, Sheikh *et al*. proposed an acoustic emission-based corrosion detection technique that integrates high-frequency signal processing with machine learning to evaluate corrosion severity in pipelines [7]. Diao *et al*. refined corrosion rate prediction models by optimizing input features related to chemical composition and environmental conditions, thereby improving predictive reliability [8]. Tran *et al*. applied ANN modeling for atmospheric corrosion prediction using meteorological and chemical parameters such as temperature, humidity, and sulfur dioxide concentration, which proved effective in tropical climates [9]. Zuo *et al*. compared several residual life prediction models, including neural networks, grey theory modeling, and time-series analysis, and found that grey theory provided superior long-term corrosion rate estimation [10]. Thanush *et al*. introduced a hybrid Support Vector Regression–Random Forest model with a prediction accuracy of 91.46% for atmospheric corrosion in steel pipelines [11]. Likewise, Alfred *et al*. developed an ANN-based corrosion prediction system optimized using the Levenberg–Marquardt backpropagation algorithm, outperforming traditional analytical models [12]. Collectively, these studies demonstrate that data-driven and machine-learning approaches are effective for corrosion rate prediction under various environmental and operational conditions. However, most of these works focused primarily on internal or atmospheric corrosion**,** with limited attention to external corrosion dynamics in buried pipelines under soil–environmental interactions**.** To address this gap, the present study employs Computational Fluid Dynamics (CFD) simulations to model external corrosion mechanisms in Nigerian oil and gas pipelines, providing quantitative insights into how soil pH, temperature, and moisture content influence corrosion behavior along the Ajaokuta–Kaduna–Kano (AKK) pipeline corridor.

3 MATERIALS AND METHODS

3.1 Materials

This study utilized both experimental and computational resources for the modeling and prediction of external corrosion in buried gas pipelines. The materials and tools used are outlined below.

3.1.1 Pipeline and Soil Parameters

Five locations along the Ajaokuta–Kaduna–Kano (AKK) gas pipeline—Ajaokuta, Lokoja, Abaji, Kaduna, and Kano, were selected for simulation. Soil samples were collected at depths of 1.0–1.5 m and characterized to determine physical and chemical properties, as presented in Table 1.

3.1.2 Soil Characterization

Soil pH: Determined using a portable pH meter (HANNA HI99121, ±0.02 accuracy). Moisture Content: Measured using the oven-drying method (ASTM D2216-19). Temperature & Humidity: Recorded onsite using a Testo 605-H1 thermohygrometer. Soil Type: Classified using the Unified Soil Classification System (USCS). Rainfall Data: Obtained from NiMet [13].

Table 1. Properties of the Soil and Environment across Pipeline Locations

Location	Soil Type	Moisture Content (%)	Soil pH	Temperature (°C)	Humidity (%)	Annual Rainfall (mm)
Kaduna	Clayey-Loamy	23	6.5	30	55	1.00
Ajaokuta	Sandy-Loam	24	6.25	28	40	1.25
Lokoja	Clayey	32	6.25	31	60	1.75
Abaji	Clayey	13	8.7	29	54	1.25
Kano	Sandy-Loam	23	6.8	30	45	1.15

3.1.3 Software and Computational Resources

Computational Fluid Dynamics (CFD) simulations were performed using ANSYS Fluent 2022 R1, which is widely validated for coupled flow, heat transfer, and electrochemical corrosion modeling in engineering applications. Three-dimensional pipeline and soil domain geometries were developed using SolidWorks 2023, while post-processing and data visualization were conducted using ANSYS CFD-Post and MATLAB R2022b. All simulations were executed on an HP Elite Dragonfly G2 Notebook PC equipped with an Intel® Core™ i7-1165G7 processor (2.80 GHz), 32 GB DDR4 RAM, and Intel Iris Xe Graphics, running Windows 11 Pro (64-bit). This computational configuration has been demonstrated in previous studies to provide sufficient numerical stability, convergence accuracy, and computational efficiency for transient CFD simulations involving corrosion and soil–pipeline interaction problems [2, 14].

3.2 Methods

3.2.1 Research Workflow

The study followed a structured and widely adopted workflow for simulating and evaluating external corrosion behavior in buried pipelines. First, CFD-based electrochemical modeling was employed to develop soil–pipeline interaction models under varying soil pH, moisture content, and temperature conditions, enabling spatial resolution of corrosion-related transport and reaction phenomena. Next, feature extraction was performed by identifying and quantifying key environmental parameters, such as soil pH, moisture content, temperature, and humidity, that are known to govern corrosion kinetics in buried steel pipelines. Finally, corrosion rate evaluation was carried out by extracting corrosion current density from the CFD simulations and converting it to metal loss rate using Faraday's law, providing quantitative inputs suitable for corrosion prediction and integrity assessment. This workflow is consistent with established corrosion modeling and CFD-based pipeline integrity assessment methodologies reported in the literature [2, 10].

3.2.2 CFD Model Setup and Simulation

A representative 5 m section of the buried pipeline was modeled using SolidWorks and imported into ANSYS Fluent within a surrounding 6 m × 2 m × 2 m soil domain, a domain size sufficient to minimize boundary effects while capturing soil–pipeline electrochemical interactions. The pipeline material was defined as API 5L Grade X70 carbon steel, protected with a Fusion-Bonded Epoxy (FBE) coating, which is widely used for buried oil and gas pipelines. An unstructured tetrahedral mesh was generated, with local mesh refinement applied near the pipeline surface to accurately resolve electrochemical gradients at the steel–soil interface. The minimum element size near the pipe wall was 2 mm, gradually coarsening to 10 mm toward the outer soil boundaries. Mesh independence was confirmed, with less than 5% variation in predicted corrosion rates between successive mesh refinements, ensuring numerical accuracy and stability.

Boundary and operating conditions were defined based on measured field data and established industry standards, in accordance with NACE SP0169-2013 guidelines for external corrosion control. Soil moisture content ranged from 10–35%, soil pH from 4.5–7.0, operating temperature from 288–313 K, and relative humidity from 60–90%. The outer soil domain was specified as a pressure outlet boundary, while the pipeline surface was modeled as an electrochemical reactive wall. To simulate corrosion kinetics, a user-defined function (UDF) was implemented to incorporate the Butler–Volmer equation, enabling the modeling of anodic iron dissolution and cathodic oxygen reduction reactions at the steel–soil interface. The resulting corrosion current density was subsequently used to compute metal loss rates, consistent with electrochemical corrosion modeling practices reported in the literature [4, 14].

3.2.3 Solver Execution and Corrosion Rate Determination

The transient simulations were run for 2,800 iterations, ensuring solution stability. The corrosion current density (i_{corr}) was obtained at the interface and used to compute corrosion rate (CR) using Faraday's law shown in equation 1.

$$CR = \frac{K \times i_{corr} \times EW}{\rho \times n} \quad (1)$$

where $K = 3.27 \times 10^{-3}$, $EW = 27.92$ g/equiv, $\rho = 7.87$ g/cm^3, and $n = 2$. The resulting corrosion rates ranged between 0.0114 mm/year (Kano) and 0.1143 mm/year (Abaji), consistent with environmental variations across locations. These rate values were validated against literature data for comparable pipeline environments and subsequently used for further predictive analysis [4, 15].

4 RESULTS AND DISCUSSION

4.1 External Corrosion Rates (CFD Simulation)

Computational Fluid Dynamics (CFD) simulations were conducted to evaluate external corrosion rates along five locations of the Ajaokuta–Kaduna–Kano (AKK) gas pipeline: Ajaokuta, Lokoja, Abaji, Kaduna, and Kano. Each location represents a unique combination of soil type, pH, moisture content, and climatic conditions that influence corrosion mechanisms. The CFD results showed that corrosion intensity varies along the pipeline circumference, with localized zones exhibiting higher electrochemical activity (Figures 1–10). Corrosion rates were extracted at the soil–pipeline interface using Faraday's law of electrolysis based on computed current densities.

4.1.1 External Corrosion Rates at Ajaokuta

As shown in Figure 1, corrosion rates at Ajaokuta ranged from 0.0114 to 0.1141 mm/year, with maximum degradation observed at regions of high soil moisture and slightly acidic pH (5.5–6.5). The temperature distribution around the pipeline, presented in Figure 2, was relatively uniform at 308 K. Higher temperature and humidity contributed to faster anodic dissolution in localized spots, consistent with well-established electrochemical corrosion theory. Elevated temperatures increase the kinetics of electrochemical reactions and mass transport processes at the metal–electrolyte interface, thereby raising corrosion current densities and lowering polarization resistance, which collectively accelerate metal dissolution under corrosive conditions. Experimental studies on pipeline steels and iron-carbon alloys have documented that corrosion rate and corrosion current density systematically increase with temperature due to enhanced ionic mobility and reaction kinetics in the electrolyte, in line with Arrhenius behavior for electrochemical processes. For example, research on pipeline steels demonstrates that increasing temperature leads to higher corrosion current densities and lower polarization resistance, indicating weakened corrosion resistance and faster metal loss, attributable to accelerated anodic and cathodic reaction rates at elevated temperatures. Similarly, controlled studies of iron-carbon alloys show that an approximate 10 °C temperature increase can more than double the corrosion rate, confirming the strong influence of thermal activation on corrosion kinetics. These findings corroborate the observation that the combined effect of higher soil temperature and humidity at Ajaokuta promotes more rapid anodic dissolution and localized corrosion, consistent with the general understanding that elevated temperatures accelerate electrochemical corrosion kinetics [2].

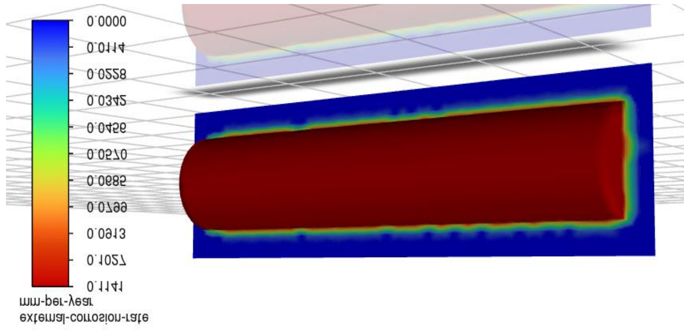

Figure 1. External corrosion rates profile around the pipeline (Ajaokuta)

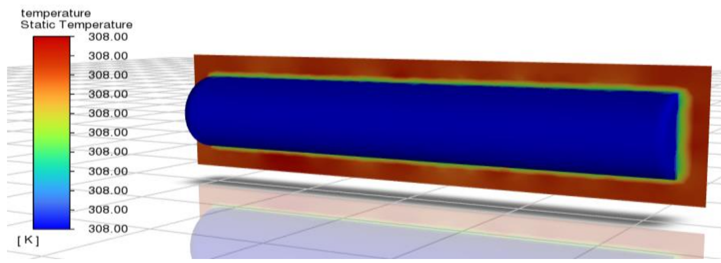

Figure 2. External operating Temperature profile around the pipeline (Ajaokuta)

4.1.2 External Corrosion Rates at Lokoja

The external corrosion rates at Lokoja are shown in Figures 3 and 4.

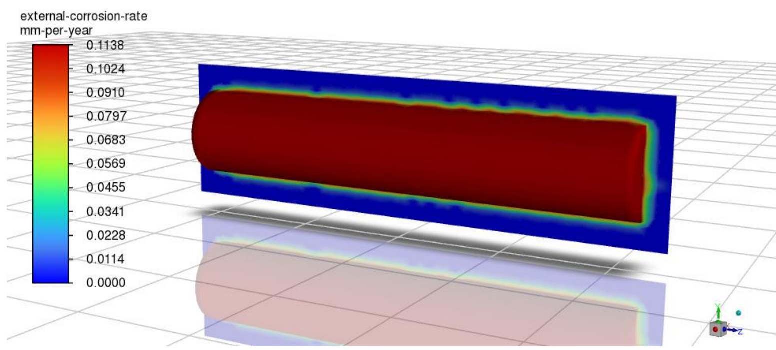

Figure 3. External corrosion rate profile around the pipeline (Lokoja)

The temperature observed around the pipeline in Lokoja revealed a temperature profile centering around 310 Kelvin (Figure 4).

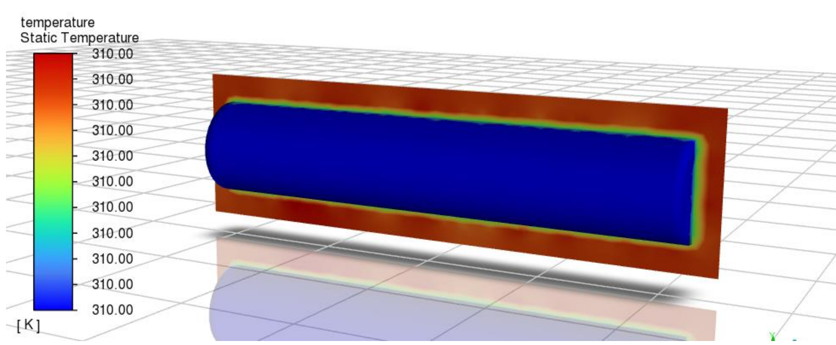

Figure 4. External operating Temperature profile around the pipeline (Lokoja)

In Lokoja, corrosion rates ranged from 0.0114 to 0.1138 mm/year (Figure 3). The area exhibited the highest average moisture content (32%) and relative humidity (~85%), which enhanced the formation of a conductive electrolyte layer on the pipeline surface, promoting corrosion. The temperature profile (Figure 4) showed an average of 310 K, correlating with increased corrosion activity. This behavior agrees with [4], who noted that moisture retention near pipeline walls increases cathodic current density and accelerates pitting corrosion.

4.1.3 External Corrosion Rates at Abaji

The external corrosion rates at Abaji are shown in Figures 5 and 6.

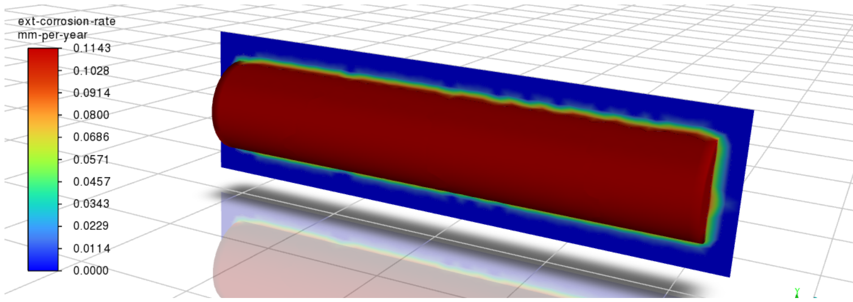

Figure 5. External corrosion rate profile around the pipeline (Abaji)

The temperature profile obtained from the CFD simulation results, as depicted in Figure 6, shows a range centering around 309 Kelvin.

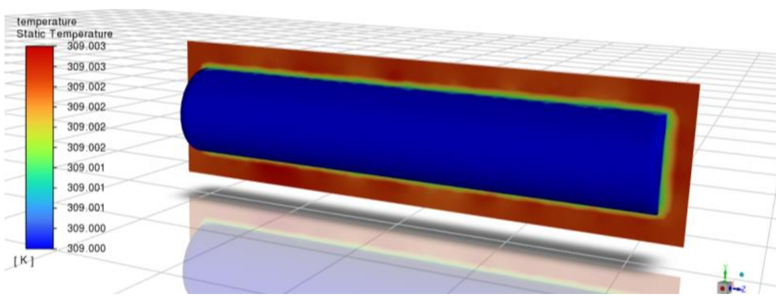

Figure 6. External operating Temperature profile around the pipeline (Abaji)

At Abaji, the corrosion rate ranged from 0.0114 to 0.1143 mm/year (Figure 5). Although the site recorded a relatively low moisture content (13%), the soil pH (8.7) was alkaline, which typically suppresses corrosion. However, the presence of stray currents and variable oxygen concentration contributed to local corrosion peaks. The temperature distribution, centered at 309 K (Figure 6), suggests minor thermal influence. These results support the findings of [3] that alkaline soils slow down uniform corrosion but can still promote localized attack under differential aeration conditions.

4.1.4 External Corrosion Rates at Kaduna

The external corrosion rates at Kaduna are shown in Figures 7 and 8.

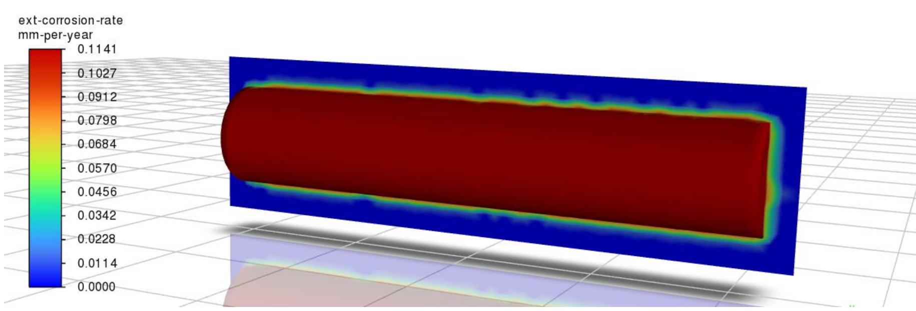

Figure 7. External corrosion rate profile around the pipeline (Kaduna)

For this corrosion rate obtained in Kaduna, an associated temperature profile centering around 305K was also obtained, as seen in Figure 8.

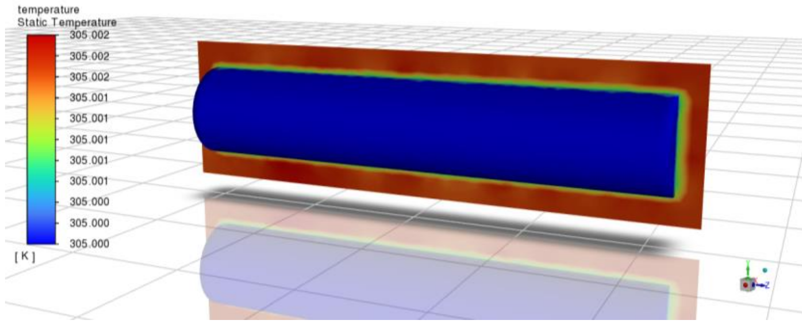

Figure 8. External operating Temperature profile around the pipeline (Kaduna)

The simulated corrosion rate in Kaduna ranged from 0.0114 to 0.1141 mm/year (Figure 7). The temperature profile (Figure 8) averaged 305 K (32°C), with moderately acidic soil (pH 6.5). The corrosion activity was less severe than in Lokoja but higher than in Kano due to increased soil moisture (23%) and humidity (55%). The trend corresponds with [1], who observed that moderate humidity with neutral soil favors mild electrochemical reactions leading to general surface corrosion.

4.1.5 External Corrosion Rates at Kano

In Kano, corrosion rates ranged from 0.0114 to 0.1139 mm/year (Figure 9). The arid conditions (relative humidity 45–55%) and near-neutral pH (6.8–7.2) resulted in the lowest overall corrosion rate among all sites. The temperature profile (Figure 10) showed an average of 307 K, slightly higher than Kaduna, but the reduced soil moisture limited electrolyte formation, minimizing corrosion. This aligns with [5] who concluded that reduced soil moisture and oxygen diffusion decrease external corrosion propagation.

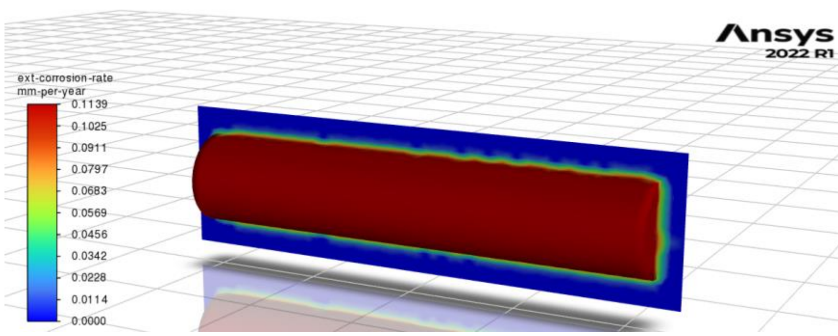

Figure 9. External corrosion rate profile around the pipeline (Kano)

Similarly, the temperature profile obtained for this external corrosion study around Kano provided results centering around 307K (Figure 10).

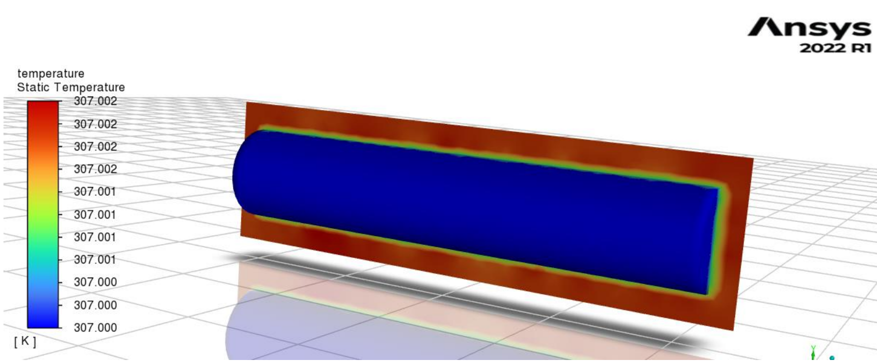

Figure 10. External operating Temperature profile around the pipeline (Kano)

4.1.6 Summary of Key Simulation Parameters

Table 2 has been subdivided into separate tables (a – e) summarizing the main environmental and electrochemical factors.

Table 2a. External Corrosion Rate Range across Locations

Location	Corrosion Rate (mm/yr)	Dominant Corrosion Zone	Remarks
Ajaokuta	0.0114–0.1141	0.085–0.1141 mm/yr	High moisture and acidic soil
Lokoja	0.0114–0.1138	0.080–0.1138 mm/yr	High humidity and temperature
Abaji	0.0114–0.1143	0.060–0.1143 mm/yr	Variable soil chemistry
Kaduna	0.0114–0.1141	0.040–0.085 mm/yr	Moderate corrosion
Kano	0.0114–0.1139	0.0114–0.035 mm/yr	Lowest corrosion rate

Table 2b. Moisture Content

Location	Range (%)	Observations
Ajaokuta	12–25	High corrosion where moisture >20%
Lokoja	15–45	Highest overall moisture
Abaji	15–35	Moderate variability
Kaduna	10–20	Moderate effect on corrosion
Kano	12–18	Low moisture, minimal corrosion

Table 2c. Relative Humidity

Location	Range (%)	Observation
Ajaokuta	60–85	Corrosion intensified in high humidity zones
Lokoja	50–85	High correlation with corrosion zones
Abaji	60–90	Broad variation
Kaduna	65–90	Moderate
Kano	70–85	Minimal impact due to low soil conductivity

Table 2d. Temperature Distribution

Location	Temperature (K)	Effect
Ajaokuta	308	Accelerates reaction rate
Lokoja	310	Highest observed
Abaji	309	Moderate
Kaduna	305	Cooler, mild corrosion
Kano	307	Stable, low impact

Table 2e. Soil pH

Location	Range	Corrosion Implication
Ajaokuta	5.5–7.8	Acidic zones highly corrosive
Lokoja	5.0–7.0	Low pH increased metal loss
Abaji	6.5–7.2	Neutral to slightly basic
Kaduna	6.0–8.5	Mild environment
Kano	6.5–8.2	Least corrosive region

4.2 Discussion and Interpretation

4.2.1 Influence of Environmental Factors

Figures 1–10 clearly show that corrosion intensity corresponds strongly to local soil and climatic conditions. Lokoja and Ajaokuta demonstrated the highest corrosion rates due to high humidity and acidic soils, while Kano exhibited minimal degradation. This trend supports the electrochemical principle that corrosion rate increases with electrolyte conductivity and decreased soil resistivity. Temperature also influenced corrosion kinetics. As observed in Figures 2, 4, 6, 8, and 10, higher soil temperatures (>308 K) increased metal oxidation rates, consistent with [2, 4] who reported that elevated temperature enhances anodic dissolution. Conversely, Kaduna's relatively lower temperature (305 K) reduced corrosion severity, illustrating the inverse relationship between temperature and soil resistivity.

4.2.2 Comparison with Literature

The results align with previous studies; [2] observed that temperature and pH govern external corrosion rates in tropical regions. [4] emphasized that moisture retention in fine-grained soil increases corrosion risk. [3] found that alkaline soils slow uniform corrosion but may encourage localized attack under differential aeration. However, this study extends these findings by integrating CFD-based electrochemical modeling with site-specific soil data, providing quantitative insight into corrosion rate distribution along Nigeria's AKK pipeline corridor, a contribution rarely explored in earlier works.

4.2.3 Practical Implications for Pipeline Integrity

Results from the simulations highlight the need for location-specific corrosion control strategies. In Ajaokuta and Lokoja, corrosion mitigation should focus on enhanced cathodic protection and soil pH regulation. Kaduna and Kano require periodic coating inspection and real-time moisture monitoring to prevent local failure initiation. The integration of CFD and predictive modeling can aid in developing smart corrosion monitoring systems for Nigeria's oil and gas network.

5 CONCLUSIONS

This study investigated the external corrosion behavior of the Ajaokuta–Kaduna–Kano (AKK) gas pipeline using Computational Fluid Dynamics (CFD) simulations under varying environmental and soil conditions. The results revealed that external corrosion is highly location-dependent. The highest corrosion rates occurred at Abaji (0.1143 mm/year) and Lokoja (0.1138 mm/year), while the lowest rate was recorded at Kano (0.0114 mm/year). Variations in soil pH (5.0–8.5) and moisture content (10–45 %) were the most influential factors governing corrosion behavior. In addition, temperature and humidity modified corrosion kinetics, with higher values accelerating degradation. Soil acidity was particularly detrimental, weakening coating performance and intensifying anodic activity at the steel–soil interface. These results demonstrate that the combined effects of soil chemistry, moisture, and temperature critically determine the rate and distribution of external corrosion along Nigeria's buried pipelines.

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