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Examination of the Potential Effect of Corrosion Current Density of Ship Hulls on the Sacrificial Anode Cathodic Protection

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Abstract
In this study, the sacrificial anode cathodic protection system, which is one of the electrical protection methods in the prevention of corrosion in ships, was examined. Within the scope of the study, the potential effects of corrosion current density, which is an important parameter for cathodic protection design, were studied. The study includes cathodic protection calculations for a bulker with a protected hull area of 9406 m^2 and a general cargo ship with a protected hull area of 1770 m^2. As a result, it was estimated that each 1 mA/m^2 change in the electric current density parameter changes the anode usage amount by 64 kg in bulker and 12 kg in general cargo, depending on the reference parameters such as protected hull area, anode type, and design life. It can be stated that the evaluation of the corrosion current density parameter, taking into account the operating conditions of each ship, will be beneficial in terms of optimizing the sacrificial anode consumption.

1. Introduction

Cathodic protection is an electrical control method that protects metallic structures in contact with soil or water from corrosion [1]. In the Earth's atmosphere, most alloys and metals have an unstable structure. As a result, it will always be undefended against corrosion as it will decompose into a lower-energy inorganic compound [2]. Corrosion can be defined as the damage to metallic structures as a result of chemical or electrochemical interactions with their environment [3]. Depending on the characteristics of the deterioration in the metallic structure, corrosion is divided into various classes, such as intergranular corrosion, crevice corrosion, and pitting corrosion. However, methods such as coating, alloying, anodic protection, and cathodic protection are used to minimize the formation of corrosion in the metal [4]. Although the effect of corrosion is limited in an individual sense, it causes serious costs in a global sense. Globally, the cost of corrosion is approximately US$4 trillion per year [5]. Therefore, many industries, such as oil, gas, and maritime, work hard to control corrosion.

When the subject is observed from a maritime perspective, seawater causes an aggressive environment on ships and offshore structures due to its high oxygen content and high electrical conductivity [6]. In addition to offshore structures, the protection of ships from corrosion is one of the industry's main priorities. Also, the most vulnerable area of a ship to corrosion is the hull [7]. In general, the ship hull is protected against corrosion by both passive (coating) and active (cathodic) protection. In addition to factors such as chlorine ions, chlorine compounds, humidity, and oxygen content in the marine environment, interactions arising from frictional resistance increase the importance and role of cathodic protection [8]. The sacrificial anode cathodic protection system is one of the most widely used cathodic protection methods on ships [9]. In the literature, cathodic protection systems used to prevent corrosion on ships have been discussed from different perspectives. Kim et al. [10] investigated the effect of anode amount and location on underwater electric

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fields for cathodic protection of ship hulls. Koli et al. [11] suggested the aluminum-based (Al-based) sacrificial anode alloy to improve the cathodic protection quality of ship hulls. Kalovelonis et al. [12] designed the impressed current cathodic protection system to protect a container ship from corrosion using the boundary element method. Kramar et al. [13] developed a cathodic protection model for ship hull structures using neural network technology. Clematis et al. [14] analyzed the sacrificial anode cathodic protection system for ships, compared it to the ISO (International Organization for Standardization), and actually implemented corrosion protection schemes. Yiğit and Adanur [15] compared the potential economic effects of Al and zinc (Zn) anodes, which are preferred for sacrificial anode cathodic protection for a cruise ship.

As can be seen in the literature, various studies have been carried out on corrosion and cathodic protection in ships. While some studies focus on passive protection systems to prevent corrosion, others emphasize the importance of active protection systems. It can be said that sacrificial anode cathodic protection is one of the most common methods used for active protection on ships. At this point, the choice of parameters necessary for the ship's cathodic protection design will affect the amount of sacrificial anode. One of the most important parameters affecting cathodic protection is the electrical current density of the structure. To the best of the authors' knowledge, although various cathodic protection designs have been made in the literature, the impact of corrosion current density on the amount of sacrificial anode has not been adequately studied. For this reason, in this study, the effect of corrosion current density on the design of a sacrificial anode cathodic protection system for ship hulls has been analyzed. The aim of this study is to examine and compare the impact of corrosion current density on the sacrificial anode consumption rate of Al during cathodic protection of steel hulls.

2. Material and Method

The technique of eliminating anodic currents from a metal surface by converting the metal to be protected into the cathode of the electrochemical cell to be constructed is known as cathodic protection. The metal can be protected by applying an external current to it or by connecting it to a more active metal, such as a sacrificial anode [16]. In this study, the effect of the corrosion current density parameter on the sacrificial anode cathodic protection design in ship hulls was examined. In the cathodic protection design, first the total net anode weight needed on the ship was defined. The total net anode weight can be calculated using Equation 1 [17].

$$W = \frac{A \times i \times C \times T}{1000} \tag{1}$$

Here, W is the total net anode weight (kg), A is the protected area of the ship (m^2), i is the corrosion current density of the structure (mA/m^2), C is the sacrificial anode consumption rate (kg/A/y), and T is the design life of the system (year).

In this study, two different hull areas were considered for cathodic protection design. The protected areas for a bulker and a general cargo were taken as 9406 m^2 and 1770 m^2, respectively. These values reflect the average wetted surface areas for the two different ship types [18]. Some metals, such as Al, Zn, and magnesium (Mg), can be preferred as sacrificial anodes in cathodic protection. However, the Mg anode is not recommended for use in ship hulls due to the high release of hydrogen gas during corrosion in seawater (saline or brackish water) environments. In addition, it has been stated that the use of Al anodes in the ship's hull provides an economic advantage over the use of Zn anodes [17], [19]. Therefore, it is assumed that an Al anode alloy is used in the design. For the consumption rate, the value of 3.39 kg/A/y given by the supplier was taken [17]. In general, the design life of the system varies between one and four years [20]. A two-year design life was determined for this study. The required current density of the ship's hull structure depends on different parameters, such as coating specifications, seawater characteristics, and flow conditions. For this reason, evaluations were made, considering different current density values for different situations in the literature. Within the scope of this study, current density values that can be used for cathodic protection of coated ship hulls were explored as far as can be obtained from the literature. The current density values expressed in various studies are shown in Figure 1 [17], [20-23].

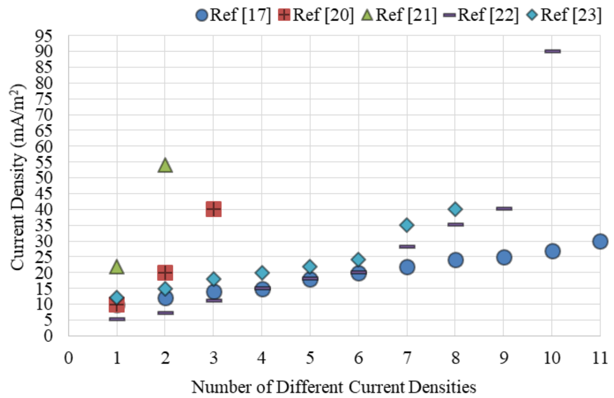


Figure 1. Electrical current density range required for coated ship hulls.

As seen in Figure 1, it can be said that the required current density values for the whole wetted surface area vary between 5 mA/m^2 and 90 mA/m^2 according to different situations. The frequency of the current density values expressed in the studies can also be seen in Figure 2.

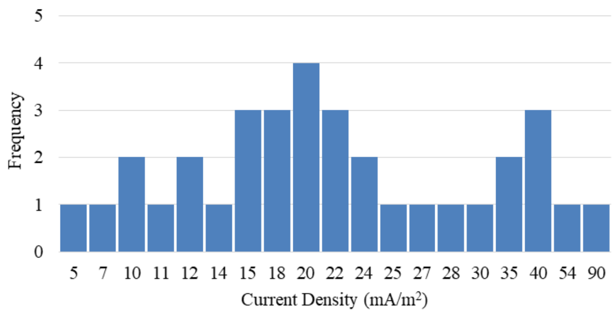


Figure 2. Distribution by current density.

Figure 2 shows that the most common electric current density reference value for a coated hull is 20 mA/m^2. Figure 1 and Figure 2 also show that the current density requirement of the material to be protected can significantly affect the cathodic protection design. It is therefore critical to obtain as much information as possible about the average current density of each ship's hull. This situation may not mean much for a single ship. However, considering the world maritime fleet, a significant increase in efficiency can be achieved in the use of sacrificial anodes in the process of protecting ships from corrosion. Therefore, in this study, the impact of the corrosion current density parameter on sacrificial anode cathodic protection design has been estimated in terms of two different ship models. Thus, the potential effect of sacrificial anode consumption on ships, depending on the current density parameter, is emphasized.

3. Results and Discussion

In order to show the effect of corrosion current density in the sacrificial anode cathodic protection design, two different ship models are considered. In the cathodic protection calculation, it is assumed that the required corrosion current density value for each ship hull varies between 5 mA/m^2 and 90 mA/m^2. In this case, the total net Al anode alloy weight required for cathodic protection is calculated for two ship models and shown in Figure 3.

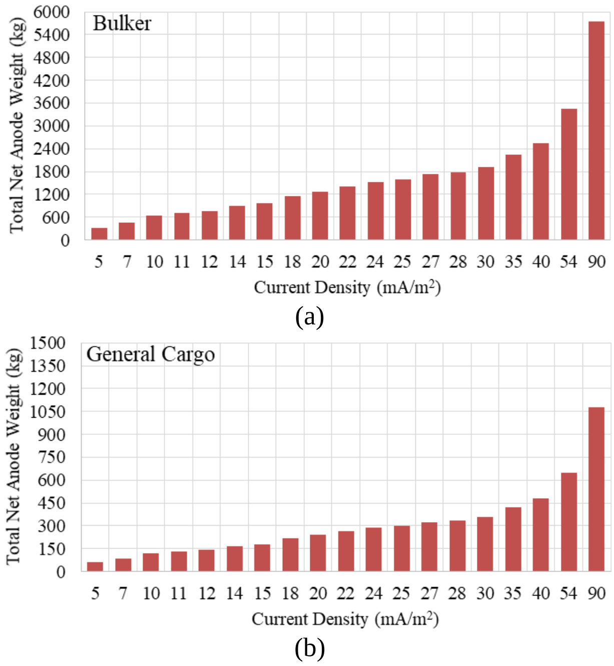


Figure 3. Total net anode weight depending on current density.

Figure 3(a) shows that the total net anode weight required to protect the hull of the bulker is calculated as 319 kg if the corrosion current density is taken as 5 mA/m^2. When the corrosion current density is taken as 90 mA/m^2, this amount is 5740 kg. Figure 3(b) shows that if the corrosion current density varies between 5 mA/m^2 and 90 mA/m^2 on the general cargo, the total net anode requirement is between 60 kg and 1080 kg. The difference between these two extreme corrosion current densities gives remarkable results in terms of efficiency. For this reason, a calculation to be made over the corrosion current density value (20 mA/m^2), which was determined to be emphasized more as a result of the literature study, may give more reasonable results. If the corrosion current density is taken as 20 mA/m^2, the total net amount of anode required for bulker and general cargo is 1275 kg and 240 kg, respectively.

The percent change in total net anode weight for different corrosion current densities compared to 20 mA/m^2 in cathodic protection calculations is shown in Figure 4.

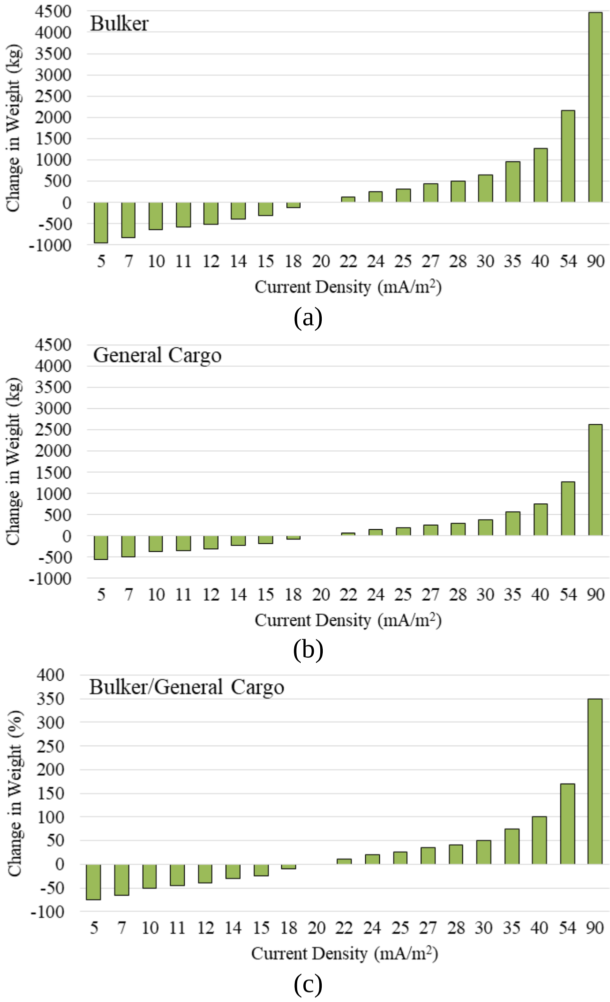


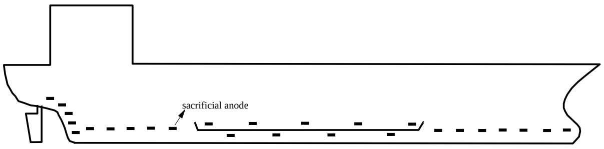
Figure 4. Change in anode use for different corrosion current densities compared to 20 mA/m^2.

Figures 4(a) and (b) show that choosing a corrosion current density of less than 20 mA/m^2 in the cathodic protection calculation reduces the total amount of anode required for the bulker and general cargo hulls. In the opposite case, the amount of sacrificial anode required will increase. As seen in Figure 4(c), this means that the amount of sacrificial anode to be used is reduced by 75% when the corrosion current density drops from 20 mA/m^2 to 5 mA/m^2 for both ship types. If the corrosion current density rises from 20 mA/m^2 to 90 mA/m^2, the increase in the amount of sacrificial anode will be 350%.

In this study, the effect of corrosion current density change on anode consumption is tried to be explained by taking average bulker and general cargo ship hulls as a reference. Thus, the effect of this parameter, which is used in the calculation of sacrificial anode cathodic protection in ships, on anode consumption is emphasized. As seen in Figure 1, the corrosion current density of the ship hull may vary depending on different parameters such as sea water, material, and environment. Also, Figure 3 shows that the change in this parameter significantly changes the sacrificial anode consumption. Here, it is possible to say that while some studies emphasize generally accepted values, in others, more specific values are emphasized according to ship types. Therefore, in order to determine the average Al anode alloy consumption values for these two ships, [23] can also be taken into account. In other words, if the corrosion current density is taken as 15 mA/m^2, the total net amount of anode required for bulker and general cargo is 959 kg and 181 kg, respectively. Moreover, each 1 mA/m^2 change in the corrosion current density parameter will decrease or increase the amount of anode used in selected bulker and general cargo hulls by 64 kg and 12 kg, respectively.

In the design of sacrificial anode cathodic protection for ships, attention should be paid to the anode distribution in the hulls as well as the amount of sacrificial anode. The anodes should be distributed symmetrically on both sides of the wetted surface area to protect the entire ship and obtain good current distribution. Placing a large number of small anodes evenly spaced along the hull can also further increase efficiency. The anodes are placed on the hull at intervals of about 6 m. About 25–30% of the anodes to be used are also placed on the stern. In the hull, flat anodes should be preferred to minimize flow resistance [20], [22]. To summarize, the corrosion of the ship's hull and the design and application examples of sacrificial anode cathodic protection to prevent this corrosion are illustrated, respectively, in Figure 5 [24]-[26].

(a)



(b)

(c)

Figure 5. Ship hull corrosion and sacrificial anode cathodic protection.

As a result, corrosion-related deterioration in ship hulls is highly dependent on environmental factors, seawater compositions, and the protection quality of steel structures. Many parameters, such as deterioration in the protective layer of the ship's hull in contact with seawater, changes in the temperature, flow rate, and chemical components of seawater, can affect the rate of corrosion. The uncertainties in these parameters make it difficult to determine the amount of anode to be used in the design of the sacrificial anode cathodic protection system on board. There are international organizations that have published specifications that address these variables, and they may offer slightly different values. Therefore, it may not be appropriate to state whether the specified characteristics are strictly true or false, as the methods for collecting the calculated data may differ [27]. As a result of shipyards' long years of experience, adaptation of previous cathodic protection systems to similar ships may also affect sacrificial anode consumption [14]. Such reasons may indirectly cause the calculated amount of sacrificial anode to be less or more. Obviously, the corrosion current density values specified in the literature for different situations make a great contribution to reducing such errors. To minimize these errors, various solutions can also be evaluated. e.g., for cathodic protection optimization, physical modeling technique and computational simulation techniques such as boundary element, finite difference, and finite element methods can be used [28], [29]. Since electrochemical protection techniques depend on the nature of the material and ambient conditions, the cathodic protection design can be supported by experimental studies that take into account the operating conditions of the ship [30]. Thus, it can contribute to reducing the global effects of corrosion.

4. Conclusion and Suggestions

In this study, the impact of the corrosion current density parameter on sacrificial anode cathodic protection design in ships was investigated. For the calculation of cathodic protection, a bulker model with a 9406 m^2 hull to be protected and a general cargo model with a 1770 m^2 hull to be protected were considered. Then, the amount of Al alloy anode to be used for each ship model was calculated if the electrical current density of the coated hull changed between 5 and 90 mA/m^2. As a result, for the 5–90 mA/m^2 range, the amount of sacrificial anode used in the bulker and general cargo over the two-year design life is expected to range between 319–5740 kg and 60–1080 kg, respectively. In addition, it was concluded that each 1 mA/m^2 change in current density will change the anode usage amount by 64 kg in bulker and 12 kg in general cargo.

It can be stated that the evaluation of the corrosion current density parameter for each ship as much as possible in the cathodic protection design will contribute to the increase in efficiency in this area. In this context, increasing experimental studies as well as computational simulation techniques can contribute to the improvement of reference parameters. In addition, examining the historical navigation plans of existing ships can also reduce the error in the cathodic protection calculation. Because if the ship is constantly navigating the same route, cathodic protection parameters can be determined by considering the environmental conditions of that route. In this way, a clearer approach can be presented for the reference value of the corrosion current density parameter to be considered during the replacement phase of the sacrificial anodes on the ship. For new ships under construction, estimating the corrosion current parameters for the conditions of that area may be a more efficient approach if the ship is to be operated on a particular course. Thus, the anode consumption in the cathodic protection design can be optimized, and the negative effects of corrosion can be reduced further.

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Contributions of the authors

All authors contributed equally to the study.

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics

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