Comparative Analysis of Cathodic Protection of Steel Pipeline under the Sea using Different Sacrificial Anodes

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Abstract- Corrosion is a major problem in piping system specially in the sea atmosphere. Cathodic protection technique is effectively used to mitigate this problem. A predictive model is always required to have an idea about performance of cathodic protection of pipelines and to know the electrolytic effect of seawater on the corrosion resistance of the pipe material. In this study, cathodic protection model of a steel pipeline in marine environment is made using COMSOL Multiphysics 6.2 software. The design of the pipeline is made in SOLIDWORKS 2023 software. Two sacrificial anodes made of three materials i.e. Aluminium, Zinc and Magnesium are used. Seawater environment with an infinite element domain of sea water around the pipe is generated and electrode potentials of the pipe with reference to Ag/AgCl electrode are studied. The potential profile suggests the capacity of the pipe to get corroded. The results from the comparative analysis indicate that Aluminium sacrificial anode provides the best protection of marine pipeline with the maximum potential of 0.965 V vs Ag/AgCl reference. Zinc also provides borderline protection for pipelines. Whereas Magnesium may overprotect the pipeline with such design consideration. Moreover, if protection with Magnesium sacrificial anode is required, the size, the distance and the number of anodes must be adjusted properly to avoid overprotection and reduction of water (which can result in hydrogen gas).

Keywords- Corrosion, Cathodic Protection, Marine Pipeline, Sacrificial Anodes, CP Modeling.

I. INTRODUCTION

Corrosion is a very dangerous electrochemical phenomena which can occur in both metals and non-metals which results in the destruction of metal through some electrochemical reactions. In every 90 seconds, about one ton of the steel is corroded and converted into rust all over the world [1]. Correct interpretation of corrosion during design phase can prove to be a very solid strategy against corrosion [2]. Corrosion in pipelines exposed to corrosive environment is a very serious issue. Corrosion is a leading cause of failures of both onshore and offshore pipelines. The damage to these transmission pipelines carrying any liquid or gas can be costly in terms of capital, health and disruption of processes [3]. Corrosion in pipelines can be more severe in more acidic environments which can lead to decrease in tensile strength and fracture toughness of the pipes [4].

The mechanism of corrosion of pipelines is very simple. A galvanic cell is made between two dissimilar metals at a pipe junction where a less noble metal acts as an anode and more noble metal acts as a cathode. The anode is oxidized and corroded. Whereas the cathode is generally protected from the corrosion [5]. If the junction is made of less noble metal, then, there are many chances that it will get corroded. Somehow, this galvanic corrosion can also be used as a mitigation technique to protect against corrosion by introducing a sacrificial anode which will be destroyed but it will protect the cathode. There are generally two types of cathodic protection i.e. sacrificial anode cathode protection (SACP) and impressed current cathodic protection. SACP technique involves the attachment of less noble metal in the galvanic series to the pipeline. These sacrificial anodes serve as a power source and no external power is required. They sacrifice themselves while saving the pipeline. ICCP utilizes DC power from external source such as rectifier for generation of galvanic cell [6].

Mitigating the corrosion threat has been a key topic for research for many researchers. For instance, research has been done by Jayapalan which focused on the protection of pipeline using cathodic protection technique by Distributed Control System (DCS). Impressed Current Cathodic Protection was used in DCS. Proportional-integral (PI) controller available in DCS was used for controlling actions. The output was satisfactory as the DCS prevented the pipeline by controlling the pipe to soil potential in the allowable limits. Self-tuning feature of DCS allowed the auto-adjustment of PI controller's parameters. This design provided the advantage of using multiple transformer rectifiers in parallel [7]. Gurappa reported that Aluminium alloy anodes can provide significant benefits in cathodic protection in comparison to magnesium because Aluminium is economical, light weight and has longer life [8].

Oghli have done research which involved the development of advanced cathodic protection model for pipelines which can be utilized in other structures too. The only difference between the old and this advanced model was real time monitoring of soil resistance instead of using a single average value. The distributed equivalent circuit model provided better cathodic protection results of buried pipelines. It was observed that the new model improved the quality of cathodic protection by using actual soil resistance parameters [9]. Bawa conducted a comprehensive experimental study on cathodic protection. They used sacrificial anodes of four different materials which were locally produced. Then, they buried a set of anodes and a steel pipe in different locations in soil where aggressive environment was created with the help of NaCl solution. The results indicated that lead anode was best among all after 21 days of test. Lead provided better protection than copper and aluminium based anodes [10].

Vasyliev conducted a corrosion localization analysis in T junction pipe recently. The results showed that different aeration cells are formed based on the flow distribution. The side channel's bottom portion contains one anodic area. Its surroundings, the side walls of the side channels, and the upper portion of the main channel before to the junction all include cathodic regions. Anodic current density in this area may be greater than 25 A/cm2, which is equivalent to a corrosion penetration rate of 0.3 mm per year. After the junction, a second, less concentrated anodic zone may be seen in the main channel's lower portion. The upper side of the primary channel is where the cathode is mostly located. Anodic current density in this area is limited to 12 A/cm2 [11]. In another study, Ma conducted cathodic protection analysis of 304 stainless steel using MoS2/TiO2 nanocomposites. The results of cathodic protection were then compared with the TiO2 nanotubes array and they reported that their composite had yielded better cathodic protection results than TiO2 nanotubes array [12].

Wang created composite film of NH2-MXene/TiO2@sodium alginate for cathodic protection. The film was mechanically and electrically tested. This film provided exceptional mechanical and anti-corrosion properties [13]. In another study, Bukhari presented a FEA-based CP model to protect Y-bent pipe in seawater environment using the magnesium sacrificial anode. They indicated that cathodic protection can effectively protect steel bent pipes in the sea. Moreover, the areas with bends had less protection as compared to other areas [14]. García-Corredera investigated Mg-3Pb sacrificial anode for cathodic protection of AZ31, AM60 and AZ91 alloys. The results indicated that this anode can effectively protect the alloys from corrosion [15].

With the advancement in design and manufacturing in the areas related to sea, the use of high-strength steel for building structures has emerged. Along with the pros, there is a demerit of stress corrosion cracking in seawater [16] which has significantly raised the importance of cathodic protection in the said scenario. Based on this gap, this study utilizes the oil pipeline in the seawater environment with the presence of sacrificial anodes made of different materials to understand the effectiveness of cathodic protection in the marine environment. The 3D CAD model is simulated in the seawater using COMSOL Multiphysics and cathodic protection is applied on it and the results are analyzed in the end.

II. MODELLING OF PIPE

First of all, the 3D design model of the pipe was made in SOLIDWORKS 2023 software. Instead of designing the whole pipeline, a small portion of the pipe was designed which mimic the whole pipeline. A pipe of 1 m was designed with the outer diameter of 0.30 m and thickness of 0.01 m. Along with the pipe, two cylindrical anodes were also designed to act as the sacrificial anodes in the cathodic protection. The design characteristics of the model are provided in the table I whereas the design geometry is shown in Figure 1.

Table 1: Design Characteristics of Marine Pipeline

Sr. #	Design Characteristics	Numerical Value
1	Length of Pipe (m)	1
2	Pipe Thickness (m)	0.01
3	Outer Diameter of Pipe (m)	0.30
4	Anode Diameter (m)	0.03
5	Anode Length (m)	0.10
6	Number of Anodes	2
7	Anode Spacing	Equal

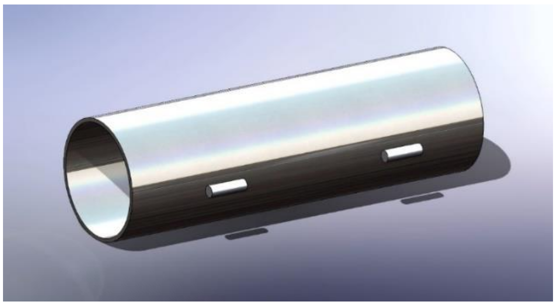


Figure 1: 3D Model of Marine Pipe with Anodes

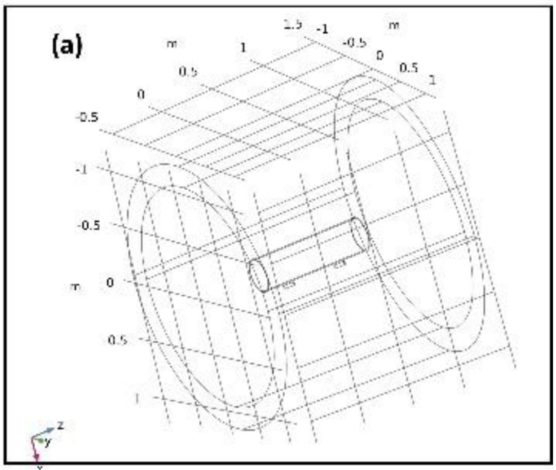
III. MODELING OF CATHODIC PROTECTION

After the creation of 3D geometry, the parameters of current density and potentials for the anodes i.e. Aluminium, Zinc and Magnesium in our case, were defined before the import of geometry into the simulation software. First of all, limiting current for oxygen reduction at the Y-junction steel pipe (i_oxygen) was defined to be −0.1 A/m². Then, anode equilibrium potentials vs Ag/AgCl were defined. The defined current and potential parameters are given in Table II.

Table 2: Galvanic Parameters for the all Anode Materials

Sr. #	Parameter	Aluminium	Zinc	Magnesium
1	Limiting Current for Oxygen Reduction (i_oxygen)	−0.1 A/m²	−0.1 A/m²	−0.1 A/m²
2	Anode Equilibrium Potential vs Ag/AgCl (E_{Eq})	−1.1 V	−1.03 V	−1.55 V

Then the geometry was imported into the cathodic protection module of COMSOL Multiphysics 6.2. After that, the next step was to simulate the marine environment.



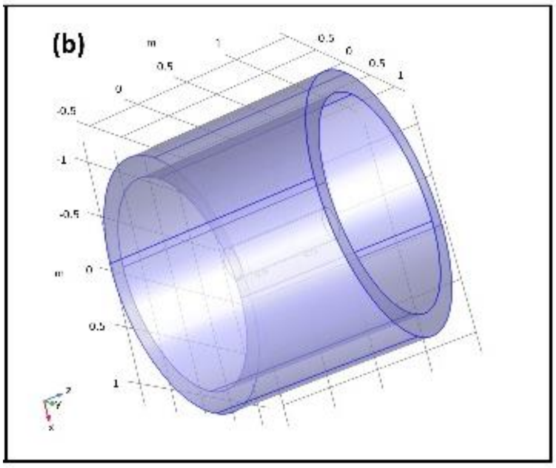


Figure 2: Marine Pipeline and Cylindrical Anodes inside the (a) Whole Setup and (b) Infinite Element Seawater Domain

For the said purpose, two cylinders enclosing the pipeline were generated inside the COMSOL Multiphysics's geometry builder. The radius and the height of cylinder 1 and cylinder 2 were 1 m, 2 m and 1.2 m and 2 m respectively. the cylinder one enclosing the pipeline was meant to mimic the seawater whereas the area between both the cylinders were m,eant to simualate the infinite element domain of the sea. The model after the creation of seawater domain is shown in Figure 2.

The statistics of the geometry are shown in Table 3.

Table 3: Geometry Statistics

Feature	Value
Space Dimension	3
Number of Domains	2
Number of Boundaries	26
Number of Edges	48
Number of Vertices	32

After that, seawater material was assigned to the assembly. This was done by selecting the corrosion electrolyte material from the pre-installed materials library of COMSOL Multiphysics 6.2. Then the electrolytic conductivity data was provided to the model as shown in table 4. The interpolation function was used for the electrolyte conductivity. The interpolation curve and electrolyte domain are shown in Figure 3. In the next step electrolyte properties were attributed to seawater. Electrolyte conductivity was chosen from the material.

Table 4: Electrolyte Conductivity Inputs

Property	Expression/Value	Unit
Electrolyte conductivity	sigma0*int1(S, -273.15 + T)	S/m
Temperature	283.16	Kelvin

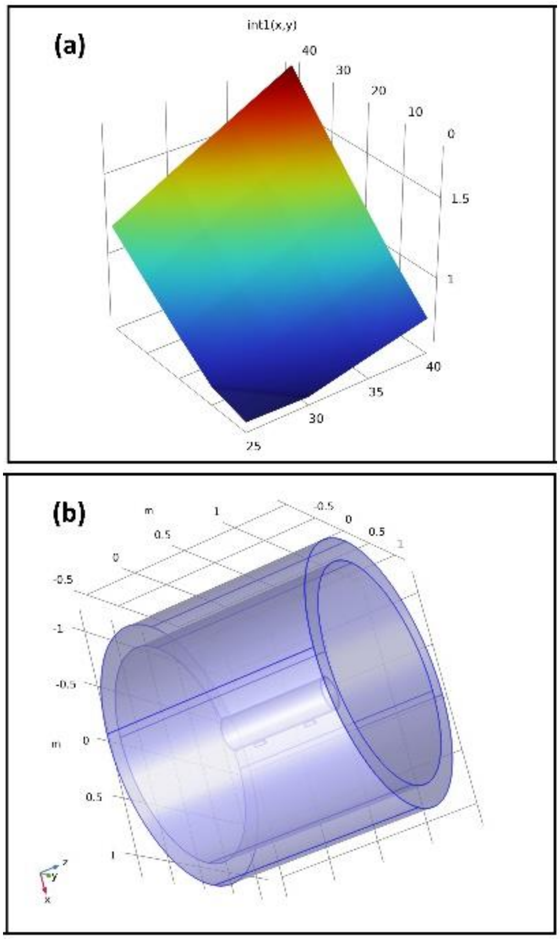


Figure 3: (a) Electrolyte Conductivity Interpolation Plot and (b) Electrolyte Domain

The equations of cathodic protection model are given below as equations 1, 2, and 3.

$\nabla \cdot i_l = Q_l,\ i_l = -\sigma_l \nabla \phi_l$ (1)

$\nabla \cdot i_s = Q_s,\ i_s = -\sigma_s \nabla \phi_s$ (2)

$\phi_l = phil,\ \phi_s = phis$ (3)

3.1 Setup of Sacrificial Anodes and Protection Surfaces:

For cathodic protection of any structure using the finite element analysis, the proper definitions of structures and anodes are essential. In the next step, both the electrodes were defined. From the boundaries section, electrode surface was selected and from the imported geometry, both the cylindrical anodes boundaries were selected. After that, the electrode reactions were also defined. For this purpose, potentials of all the three sacrificial anodes were defined one by one. The equations used for the electrode in terms of current and for electrode reactions are given below as equations 3, 4, and 5.

$n \cdot i_l = i_{total}$ (4)

$i_{total} = \sum_m i_{loc,m}$ (5)

$\eta = E_{ct} - E_{eq}\ ,\ E_{ct} = \phi_{s,ext} - \phi_l$ (6)

Equilibrium Potential was set to user defined and value was designated to Eeq which was defined in the beginning. The selected anodes boundaries are shown in Figure 4.

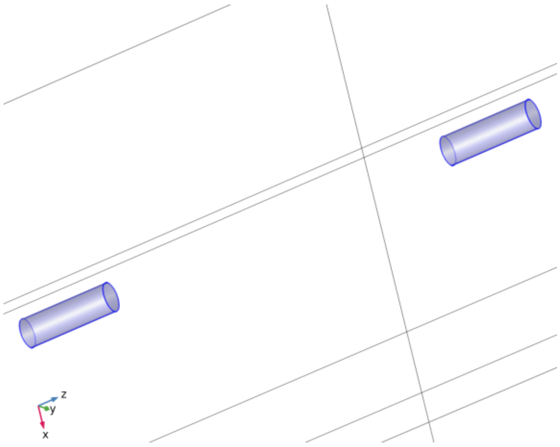


Figure 4: Selected Anode Surfaces

Next, the structure to be protected was defined which in this case was oil pipeline. For this, from boundaries dropdown of physics section, protected metal surface was selected, and pipe was selected as the surface to be protected. After that, oxygen reduction current density of steel was linked with the data provided in table 1. The background process inside the software was based on $n \cdot i_l = i_{O2}$. The protected pipe is also shown in Figure 5.

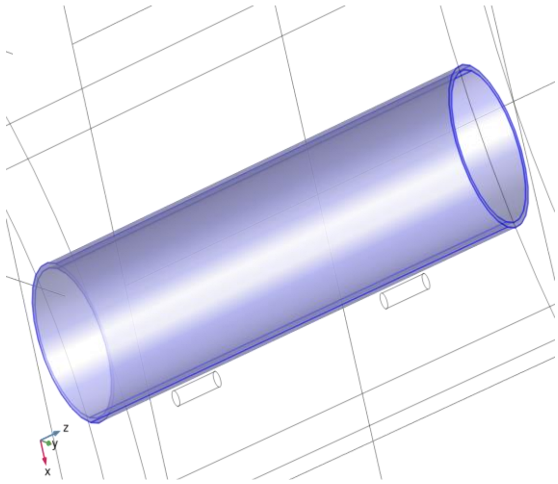


Figure 5: Selected Surface to be Cathodically Protected

3.2 Meshing:

Lastly, the whole model was meshed to discretize into finite elements [17-22]. This meshed model contained all the three key components for cathodic protection i.e. pipeline, sacrificial anodes and seawater domain. Initially, physics-controlled mesh was generated which coarse in nature and didn't capture all the features of the model properly. After that, the model was made extremely fine from the element size dropdown menu. The final mesh statistics are presented in Table 5 and models with coarse and fine element size are shown in Figure 6.

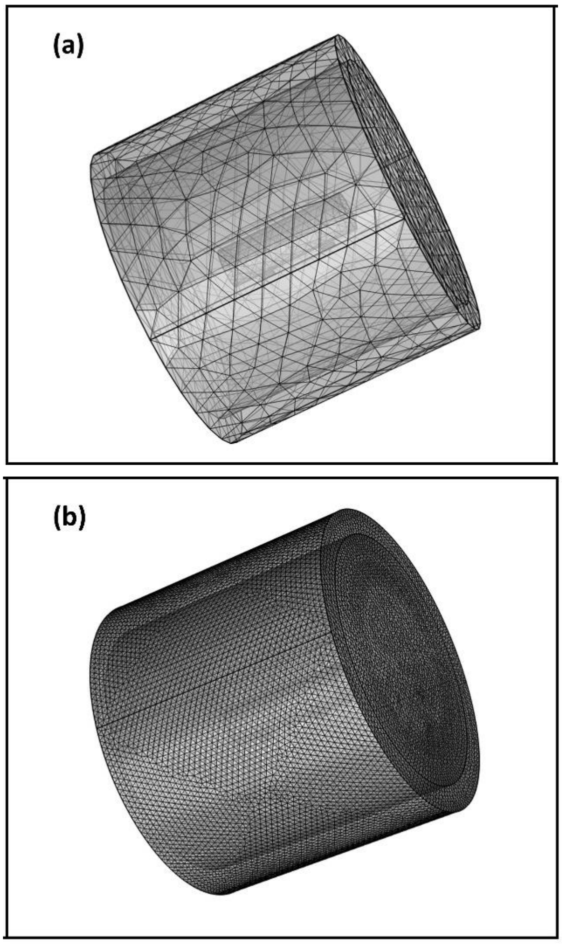


Figure 6: Cathodic Protection Model with (a) Coarse Mesh and (b) Fine Mesh

Table 5: Statistics of Final Mesh

Property	Expression/Value
Total Elements	1565901
Minimum Element Size	4.8E-4 m
Curvature Factor	0.2
Vertices	270180
Mesh Volume	9.037 m³

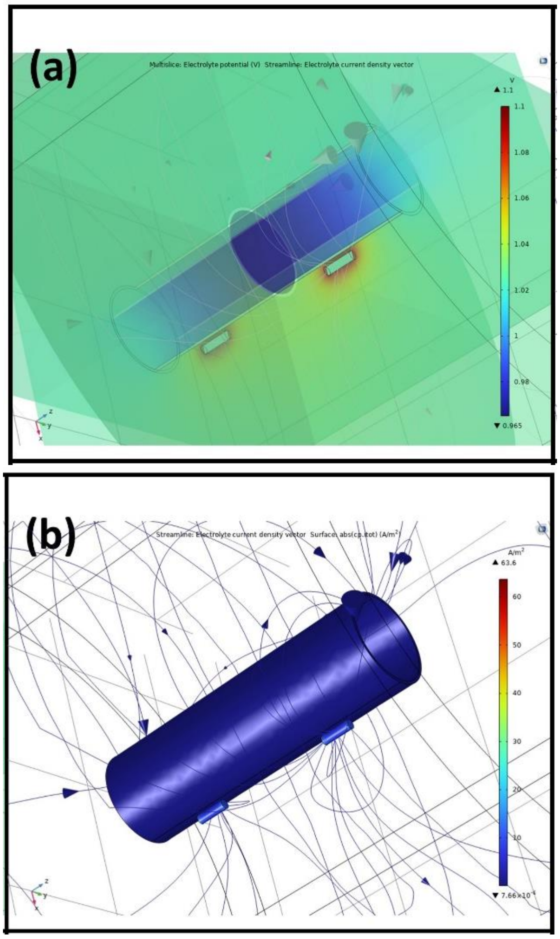
3.3 Cathodic Protection Analysis:

After following all the necessary steps to build the model for cathodic protection, the model was solved using the computation solver. Same process was followed for all the three sacrificial anodes and solutions were obtained. Three output results were used to compare and identify the corrosion mitigation by three different sacrificial anodes. These results included electrolyte potential, electrolyte current density and the most important one i.e. electrode potential vs Ag/AgCl reference electrode.

IV. Results and Discussions

4.1 Aluminium Sacrificial Anode Results:

The cathodic protection results using sacrificial anode made of Aluminium showed satisfactory results in terms of corrosion protection of marine oil pipeline. For steel structures, the electrode potential should be more negative than -0.85 V vs Ag/AgCl reference electrode inside the marine environment to remain free from corrosion through cathodic protection [23]. In case of Aluminium sacrificial anode, the maximum electrode potential was recorded to be -0.965 V which lies in the safe limit. The practical applications might have potential values higher than that but still the difference is more than 0.1 V which suggests that the pipe would remain protected based on the simulated values. To be on the safer side, the diameter of the anodes can be slightly increased which will further decrease the electrode potential. The results of Aluminium sacrificial anode showing electrolyte potential, electrolyte current density and electrode potential vs reference electrode are shown in Figure 7. From the figure & (a), it can be seen that anodes are at red areas showing high electrolyte potential whereas the pipe structure is at relatively lower potential indicated by blue area. This confirms that sacrificial anodes are providing sufficient current to polarize the steel pipeline.



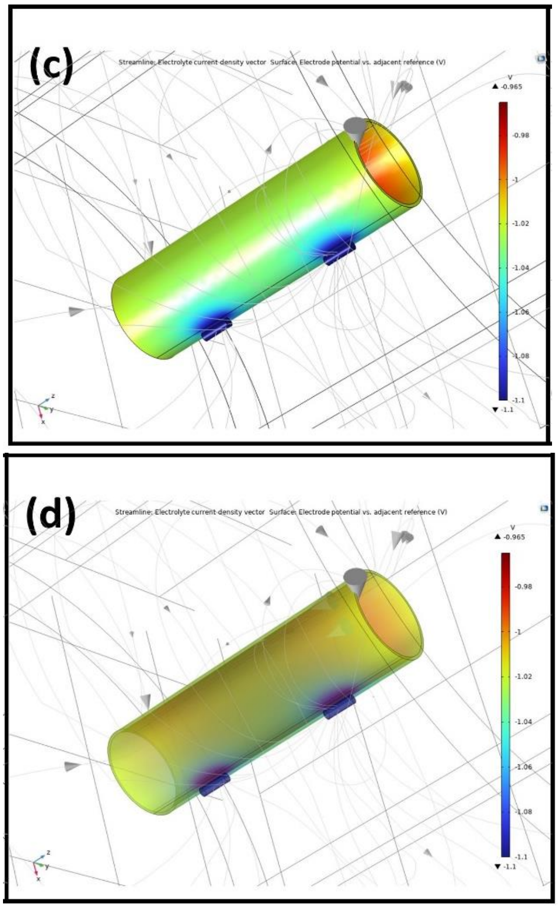
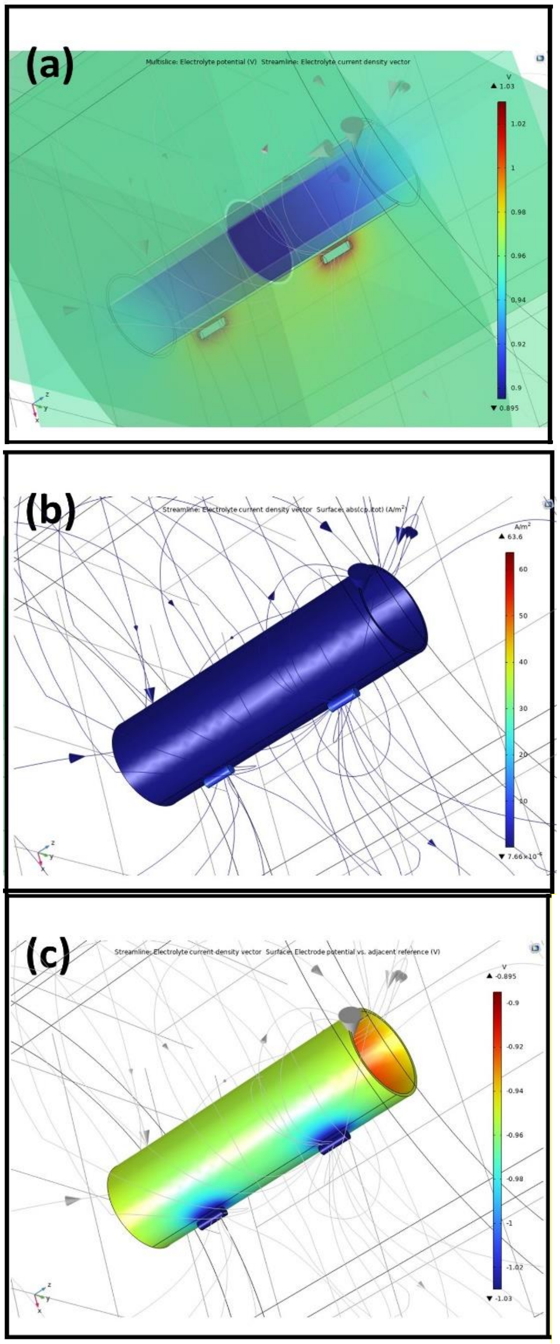


Figure 7: Cathodic Protection Results of Pipeline using Aluminium Sacrificial Anode showing (a) Electrolyte Potential, (b) Electrolyte Current Density, (c) Electrode Potential vs Ag/AgCl Reference Electrode, and (d) Transparent View of Electrode Potential vs Ag/AgCl Reference Electrode

Similarly, Figure 7 (b) shows that sacrificial anodes have high current density and flow of current from anodes to pipeline is smooth and current density distribution is smooth. Figure 7 (c) and 7 (d) confirm that the electrode potential vs Ag/AgCl electrode is in the range of -0.965 V to -1.1 V which lies in the safe range for seawater. From the transparent view, it can be seen that areas inside the pipe are red i.e. at relatively high potential than the outer surface but still, the potential is in the allowable limit. These results ensure that Aluminium sacrificial anode would protect the steel pipeline sufficiently from the threat of corrosion.

4.2 Zinc Sacrificial Anode Results:

The simulation results of cathodic protection using the Zinc sacrificial anode are presented in the figure 8. The results demonstrated that although the zinc sacrificial anode is protecting the pipeline, but the margin is very low i.e. the protection is at the border line of the allowable limit for this design of the anodes. Same as Aluminium sacrificial anode, the Zinc sacrificial anode is at higher electrolyte potential than the pipeline showing the cathodic protection is functioning well as the current flows from the sacrificial anodes to the pipe as shown in the Figures 8 (a) and 8 (b). Figures 8 (c) and 8 (d) show that highest electrode potential vs Ag/AgCl electrode is -0.895 V which is in the safe limit but the margin between the maximum threshold of electrode potential vs Ag/AgCl electrode in seawater and this value is very small i.e. it lies on the border line. It may be noted that the pipe would be protected but safety factor would be low. To ensure more safety with the Zinc sacrificial anode, one small anode may be added, or the dimension of the current anodes may be increased to ensure more margin.



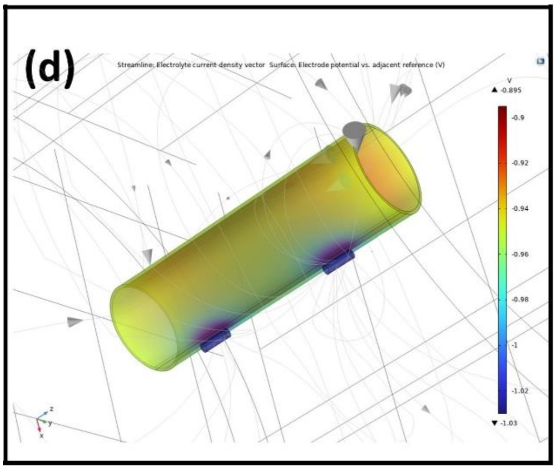


Figure 8: Cathodic Protection Results of Pipeline using Zinc Sacrificial Anode showing (a) Electrolyte Potential, (b) Electrolyte Current Density, (c) Electrode Potential vs Ag/AgCl Reference Electrode, and (d) Transparent View of Electrode Potential vs Ag/AgCl Reference Electrode

4.3 Magnesium Sacrificial Anode Results:

Among all the three anodes, magnesium provided the highest protection of the pipeline. The trend of all the output parameters was same as for other sacrificial anodes (like the flow of current from the anodes to pipeline, high electrolyte potential at anodes, etc.) with the exception that the electrode potential was extremely low. The electrode potential of pipe vs Ag/AgCl reference electrode with the range of -1.42 V to -1.55 V which was way more negative than the allowable limits. This potential value approaches the limit of overprotection. During the overprotection, the corrosion is prevented however, hydrogen gas diffuses into the steel and reduces the structure strength. Overprotection results in reduction of water to hydrogen gas with the following equation:

$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$

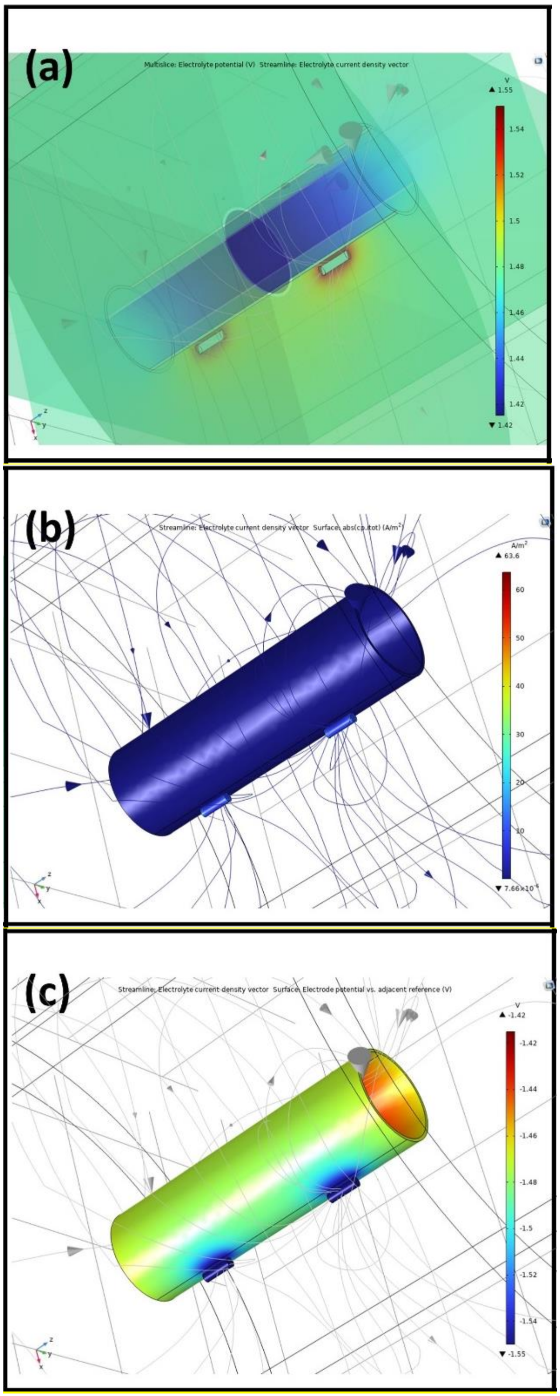
This hydrogen gas can penetrate into the paint or coating and destroy it. In the current scenario of simulation, if the overprotection is triggered by the formation of hydrogen gas, along with the demerits of overprotection, the quick depletion of anodes may be started which can consume anodes quickly due to fast chemical reactions. To prevent overprotection in this case, the size of anodes can be reduced or only one anode can be used for this one-meter long pipe. The simulation results of Magnesium sacrificial anode are shown in Figure 9.

4.4 Comparison:

According to the simulation results, all the three tested anodes exhibit different behavior. Theoretically, all three anodes protect the steel pipeline but in practical considerations, several constraints may appear like overprotection in the case of Magnesium and border-line protection for Zinc (for the design presented in this study). The results of this study aligns with the study presented by Rafait [24]. The comparison of electrode potentials vs Ag/AgCl reference for all three anodes is shown in Figure 10 and Table 6.

Table 6: Comparison of Maximum Potentials of Anodes

Anode Material	Maximum Electrode Potential vs Ag/AgCl Reference
Aluminium	-0.965 V
Zinc	-0.895 V
Magnesium	-1.42 V



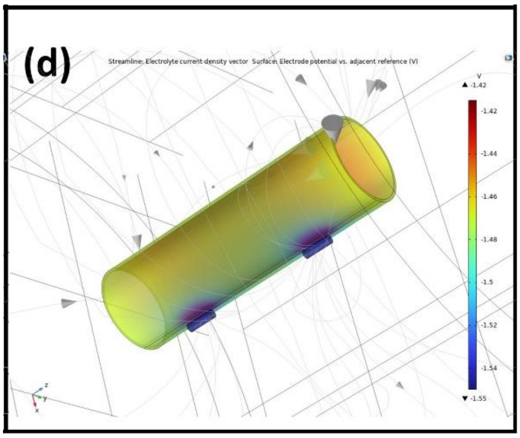


Figure 9: Cathodic Protection Results of Pipeline using Magnesium Sacrificial Anode showing (a) Electrolyte Potential, (b) Electrolyte Current Density, (c) Electrode Potential vs Ag/AgCl Reference Electrode, and (d) Transparent View of Electrode Potential vs Ag/AgCl Reference Electrode

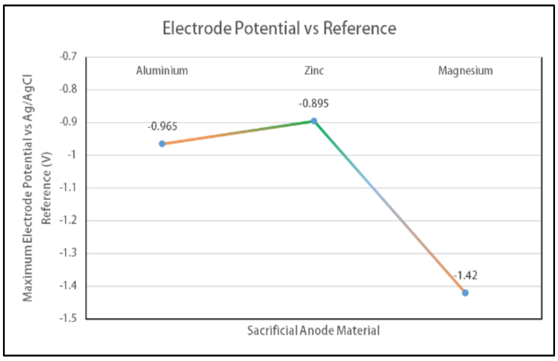


Figure 10: Comparison of Electrode Potential vs Ag/AgCl Reference

Among all three anodes in this design, Aluminium exhibits perfect cathodic protection of the steel pipeline. For Zinc sacrificial anodes, a very small extra anode may provide more protection and increase the safety factor. Or the size of existing anodes can slightly be increased so that the maximum potential drops to more negative value than -0.9 V. Similarly, for Magnesium sacrificial anodes to be used for cathodic protection of steel pipeline, the scenario is opposite. Prevention of overprotection is required in this case. This can be done either by removing one anode from the design. In this way, the value of potential vs Ag/AgCl electrode can be increased. For Aluminium, no such adjustments are required.

V. CONCLUSION

This study aims to compare and select the optimized sacrificial anode material for cathodic protection of steel pipeline in the sea. Three materials including Aluminium, Zinc and Magnesium were considered for the analysis. The small portion of pipeline having a length of 1 meter was designed in SOLIDOWRKS 2023 along with 2 sacrificial anodes. The cathodic protection modeling was done in cathodic protection module of COMSOL Multiphysics 6.2. Infinite element domain was also provided to simulate the real sea condition and model was solved for all the three materials. The major conclusions are as follows:

- Cathodic protection can effectively protect the marine structures.
- Aluminium is the optimal material for cathodic protection of oil pipeline under the seawater with the maximum electrode potential of -0.965 vs Ag/AgCl reference. This means that for every 1 m length of the pipeline, two equally spaced aluminium sacrificial anodes are required having length of 0.1 m and diameter of 0.03 m.
- Zinc can also protect the pipeline, but the safety margins are very low. The maximum potential recorded for Zinc sacrificial anode is -0.895 V which is close to borderline. But theoretically, it can still protect the steel pipeline.
- Magnesium may be subjected to overprotection as the potential of pipeline vs Ag/AgCl pipeline is very low i.e. -1.42 V. This may result in hydrogen evolution which can compromise the pipe structure. So, number of electrodes must be carefully selected in this scenario.
- The size and the design of sacrificial anodes is very important because according to simulations, Magnesium results require less or small anodes whereas Zinc simulation requires More or big anodes for effective cathodic protection.
- To prevent the internal corrosion due to the flow of oil, corrosion inhibitors may be added.

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