Asia-Pacific Journal of Science and Technology: Volume: 30. Issue: 01. Article ID.: APST-30-01-10. Research Article

Asia-Pacific Journal of Science and Technology

https://www.tci-thaijo.org/index.php/APST/index

Published by Research Department,
Khon Kaen University, Thailand

Modelling and simulation of cathodic protection using magnesium sacrificial anode for steel Bent-Y-Pipe in seawater environment

Syed M. A. Bukhari[1], Syed A. R. Gardezi[1,*], Naveed Husnain[1,*], Rauf Ahmad[1], Muhammad F. Zaman[1], Rashida Qurashi[2] and Nosheen Baloch[3]

[1]Department of Mechanical Engineering, Faculty of Engineering and Technology, Bahauddin Zakariya University, Multan, Pakistan
[2]Government Graduate College for Women, Makhdoom Rasheed, Multan, Pakistan
[3]Department of Building Architectural Engineering, Faculty of Engineering and Technology, Bahauddin Zakariya University, Multan, Pakistan
[*]Corresponding authors: naveedhusnain@bzu.edu.pk, asad.gardezi@bzu.edu.pk

Received 24 April 2024
Revised 13 June 2024
Accepted 24 June 2024

Abstract

Pipelines under the sea are at great risk of corrosion due to highly conductive seawater acting as a strong electrolyte. Current study is aimed to resolve this issue of corrosion of pipes in seawater. This computational study exhibits the modeling and simulation of corrosion protection of a bent y-pipe using the sacrificial anode cathodic protection method. Steel is selected as pipe material and the pipe is studied under seawater conditions. A high-potential cylindrical Magnesium anode is selected to study its effect on corrosion prevention of the Y-pipe. The size of the anode is varied to study its effect on corrosion protection. COMSOL Multiphysics is used for the computational study of cathodic protection. The results indicated that cathodic protection can be a good choice for the protection of pipelines under the sea. However, a proper design and size of the anode must be incorporated for effective corrosion protection. Decreasing the radius of the cylindrical anode reduced the protection of the Y pipe as 0.2 mm radius anode exhibits -1.471 V pipe potential vs Ag/AgCl which is -1.498 V for anode size of 15 mm. Areas having bends tend to have more corrosion potential due to stress concentration and are at a greater risk of corrosion. Moreover, the model also indicated that apart from cathodic protection, corrosion inhibitors are also required inside the pipelines to prevent internal corrosion.

Keywords: Corrosion potential, Sacrificial anodes, Cathodic protection, COMSOL Multiphysics, CP modeling, Y pipes

1. Introduction

Pipelines under the sea are at great risk of corrosion due to highly conductive seawater acting as a strong electrolyte. As mentioned by Bukhari et al., steel is widely used alloy around the globe and around 1-ton steel corrode every ninety seconds [1, 2]. Corrosion has been a major concern in Oil and Gas sectors. Whether the pipelines are underground or under the sea, they are always in danger of failure due to corrosion as these pipelines cover a long distance. Not only it can destroy pipelines, but it can also destroy nearby structures and human lives may come into danger [3]. That's why, the prevention of corrosion becomes a top priority. Corrosion in pipes under the sea usually occurs when a dissimilar metal comes in contact with the pipeline. Both metals are connected electrically and seawater acts as an electrolyte to facilitate the electrochemical reactions [4]. This may be due to the composition of the pipeline or the attachment of external bolts and flanges. In this scenario, a galvanic cell is generated. Two dissimilar metals in the pipeline act as electrodes. The metal or an alloy having more potential acts as an anode. Seawater acts as a conducting solution which carries charged ions from anode to the cathode and anode corrodes. In most of the cases, it causes destruction of pipeline [5]. However, the same principle of galvanic corrosion can be used to protect the pipeline using an electrochemical technique i.e. Cathodic Protection (CP) [6].

It is a very frequent practice to cathodically protect the main pipe using an electrode with a higher potential than the base metal. Cathodic protection is a method to reduce the corrosion of a pipeline by making it the cathode of the galvanic cell. The anode can be any other metal having more corrosion potential than the pipeline. In this technique, the anode sacrifices itself while the cathode (i.e. pipeline) is fully protected [7]. There are hundreds of applications of CP whether the metal is buried under soil or liquids like seawater, pure water, and acids [8]. Cathodic protection is generally divided into two types i.e. Impressed Current Cathodic Protection (ICCP) and Sacrificial anode cathodic protection (SACP) also known as galvanic anode cathodic protection [9]. In ICCP, an external current supply source (DC source) also known as a rectifier, is used to supply the current on the structure whereas the anode is either buried or immersed in the medium [10]. The platform to be protected is connected to the negative terminal and anodes are connected to the positive terminal. In SACP, the anode of more active and less noble material is selected which acts as an active member of the galvanic cell. As a result of galvanic current flow, the main structure is protected. Several sacrificial anodes can be utilized as per requirements. SACP is a simple technique that can potentially reduce installation costs [11].

In recent times, great importance is being given to corrosion and its protection. Fu and Cheng investigated the impact of alternating current on the efficiency of cathodic protection while employing a steel pipeline. The results indicated that alternating current can increase the pitting corrosion of steel pipe due to alkalization [12]. Xu et al. also studied the effect of interfering alternating currents on the effectiveness of the cathodic protection of pipelines. It was concluded that with the presence of AC interference, the effectiveness of cathodic protection is potentially reduced due to deviation of potential from pre-determined values [13]. Kuang and Cheng also concluded the same results [14]. Ormellese et al. inspected the effect of DC stray current on the cathodic protection of buried pipelines. The results indicated passive conditions due to alkalization. At DC anodic peak, the system was exposed to anodic corrosion [15]. Zhang et al. reported an enhancement in corrosion protection with increased current density in ICCP [16]. In another study, Shaalan et al. developed strategies to reduce the interference AC voltage of overhead transmission lines and to avoid compromising the cathodic protection of pipelines. The first strategy was to convert the AC voltage to DC voltage and use it for cathodic protection. The second strategy was the integration of a photovoltaic system into the pipelines [17].

Xu and Cheng developed a finite element model and also performed experiments to study the behavior of cathodic protection at corrosion defects on the pipeline. A non-uniform current and potential distribution were observed in the defective areas. Inside the defects, a potential drop was indicated [18]. Kuang and Cheng studied the CP shielding behavior for high-density polyethylene coating and fusion bonding epoxy coating on the pipelines at the areas of coating separation. It was observed that the latter one permitted the CP current to go through the areas of separation and protected the pipeline whereas the prior restricted the CP current and exposed the pipeline to corrosion [19]. Zaman et al. also revealed that coatings can enhance corrosion resistance [20]. Another major contribution in this field is added by Oghli et al. They proposed a new system for cathodic protection of oil and gas pipelines by measuring and considering the actual soil resistance of the area which was missing in the old method. The new method yielded better results of protection than the conventional method [21]. In another study, Chung et al. investigated the current required for effective cathodic protection of buried pipelines. They derived an equation to estimate the required current [22]. Lorenzi et al. investigated the impact of the flow of seawater and rotation of a steel propeller shaft protected by SACP using finite element analysis. Modest polarization was observed in all situations. Moreover, a decrease in the potential protection limit was observed due to oxygen consumption [23]. Bellezze et al. also studied the protection of steel propeller shaft in seawater by ICCP using a titanium anode. The results indicated satisfactory protection of the shaft [24]. Ghazi et al. revealed that crack growth rate is increased when temperature of the environment increases [25].

Chen and Hartt studied the cathodic protection of steel specimens in seawater conditions. Experimental conditions of about 899 m water depth were created. Calcareous deposits were formed on the specimens. The results indicated that water deposits were unable to restrict the cathodic process despite the significant spread of calcareous deposits [26]. Gadala et al. also studied the cathodic protection of pipelines and devised a finite element simulation model to find the appropriate design parameters for the cathodic protection of steel pipes [27]. Vasilescu et al. in another study developed a marine ICCP model for steel ships. Results indicated that a certain number of electrons from the power source are required for effective protection. They adopted the C-Shield ICCP method with special anodes which provided the benefit of longer life [28]. Liu et al. incorporated COMSOL Multiphysics' finite element method to study the corrosion protection of ship hulls and propellers. Shaft rate electric field and potential were studied before and after ICCP. It was observed that the corrosion of the hull became severe with elevation in the impressed current. Moreover, they developed a method to precisely study the effect of ICCP on the potential of the hull [29]. In another study, Kalovelonis et al. studied the cathodic protection of container ships using the boundary element method. After studying the model, they detailed an ICCP system with 10 anodes at the hull and 16 anodes at the thrusters. The estimated demand for the current was 2643 A [30].

In this study, a comprehensive computational analysis of cathodic protection has been done using the SACP method. A bent steel Y-pipe is designed under seawater conditions and CP modeling is done using COMSOL Multiphysics. A cylindrical magnesium sacrificial anode is employed and its effect on the cathodic protection of the Y-pipe is studied. Moreover, the radius and height of the anode are altered to observe the effectiveness of cathodic protection at different parameters. In the end, the results of simulations at different anode sizes are compared.

2. Materials and methods

In this research, a steel pipe is used as a structure to study its level of protection using cathodic protection. First of all, a three-dimensional (3D) model of a bent-Y-pipe was developed in SOLIDWORKS. The arms of the pipe are bent ahead. The dimensions and the geometry of the pipe are shown in Figure 1. For CP modeling and simulation, COMSOL Multiphysics 6.0 was utilized. The 3D model of the bent-Y-pipe was imported into the corrosion module of COMSOL Multiphysics. A stationary study was utilized for cathodic protection inside the module.

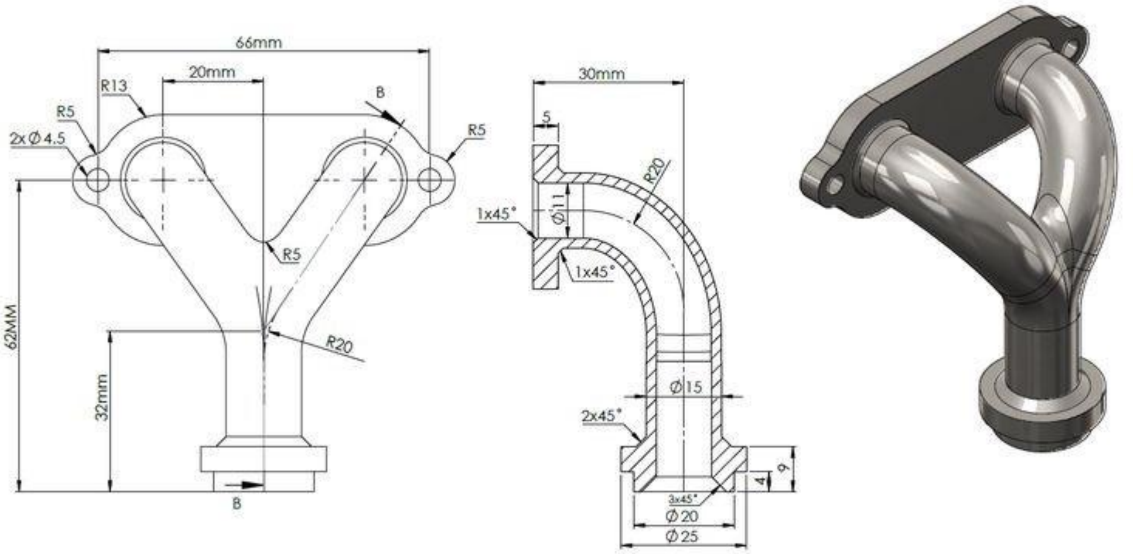

Figure 1 Geometry of Bent-Y-Pipe.

Basically, the pipe was the structure to protect so, according to cathodic protection, it was considered as a cathode. The input parameters for simulation were selected. The limiting current for oxygen reduction at the steel pipe was kept at −0.1 A/m² (i_oxygen) whereas the equilibrium potential of magnesium anode vs Ag/AgCl was set at -1.5 V (Eeq_Mg). After that, a cylindrical magnesium anode was made near the main pipe. The radius and height of the anode were varied from 15 mm radius and 30 mm height to 0.2 mm radius and 4.5 mm height.

To simulate the seawater conditions, a cylinder was drawn to represent the sea that surrounded the Y-pipe. A second cylinder, larger in diameter was drawn around the first one to apply the condition of a vast sea environment as shown in Figure 2(A). Infinite Element Domain (IED) was applied to the section around the anode and cathode i.e. inside both the cylinders as shown in Figure 2(B).

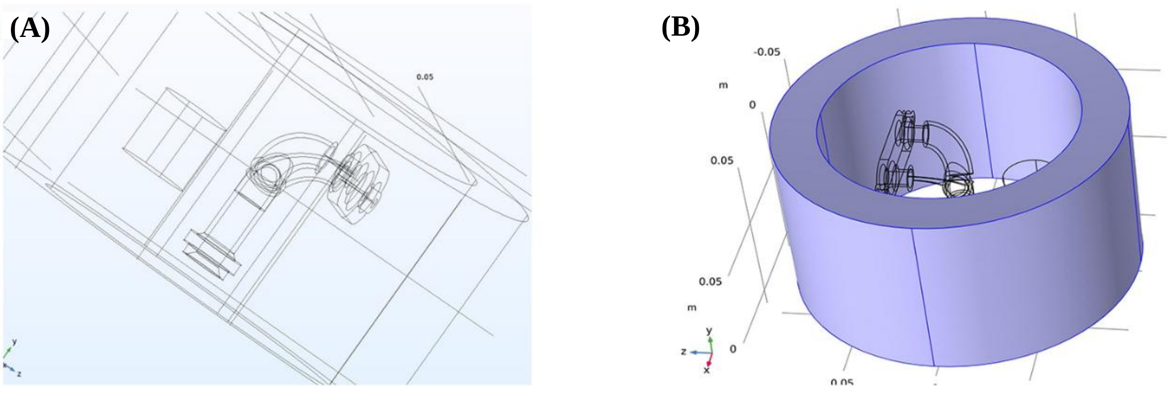

Figure 2 View of (A) Cylinders for seawater conditions and (B) IED.

The next step was to define the electrolyte i.e. seawater. Using the add material command, seawater electrolyte was assigned to the IED geometry around the pipe and magnesium anode. The used seawater material has the capacity of conduction based on the temperature conditions. Linear electrolyte potential was set up during the modeling. The temperature of the seawater was selected as 10°C. After defining the temperature value, a complete seawater environment was established around the electrodes. In the next step, the boundary conditions for the anode i.e. magnesium, and cathode i.e. steel pipe was set up. For anode reaction, the predefined value of (Eeq_Mg) was assigned. For a protected surface, steel pipe was selected and a predefined value of i_oxygen (limiting current for oxygen reduction at steel pipe) was assigned for current density. The geometry statistics of the model are depicted in table 1.

Table 1 Statistics of Geometry.

Description	Value
Space dimension	3
Domains	2
Boundaries	87
Edges	210
Vertices	132

After defining all the parameters and assigning the required values, the model was meshed using the meshing command on COMSOL Multiphysics which divided the whole model into several small elements [31, 32]. The meshed views of the solid model and transparent model are exhibited in Figure 3(A) and 3(B) respectively. After meshing, the model was computed.

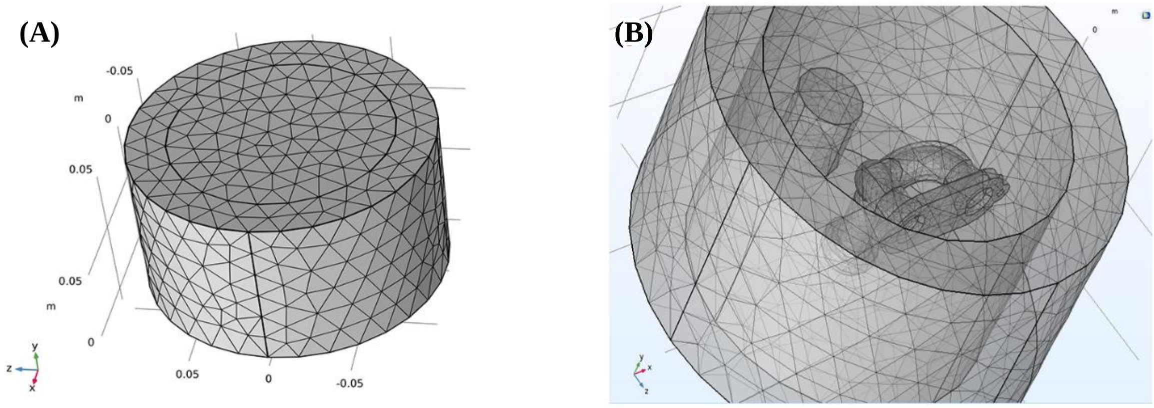

Figure 3 Meshed view of (A) solid model and (B) Transparent model.

3. Results and discussions

3.1 At anode radius 15 mm and height 30 mm

The simulation results at the anode radius of 15 mm are shown in fig. 4. Slice plot of electrolyte potential, current densities on the anode, and pipe potential vs Ag/AgCl reference are shown in Figure 4(A), 4(B), 4(C) and 4(D) respectively. Figure 4(C) indicates that the pipe is well protected with the help of cathodic protection under the sea. An increase in potential (red areas) can be observed internally, especially at the position of the bend and junction in Figure 4(D). However, it sits within the limits with a maximum potential of -1.49 V.

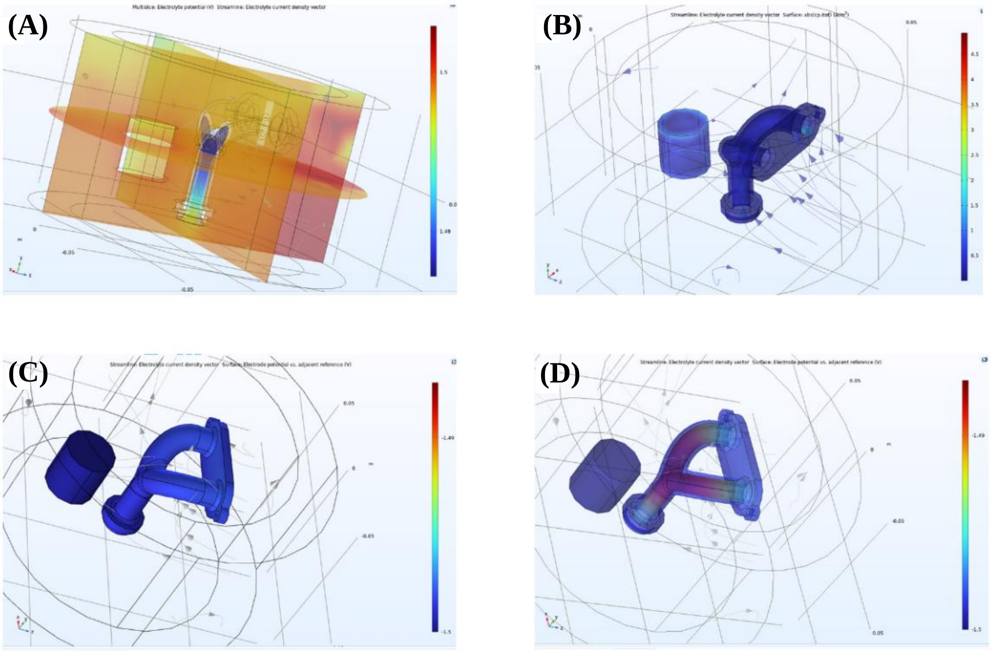

Figure 4 Simulation results (at 15 mm anode radius and 30 mm height) of (A) Electrolyte potential, (B) current densities, (C) Pipe potential vs Ag/AgCl, and (D) Pipe potential vs Ag/AgCl (transparent view).

3.2 At anode radius 5 mm and height 9 mm

In this simulation, the radius and height of the magnesium anode are decreased whereas the steel pipe is the same. Electrolyte potential, current density, pipe potential vs reference electrode, and the latter with a transparent view are shown in Figure 5(A), 5(B), 5(C) and 5(D) respectively. Figure 5(C) shows that by decreasing the size of the anode, the protection capacity of the junction is reduced. In the large-sized anode, the pipe was in the safe zone. At a smaller size, the potential of pipe vs Ag/AgCl is slightly increasing which in turn increases the threat of corrosion. However, the pipe is still within the safety limits. Red areas in Figure 5(D) shows more potential as compared to the outer surface of the pipe.

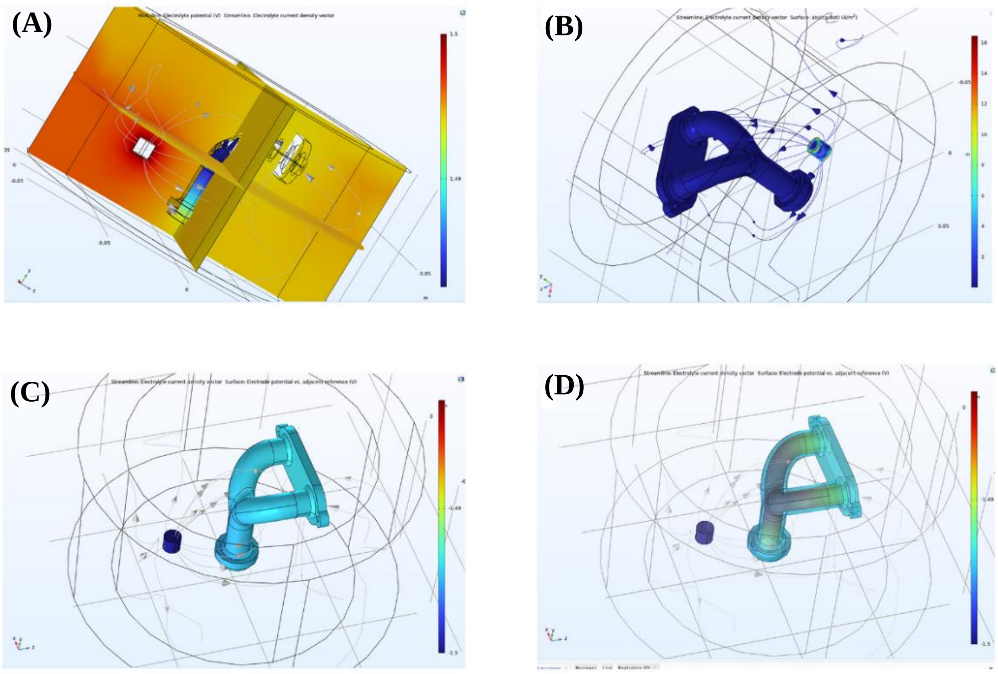

Figure 5 Simulation results (at 5 mm anode radius and 9 mm height) of (A) Electrolyte potential, (B) current densities, (C) Pipe potential vs Ag/AgCl, and (D) Pipe potential vs Ag/AgCl (transparent view).

3.3 At anode radius 1 mm and height 4.5 mm

This simulation presents a much smaller anode as compared to the base simulation (discussed in section 3.1). Figure 6(A), 6(B), 6(C), and 6(D) present the electrolytic potential, the density of currents on the anode, electrode potential vs Ag/AgCl electrode, and a transparent view of electrode potential respectively. In this simulation, the size of the anode is much smaller, that's why the potential of the junction is further increased which makes it more prone to corrosion in seawater conditions. Figure 6(C) and 6(D) clearly show an increase in the pipe potential vs Ag/AgCl as compared to the prior simulations. In such conditions, there is a high chance that galvanic corrosion might be initiated as the outer surface is also shifted towards a higher potential value.

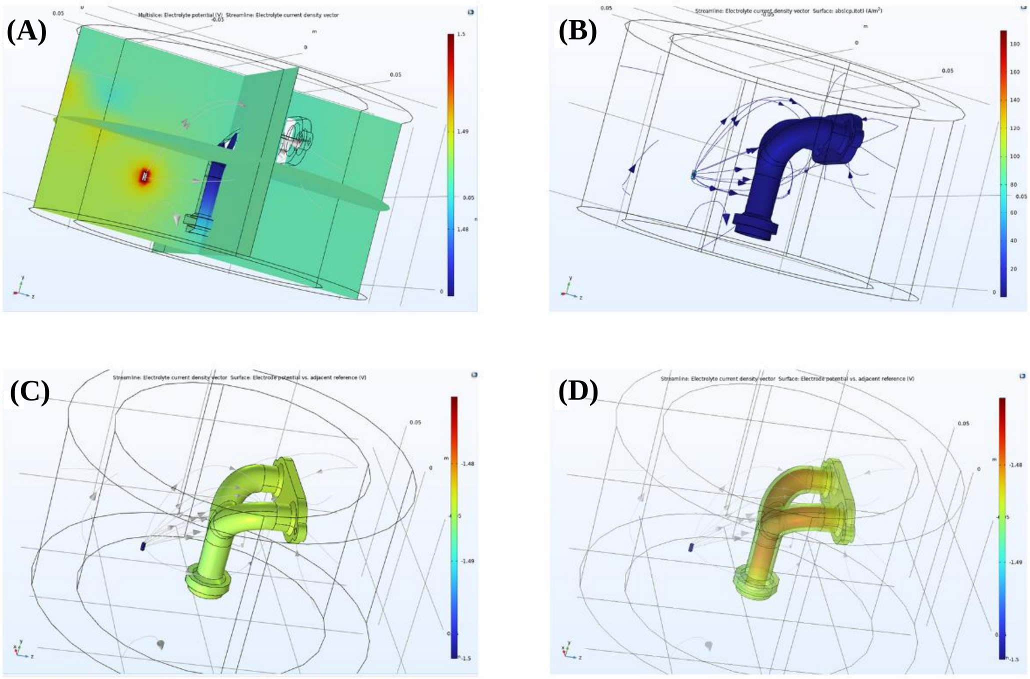

Figure 6 Simulation results (at 1 mm anode radius and 4.5 mm height) of (A) Electrolyte potential, (B) current densities, (C) Pipe potential vs Ag/AgCl, and (D) Pipe potential vs Ag/AgCl (transparent view).

3.4 At anode radius 0.2 mm and height 4.5 mm

To observe the effect of the smaller anode, the radius was further reduced to 0.2 mm. The results of this simulation are presented in Figure 7 (A), (B), (C), (D). This scenario yields more positive potential among all, it depicts that potential vs Ag/AgCl reference tends to increase. The inner surfaces are at the highest potential. While the external surface is less protected than in other scenarios. The areas with the highest potential values in Figure 7(C) and 7(D) are the least protected areas of the pipe. At these potential values, the pipes may have corrosion chances as cathodic protection comparatively decreases. In severe cases, corrosion may start in pipes under such conditions. Another aspect in this scenario cannot be neglected as with time, the sacrificial anode tends to reduce which can also lead to the same situation.

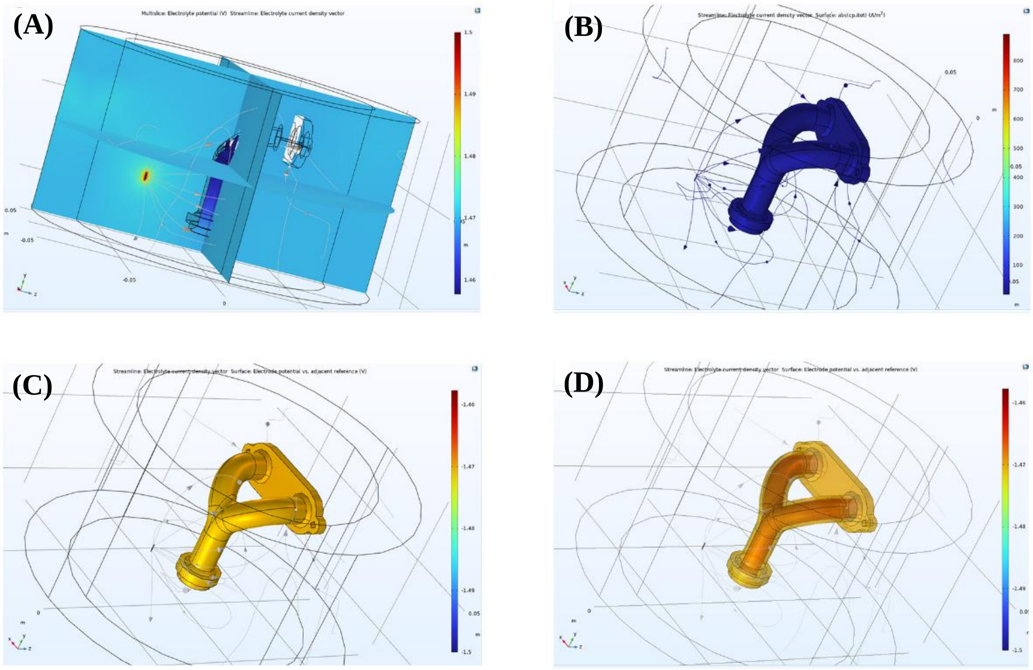

Figure 7 Simulation results (at 0.2 mm anode radius and 4.5 mm height) of (A) Electrolyte potential, (B) current densities, (C) Pipe potential vs Ag/AgCl, and (D) Pipe potential vs Ag/AgCl (transparent view).

3.5 Comparison of Pipe Potentials at different Anode Sizes

From the above simulation and table 2, it is clear that larger anode tends to protect the pipe in a better way. Variation of pipe potential with anode radius and height is graphically shown in Figures 8 and 9 respectively.

Table 2 Pipe Potential Results.

Anode Radius (mm)	Anode Height (mm)	Pipe Potential vs Ag/AgCl
0.2	4.5	-1.471
1	4.5	-1.485
5	9	-1.493
15	30	-1.4985

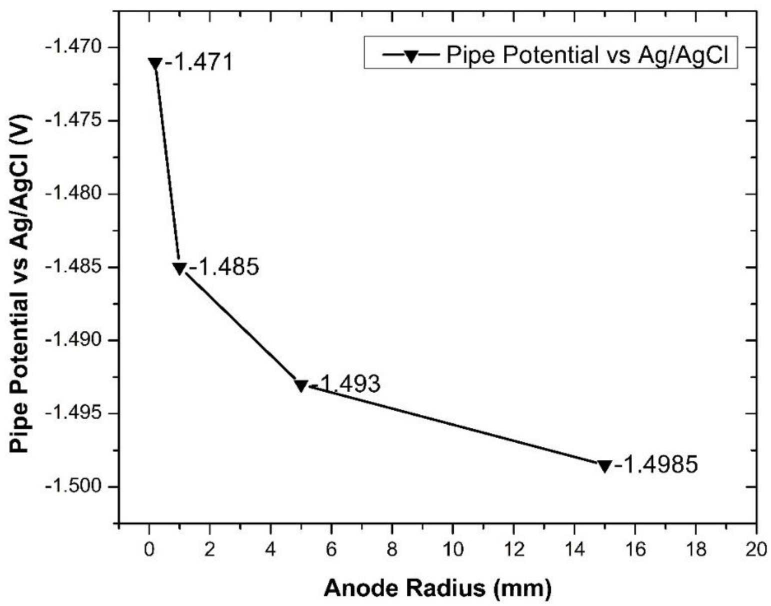

Figure 8 Pipe Potential vs Anode Radius.

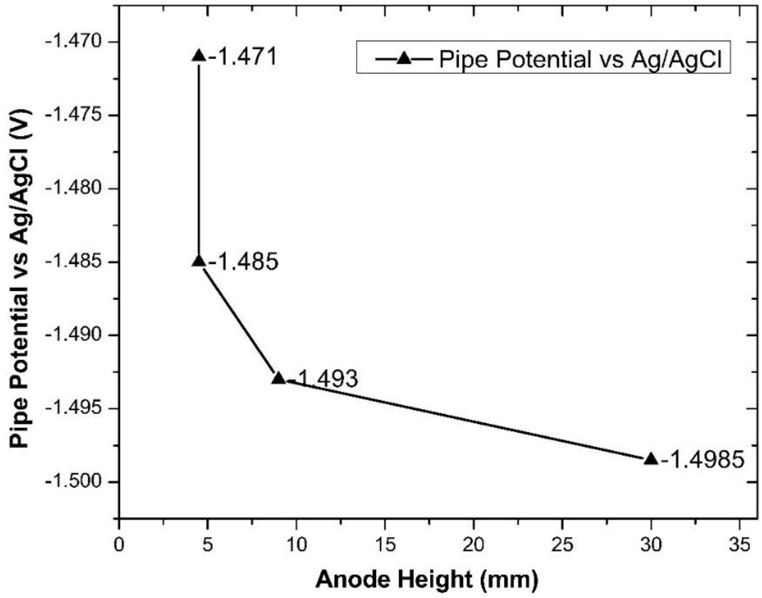

Figure 9 Pipe Potential vs Anode Height.

4. Conclusion

Modeling and simulation of cathodic protection under seawater conditions have been done using different sizes of sacrificial magnesium anode. From the above modeling and simulation, it can be concluded that cathodic protection is an effective technique for corrosion protection only when the proper analysis is done. If the required number of anodes, size of anodes, and required positions of anodes are known, then this technique can be beneficial for underwater pipes subjected to corrosion inhibitors inside the pipes depending on the size of the pipeline and other factors. The electrolytic conductivity of seawater is around 3-6 S/m which can be deadly dangerous for pipelines if proper steps are not taken. Some key conclusions of this research work are given below:

- For proper corrosion avoidance using cathodic protection, required design conditions must be known.
- Using lesser anodes or anodes with smaller sizes can potentially increase the threat of corrosion. Like in this study, sacrificial anode with smallest radius 0.2 mm yielded more positive potential.
- Anode size in CP is directly proportional to the effectiveness of SACP. Like largest anode in current study has lowest chance of corrosion with potential of -1.4985 V vs Ag/AgCl.
- The distance of the anode from the main pipeline also depends on the level of protection.
- Even after cathodic protection, corrosion inhibitors are required inside the pipes to avoid internal corrosion.
- The sacrificial anodes in the pipelines must be inspected regularly and should be replaced if consumed more than the allowable limits.
- Areas with branching, bends or irregular geometries tend to have more corrosion potential due to stress concentration and may be exposed to stress corrosion cracking.

5. Conflict of Interest

The authors have no conflict of interest to declare.

6. References

[1] Masood Arif Bukhari S, Husnain N, Arsalan Siddiqui F, Tuoqeer Anwar M, Abbas Khosa A, Imran M, et al. Effect of laser surface remelting on Microstructure, mechanical properties and tribological properties of metals and alloys: A review. Opt Laser Technol. 2023;165:109588.

[2] Bukhari SMA, Naveed A, Husnain N, Siddiqui FA, Zaman MF, Ahmad A, et al. Computational study of mechanical behavior of Ti6Al4V-Coated and Aluminium-Coated 316L stainless steel alloy under linear and cyclic loading. Tech J. 2023;28(3):12-24.

[3] Tamalmani K, Husin H. Review on corrosion inhibitors for oil and gas corrosion issues. Appl Sci. 2020;10(10): 3389.

[4] Lambert P. 6 - Sustainability of metals and alloys in construction. In: Khatib JM, editor. Sustainability of Construction Materials. 2ed ed. Woodhead Publishing; 2016. p. 105-128.

[5] Zhang X. Galvanic corrosion. Uhlig's Corrosion Handbook. 2011;51:123.
[6] Angst UM. A critical review of the science and engineering of cathodic protection of steel in soil and concrete. Corrosion. 2019;75(12):1420-1433.
[7] Cathodic protection design. Recommended practice DNV-RP-B401. Hovik: Det Norske Veritas. 2010.
[8] Wyatt BS. Practical application of cathodic protection. In: Shreir’s Corrosion. Elsevier; 2010. p. 2801–2832.
[9] Krishnan N, Kamde DK, Doosa Veedu Z, Pillai RG, Shah D, Velayudham R. Long-term performance and life-cycle-cost benefits of cathodic protection of concrete structures using galvanic anodes. J Build Eng. 2021;42:102467.
[10] Abootalebi O, Kermanpur A, Shishesaz MR, Golozar MA. Optimizing the electrode position in sacrificial anode cathodic protection systems using boundary element method. Corros Sci. 2010;52(3):678-87.
[11] Roberge PR. Handbook of Corrosion Engineering. 3rd ed. New York: McGraw-Hill Education; 2019.
[12] Fu AQ, Cheng YF. Effect of alternating current on corrosion and effectiveness of cathodic protection of pipelines. Can Metall Q. 2012;51(1):81-90.
[13] Xu LY, Su X, Cheng YF. Effect of alternating current on cathodic protection on pipelines. Corros Sci. 2013;66:263-8.
[14] Kuang D, Cheng YF. Effects of alternating current interference on cathodic protection potential and its effectiveness for corrosion protection of pipelines. Corros Eng Sci Technol. 2017;52(1):22-28.
[15] Ormellese M, Beretta S, Brugnetti F, Brenna A. Effects of non-stationary stray current on carbon steel buried pipelines under cathodic protection. Constr Build Mater. 2021;281:122645.
[16] Zhang L, Liang Z, Li S. Effect of current density on the cathodic protection efficiency and mechanical properties of pre-stressed high-strength steel wires for stay cable. Constr Build Mater. 2022;314:125671.
[17] Shaalan EM, Mostafa MA, Hamza AS, Al-Gabalawy M. Cathodic Protection Performance Improvement of Metallic Pipelines based on Different DC Compensation Methods. Electr Power Syst Res. 2022;210:108064.
[18] Xu LY, Cheng YF. Experimental and numerical studies of effectiveness of cathodic protection at corrosion defects on pipelines. Corros Sci. 2014;78:162-171.
[19] Kuang D, Cheng YF. Study of cathodic protection shielding under coating disbondment on pipelines. Corros Sci. 2015;99:249-257.
[20] Zaman MF, Bukhari SMA, Husnain N, Abbas Z, Ayyub A, Najmi MF, et al. Effect of zirconium carbide coating on thermal behavior of heavy duty V12 diesel engine using finite element method. Eng Res Express. 2024;6(2):025549.
[21] Oghli HM, Akhbari M, Kalaki A, Eskandarzade M. Design and analysis of the cathodic protection system of oil and gas pipelines, using distributed equivalent circuit model. J Nat Gas Eng. 2020;84:103701.
[22] Chung N-T, Hong M-S, Kim J-G. Optimizing the required cathodic protection current for pre-buried pipelines using electrochemical acceleration methods. Materials. 2021;14(3):579.
[23] Lorenzi S, Pastore T, Bellezze T, Fratesi R. Cathodic protection modelling of a propeller shaft. Corros Sci. 2016;108:36-46.
[24] Bellezze T, Fratesi R, Roventi G. Cathodic protection of a ship propeller shaftby impressed current anodes. Metall. Ital. 2014;106(7):3-10.
[25] Ghazi AR, Khan HI, Farooq M, Jahangir S, Anwar MT. Effect of temperature and medium environment on corrosion fatigue behavior of Inconel 625. Mater Corros. 2023;74(7):1030-1038.
[26] Chen S, Hartt W. Deepwater Cathodic Protection: Part 1Laboratory Simulation Experiments. Corrosion. 2002;58(01):38-48.
[27] Gadala IM, Abdel Wahab M, Alfantazi A. Numerical simulations of soil physicochemistry and aeration influences on the external corrosion and cathodic protection design of buried pipeline steels. Mater Des. 2016;97:287-299.
[28] Vasilescu M-V, Panaitescu M, Panaitescu F-V. Marine impressed current cathodic protection system. Hidraulica. 2019(4):45-62.
[29] Liu D, Zhang J, Wang X. Numerical simulation of submarine shaft-rate electric field based on COMSOL finite element. In: Patnaik S, Wang J, Yu, Z, Dey, N. editords. Recent developments in mechatronics and intelligent robotics. ICMIR 2019. Advances in intelligent systems and computing, vol. 1060. Singapore: Springer; 2020. p. 107-116.
[30] Kalovelonis DT, Rodopoulos DC, Gortsas TV, Polyzos D, Tsinopoulos SV. Cathodic protection of a container ship using a detailed BEM model. J mar sci eng. 2020;8(5):359.
[31] Husnain N, Siddiqui FA, Ahmad R, Bukhari SMA, Nasir I, Shafi MF, et al. Experimental and computational study of the most influential parameters of a lab-scale forced draft cooling tower by considering different number of packing ribs. Tech J. 2022;27(04):20-27.
[32] Naveed A, Bukhari SMA, Husnain N, Baloch N, Noor S, Ahmad W, et al. Structural integrity and cost analysis of a connecting rod for articulated robotic arm using various stainless steel and aluminium alloys. Tech J. 2024;29(2):24-34.