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Numerical Investigation of Hydrodynamic Behavior of Foil Shaped Zinc Anode for Reducing the Hull Appendages Effect

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Abstract – *Appendages are parts of a ship that might increase viscous resistance. The geometric shapes of appendages should be made appropriately in order to generate designs capable of reducing the negative effects of appendages. Therefore, the zinc anodes as sacrificial cathodic protection of ship hull are designed to decrease the amount of drag force that might cause an increase of the total resistance of ship, and it should be installed aligned with the direction of local flow. Regarding the effort to minimize the appendage effect, the foil shaped zinc anode has been proposed in order to improve the performance of drag force on the conventional zinc anode. This research is focused on investigating the hydrodynamic behavior of the foil shaped zinc anode in reducing the effect of hull appendages on ship performance. In this paper, a numerical study has been carried out using the Computational Fluid Dynamics (CFD) method. A comparison of the performance for each variation of foil shaped and conventional zinc anode will be discussed. The results show that foil shaped zinc anodes have generated smaller drag force compared with the conventional ones.*

***Keywords**: Foil Shaped Zinc Anode, Drag Force, Cathodic Protection, Sacrificial Anode and Hull Appendages*

I. Introduction

Cathodic protection was first used in 1824 when the iron anode was installed as corrosion protection on the copper cladding of the immersed hull in the seawater of a sailing ship, [1]. In early 1900, steel was used as the primary material for shipbuilding with consideration of economic aspects and better mechanical properties.

However, this has resulted in hull corrosion being identified as a serious problem in hull construction. The worst area of the corrosion is the stern part of the ship, where high wave turbulence and adjacent to copper propellers can cause galvanic pitting corrosion in steel structures in the stern area. This corrosion problem can be reduced by installing zinc/aluminum anode around the stern and steering area of the ship, Fig. 1. The corrosion protection practices using sacrificial anode are still widely used today. The zinc contamination in hull steel causes the anode to supply electrons so that the steel does not degrade due to galvanic corrosion. However, the installed zinc anode should be obtained from a reputable supplier so that the anodizing material provides effective protection for the vessel hull. Although the installation of sacrificial anodes can provide effective protection against hull corrosion, the installation of sacrificial anodes has provided appendages that can cause turbulence in the stern flow. The presence of appendages can cause axial losses in the propeller thrust because of the generated water turbulence in the propeller region, [2]. Propeller shafts and appendages should be located in the streamlined and aligned to the water flow in the vessel hull. This effort can reduce the barriers and the flow disturbances while the seawater is entering the propeller.

The improvements of the vessel hull design to get streamline flow can increase the efficiency of the total energy consumption by 2%, [3]. Appendages are usually not included in the small-scale tests at the towing tank.

However, these appendages provide additional resistance, especially in the form of viscous resistance. In order to obtain solutions to the problem of appendage effects on the disturbance of water flow and wake distribution, Computational Fluid Dynamics (CFD) analysis can be used. The investigation of the amount of drag force, flow pattern, and wake distribution due to the form of appendages on the stern of the ship can be done by the CFD method. Based on the above conditions, the proposed research is focused on the design of sacrificial anode geometry in order to improve the efficiency of ship propulsion through improved stern flow and wake distribution.

Fig. 1. Sacrificial Anode (Zinc Anode) for cathodic protection

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The geometrical design of sacrificial anode that will be developed is a foil shaped sacrificial anode.

Numerical investigation and CFD analysis have been carried out to obtain the magnitude of drag force that is generated by the zinc anode as a hull appendage in the stern area of the ship.

A comparison of the magnitude of the drag force at the proposed sacrificial anode with the existing geometry design has been made to identify the decrease of the generated drag force and the improvement of the hull resistance. The work is started on the literature review on the previous research that has been focused on the cathodic protection behavior and on the computational fluid analysis for estimating the drag force due to the geometry of the cathodic protection.

Furthermore, the exploration of the foil shaped geometry for the design of sacrificial anode geometry is done.

The selected geometry design of foil shaped anode is evaluated by using computational fluid dynamic method by considering the position of the anodes on the vessel hull which are include the midship region, between the midship and the stern region. The comparison between the proposed geometry with the conventional design has been explained in the result and discussion section.

II. Literature Review

In the parts of the vessel hull, the sacrificial anode protection system is used to protect the hull construction, the ballast tanks, the heat exchanger components, and the underwater pipelines. Before the design installation of cathodic protection using sacrificial anodes is conducted, some information should be available or specified, including:

1. Information on the area of protected steel;
2. Type of protective coating (coating system) to be used;
3. The length and the frequency of steel contact times with electrolytes, in the ballast tank, the only time that is taken into account is when it is fully loaded because. Only in this condition, the sacrificial anode is being operated;
4. The life required for the cathodic protection system;
5. The current density that is used to protect the structure should be determined, usually within the current range of 20 mA/m^2-4000 mA/m^2;
6. Electrolyte resistivity should be determined based on the selected anode material.

The determination of the total weight of the anode, the total current required, and the number of anodes needed following the required current and weight is:

- The total current needed:

$$I = \frac{Area(\mathrm{m}^2) \times Currentdensity\left(\frac{\mathrm{mA}}{\mathrm{m}^2}\right)}{1000}$$

- Anode Weight:

$$W(\mathrm{kg}) = \frac{current(\mathrm{A}) \times life(year) \times 8760}{Capacity\ of\ materials\left(\frac{\mathrm{A\,hrs}}{\mathrm{kg}}\right)}$$

- Required weight:

$$W = no.of\ anodes \times individual\ net\ weight$$

- Required currents:

$$I = no.of\ anodes \times indivi.current\ output$$

Several articles have been reviewed to support the development of the sacrificial anode geometry design that can improve the stern flow and wake distribution.

These articles relate to the study of cathodic protection and the design characteristics of appendages in the stern. In the development of the use of sacrificial anodes as protection of marine structures, Celis et al., [4], have carried out studies on the synthesis of corrosion-protective conversion coatings on zinc with single-step anodizing on silicate-based electrolytes. The rotating disc electrode is used as a mass transport control through the electrode, and to study the effect of hydrodynamics on the structural characteristics and corrosion resistance of the surface layers formed.

The results have showed that the anodizing in silicate-based electrolytes has increased the corrosion resistance of zinc substrates by forming a barrier layer that has shielded the base material of the parent and has formed galvanic protection. Mathiazhagan, [5], has conducted a study of the design and the programming of cathodic protection on ships. The results of the study indicate that the adequacy of the number of electrons from an external source given to the protected metal surface should be able to accommodate cathodic reactions such as oxygen reduction and hydrogen evolution. The limitation of the impressed current system is not suitable for continuous operation. The use of hybrid systems can provide better corrosion protection. Lorenzi et al., [6], have conducted a cathodic protection model on the propeller shaft. Potential and current distribution is conducted on a propeller shaft made of stainless steel. The previous studies, which are carried out on the use of impressed current and sacrificial anode as cathodic protection, can be found in [7]-[10]. Mathematical equations that define non-linear boundary conditions based on the steel polarization curve for the boundary element method can be found in [11]-[17], whereas for the finite element method in reference, [18], [19]. Empirical models for describing time variations on the polarization curve can be found in [20], [21]. The model has been developed into a model that can explain precipitation and growth mechanism, [22], [23]. In the ship navigation, the relative velocity hypothesis between steel walls and water is determined only by the shaft rotation.

The current density that limits oxygen can be assessed using the equation for turbulent Couette flow between the rotating inner cylinder and an outer coaxial and stationary cylinder that is known as the rotating cylinder electrode, [24], [25]. Instead of the turbulence, a microorganism activity can cause the steel material degradation. The microorganism activities can also promote the hydrogen permeation. The presence of sulfate-reducing bacteria might increase the hydrogen entry rate to the steel, [26], [27]. Based on several studies that are have been conducted by many researchers, it has been shown that cathodic protection has an important role in the protection of marine structures. Besides, it appears that the numerical analysis using CFD method, the Boundary Element Method (BEM), and the Finite Element Method (FEM) have acceptable accuracy and good results in predicting corrosion behavior in a structure. Although cathodic protection is very important for the protection of structural quality, the use of sacrificial anode systems can influence the magnitude of ship resistance, due to the presence of appendages in the stern that can affect the drag force of the ship. The amount of potential savings might be achieved by eliminating and optimizing zinc anodes can increase the efficiency of thrust by up to a few percent, [28]. Zinc anodes should be removed from areas of high velocity and installed in line with the local flow direction, [29].

For all the reasons, it can be seen that zinc anodes have an important role to protect the hull structure from the corrosion phenomena. However, the application of conventional sacrificial anode might reduce the efficiency of the ship propulsion system as the appendages resistance. Therefore, this research has presented the modification of the sacrificial anode geometry through the development of the foil shaped zinc anode. The modification of the zinc anode geometry is subjected to the reduction of the drag force generated by the conventional sacrificial anode as appendages on the vessel hull. Furthermore, the numerical study has been made in order to estimate the hydrodynamic behavior of the proposed foil shaped zinc anode.

III. Material and Methods

III.1. Designing on the Configuration of the Foil Shaped Zinc Anode Geometry

The design procedure to determine the foil shaped zinc anode for reducing the hull appendage effect on the resistance performance is started with generating the configuration of the proposed geometry of the foil shaped zinc anode design. The parameters considered as the geometry design configuration are the length of the anode, the thickness of the anode, the head, and the trail radius of the foil shaped anode. The illustration of the parameters of the configuration of the design geometry can be found in Fig. 1. All the generated design configurations have similar volumes and weights. The configurations of the anode geometry will be used to investigate the drag force and stern flow characteristics.

The illustration and the size of the design parameters of the generated design of anode geometry can be found in Fig. 2-Fig. 5 and Table I, respectively.

Fig. 2. Conventional design of zinc anode

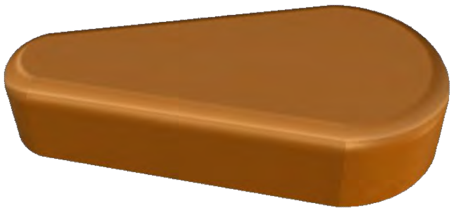


Fig. 3. Geometry design 1 of zinc anode

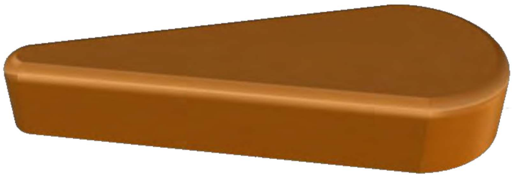


Fig. 4. Geometry design 2 of zinc anode

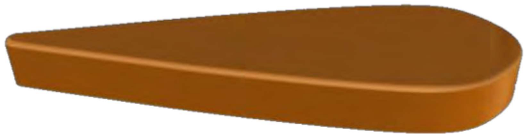


Fig. 5. Geometry design 3 of zinc anode

TABLE I
THE DESIGN CONFIGURATIONS OF FOIL SHAPED ANODE GEOMETRY [8]

Design Parameters	Conventional	Design 1	Design 2	Design 3
Length (*D*) [cm]	20	20	25	31
Thickness (*T*) [cm]	3	4.1	3.8	3.2
Width (*W*) [cm]	10	10	10	9.2
Head Radius (R_f) [cm]	-	10	10	9.2
Trail Radius (R_a) [cm]	-	4.6	2.8	1.3
Volume (*V*) [cm^3]	600	571	600	600
Weight (W) [kg]	4.2	4	4.2	4.2

III.2. Simulation Analysis for Performance Evaluation of the Foil Shaped Zinc Anode Geometry

The simulation model is generated using an enclosed prismatic fluid domain. The inlet region is determined with the axial upstream of the entry flow, and the outlet region is determined with the downstream of the exit flow. The outlet region location is defined with the distance about two times of the anode from the trailing side face of the foil shape. The anode model is defined and located on one side of the edge of the fluid domain boundary, and it is aligned with the defined fluid flow.

The other side of the boundary of the simulation model is determined with the domain width of 80 mm and the domain thickness of 800 mm, Fig. 6. The mesh of the simulation model used is the unstructured grid mesh type, Fig. 7.

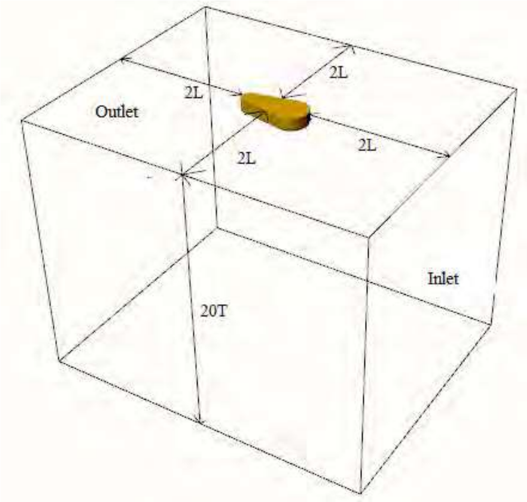


Fig. 6. The CFD domain size for the zinc anode located in the midship region

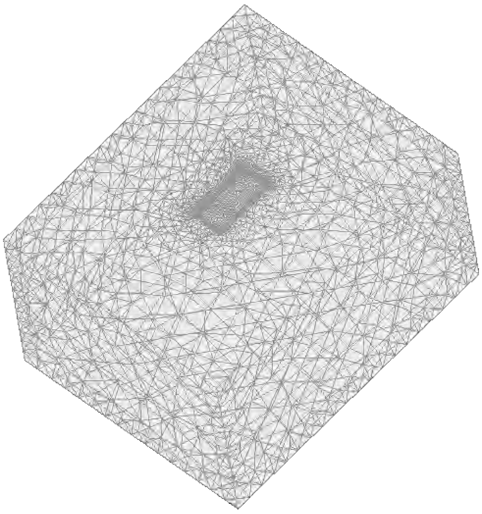


Fig. 7. Unstructured grid meshing model

In the other location of the zinc anode position models, the domain models have been developed with the simple curved geometry that represents the stern part of the vessel hull shaped. The illustration of the domain model with different locations of the zinc anode can be seen in Fig. 8 and Fig. 9.

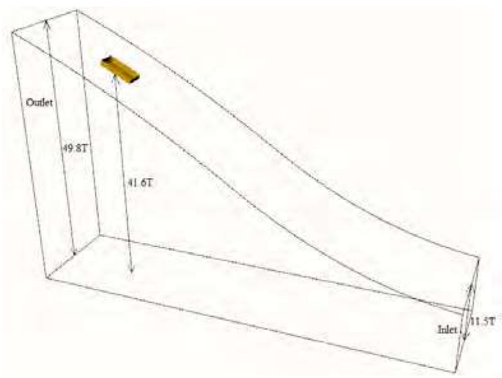


Fig. 8. The CFD domain size for the zinc anode that located in the stern

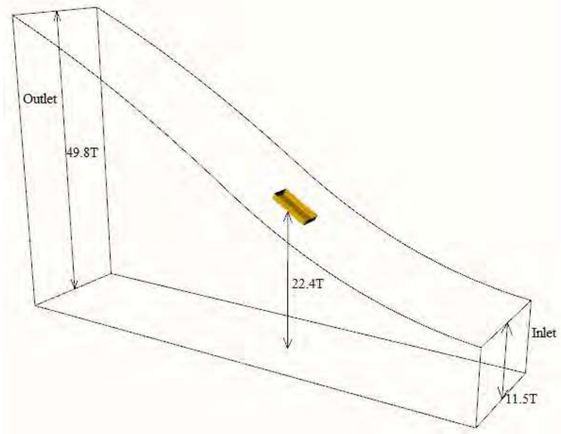


Fig. 9. The CFD domain size for the zinc anode that located between the stern and midship

IV. Results and Discussions

IV.1. The Zinc Anode in the Midship Region

In the midship region, the result of the simulation CFD analysis shows that the hydrodynamic pressure drag of the original design has the largest maximum hydrodynamic pressure drag of 3808 Pa. "Design 1" and "Design 2" have the maximum hydrodynamic pressure drag of 2426.5 Pa and 2420.4 Pa, respectively. "Design 3" shows the smallest maximum hydrodynamic pressure drag of 1896.2 Pa compares to the other design. It is indicated that the foil shaped geometry can reduce the hydrodynamic pressure drag. Therefore, the degrees of the slenderness of the foils have influenced the magnitude of the hydrodynamic pressure drag. The illustration of the pressure drag distribution can be seen in Figs. 10.

IV.2. The Zinc Anode Between the Midship and the Stern Region

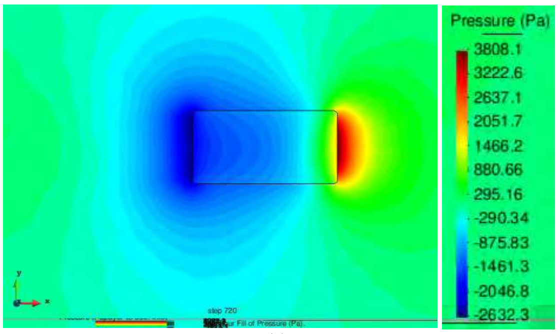
Between of the midship and the stern region, [8], all of the zinc anode designs have shown similar tendencies with the decrease of the pressure drag. The reductions of the pressure drag, which is caused by the shifted position of the zinc anode for the original designs, Design 1, Design 2, and Design 3 are 65.95%, 75.84%, 83.6%, and 81.97%, respectively. The maximum pressures drag of the original designs, Design 1, Design 2, and Design 3 are 1296.9 Pa, 586.33 Pa, 397.05 Pa, and 341.92 Pa. The illustration of the pressure drag distribution can be seen in Figs. 11.

IV.3. The Zinc Anode in the Stern Region

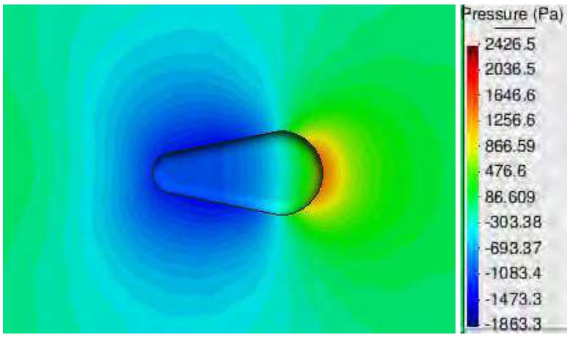
In the stern region, the simulation results have also presented the decrease of the maximum pressure drag. Compared with the pressure drag on the midship region, the reduction percentages of the maximum pressure drag of the original designs, Design 1, Design 2, and Design 3 are 77.41%, 73.61%, 75.81%, and 76.03%, respectively.

The pressure reductions due to the shifted position in the stern region of the original design have presented a larger reduction compared to the proposed foil design.

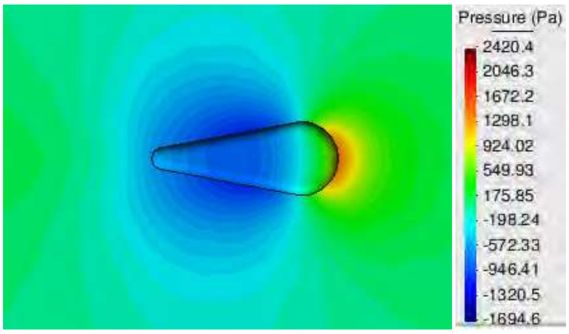
However, the proposed design has still showed a significant reduction in the maximum pressure drag compared to the original design. The illustration of the maximum pressure drag distribution can be seen in Figs. 12.



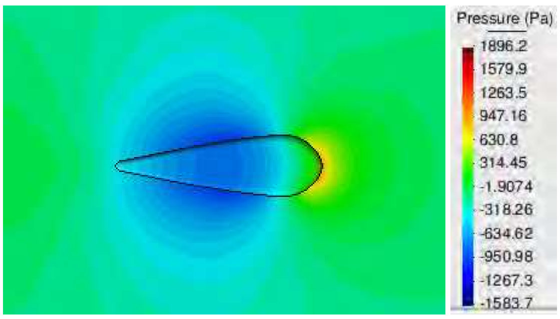
(a)



(b)

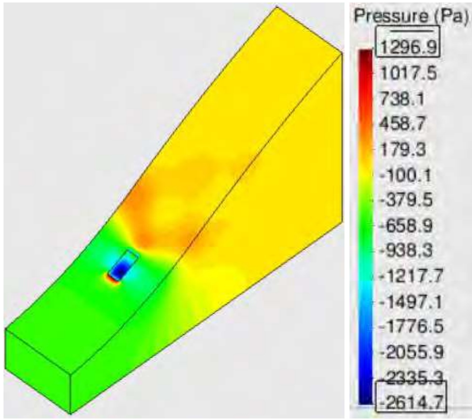


(c)

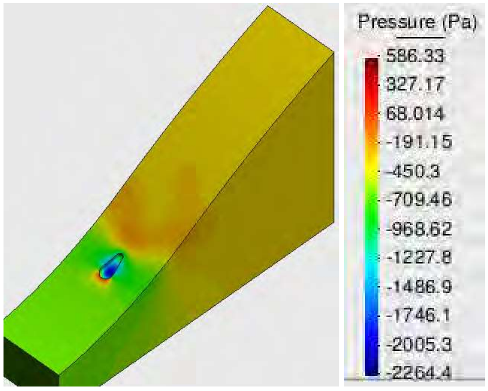


(d)

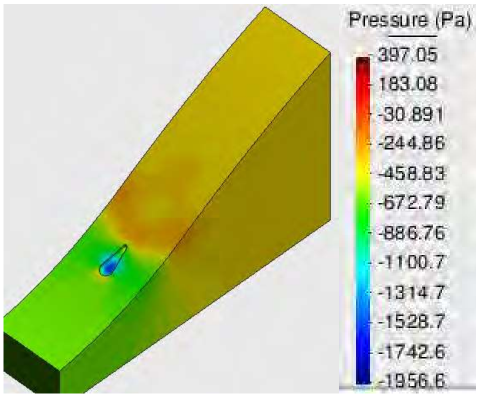
Figs. 10. The zinc anode pressure locate in the midship region: (a) original; (b) design-1; (c) design-2; (d) design-3



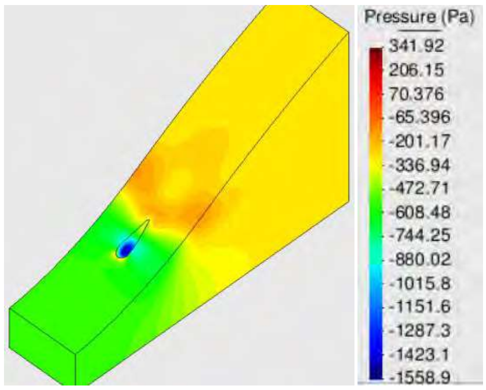
(a)



(b)

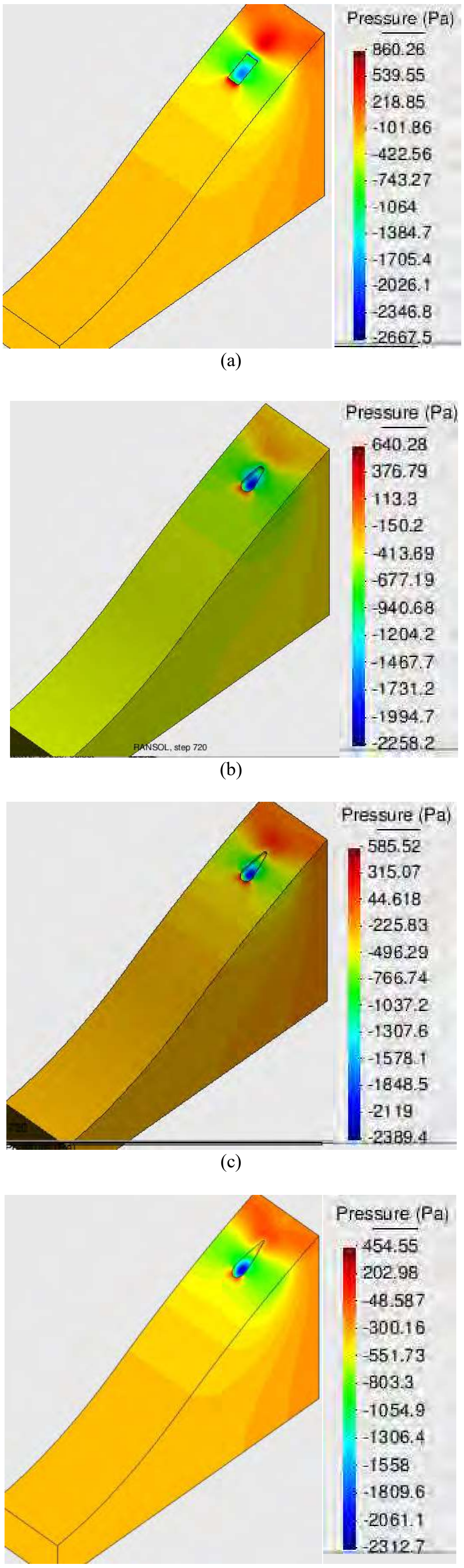


(c)



(d)

Figs. 11. The zinc anode pressure located in between the midship and the stern region: (a) original; (b) design-1; (c) design-2; (d) design-3



Figs. 12. The zinc anode pressure located in the stern region: (a) original; (b) design-1; (c) design-2; (d) design-3

According to the result of the simulation result, it can be seen that the modification of the design geometry of the sacrificial cathodic protection can reduce the maximum hydrodynamic pressure drag. Furthermore, it can be seen that the position of the anodes on the hull influences the generated hydrodynamic pressure drag. It can be concluded that the modification of the sacrificial anodes using foil shaped geometry provides a positive contribution to the improvement of the vessel hull resistance characteristics. The magnitudes of the maximum hydrodynamic pressure drag of the proposed design on the different positions of the vessel hull are presented in Table II.

TABLE II
THE MAXIMUM HYDRODYNAMICS PRESSURE DRAG OF PROPOSED DESIGN IN EACH LOCATION OF THE VESSEL HULL

Anode Design	Maximum Hydrodynamic Pressure Drag		
	Midship	Mid to Stern	Stern
Original	3808.1	1296.9	860.26
Design 1	2426.5	586.33	640.28
Design 2	2420.4	397.05	585.52
Design 3	1896.2	341.92	454.55

V. Conclusion

The developments of an alternative geometry of the sacrificial anode to reduce the effect of appendages on the vessel resistance have been presented. The foil shaped geometry has been adopted for the modification of the anode geometry. According to the computational results, it is indicated that the foil shaped geometry can reduce the maximum hydrodynamic pressure drag. The streamlined curves of the foil shaped anode have improved the flow and have distributed the hydrodynamic pressure. The slenderness of the foil geometry has also influenced the magnitude of the reduction of the hydrodynamic pressure drag. Therefore, it can be concluded that the foil shaped and the foil slenderness can reduce the appendage effect of the original geometry of sacrificial anode to the hull resistance. The magnitude of the hydrodynamic pressure drag on the sacrificial anode is also influenced by the location of the anode on the protected hull. The simulation results show that the anodes, which are located on the midship region, have a larger pressure drag compared to the other region. The percentages of pressure drag reduction due to the foil shaped anode at the midship region, between midship to stern region, and stern region are 50.21%, 73.63%, and 47.16%, respectively. It is indicated that the foil shaped anode has a larger reduction effect on the between midship and stern region. Since the significant reduction of pressure drag has been shown due to the adoption of foil shaped geometry as the sacrificial anode, it is recommended to implement the foil shaped geometry as sacrificial cathodic protection.

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