OPTIMIZATION OF OIL TANK DESIGN TO MINIMIZE LIQUID SLOSHING IN PORTABLE OIL SPILL SKIMMER

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ABSTRACT: When developing an autonomous portable oil spill skimmer, an oil tank is one of the most critical designs to be developed. The problem occurs when large amplitude or resonant frequency excitation which causes violent sloshing that can damage the oil tank structurally or even cause the portable oil spill skimmer to overturn. Therefore, this research aims to analyze liquid sloshing impact in the oil tank, both with and without the baffle. The functionality of the baffle is analyzed to prove that it is crucial to implement a baffle when designing any type of oil tank. Computational Fluid Dynamics (CFD) simulation was used to analyze the liquid sloshing effect in the oil tank as a method in this research. Furthermore, the material selection of the skimmer roller was discussed in this research. Moreover, concept screening and scoring are used to select the best material for the skimmer roller. The result shows that implementing the baffle improves the amplitudes or resonant frequencies of the oil sloshing effect. Additionally, there was a reduction of 96.92% of torque comparing the simulation of with and without baffle. Polypropylene was selected as the best material for the skimmer roller. Essentially, incorporating a baffle in the oil tank minimizes the liquid sloshing effect, thus reducing the pitching and heaving effect on the oil tank.

KEYWORDS: *Computational Fluid Dynamics (CFD); Oleophilic; Oil spill skimmer; Liquid sloshing.*

1.0 INTRODUCTION

A significant source of environmental contamination is oil spills. Liquid petroleum hydrocarbons released into the ocean or coastal regions due to human activity are sometimes referred to as marine oil spills [1]. Marine oil spills may have a significant negative economic impact and harm communities, public health, and natural systems [2]. Thus, various mechanical, chemical, in situ burning, and bioremediation methods are used to treat oil spills. This study focuses on the mechanical technique known as the boom and skimmer, which has been shown to be more advantageous than other techniques [3]. The boom serves as a barrier to prevent oil from spreading, while the skimmer gathers the oil and delivers it to the main vessel. The boom and skimmer, however, have certain drawbacks. For instance, with high tides and strong winds, the oil tends to pass over the boom, necessitating frequent reconstruction of the boom and skimmer. As a result, the procedure requires resources, costs money, and takes time. Therefore, an autonomous portable oil spill skimmer was developed to complement the current Oil Spill Respond and Recovery (OSRR) approach.

The oil spill skimmer is capable of being maneuvered and consists of an oil tank, oleophilic roller, a pair of propellers, an electronic box, and a pair of support aids [4]. However, the commercial oil skimmer does not have an oil tank, where the recovered oil is transferred directly to the main vessel via the suction pump. Furthermore, few to no studies have been conducted to develop a self-propelled portable oil spill skimmer. Most of the research was conducted on the oil skimmer [5-8], where the oil skimmer is in static positions. However, the self-propelling mechanism in the developed oil spill skimmer has the disadvantage of oil sloshing in the oil tank. The oil sloshing occurs when the oil spill skimmer brakes after moving at a uniform speed. Thus, the oil spill skimmer continues moving due to the combined action of gravity and inertia force which causes oil sloshing in the oil tank [9]. Therefore, this study aims to analyze the oil sloshing effect with and without baffle during motion. The application of baffle is crucial to minimize the liquid sloshing during maneuvering. Some sloshing is impossible to avoid, but a reduction of the effect is extremely useful in avoiding unwanted dynamics. The liquid sloshing simulation was performed using one and three baffles to differentiate the torque and force exerted on the oil tank. Moreover, the material selection of a skimmer roller is also discussed in this study.

When tanks are partially full, liquid sloshing is the movement or vibrating of the free liquid surface caused by outside influences [9]. In several engineering disciplines, including mathematics, space flight, land transportation, and marine transportation, liquid sloshing is a common occurrence. By generating the free liquid surface an initial impulse or disturbance, the free liquid surface can produce sloshing [10]. Braking, acceleration, and deceleration are the primary vehicles varying situations. The major factor for a tank truck's decreased driving stability is liquid sloshing in a partially filled tank due to the effects of liquid density and road axle weight constraints [11].

The study of liquid sloshing in tanks has piqued the curiosity of many academics. The sloshing effect as it relates to vehicle conditions was investigated using a simulation of liquid sloshing. The results demonstrate that the highest amount of force created when the liquid sloshes depend on the amount of oil in the tank [9]. In addition, Brar et al. [12], research investigates liquid sloshing in an elliptical tank using modelling and experiments with various baffle arrangements. Additionally, research was done to create a liquid sloshing framework based on the Lagrangian continuum that is claimed to effectively replicate the effects of sloshing forces under complicated vehicle motion situations [13]. It was discovered that the liquid sloshing effect tends to increase loads on specific wheels during acceleration, while decreasing pressures on other wheels, potentially endangering vehicle stability and resulting in wheel lift and overturn.

In addition, Lu et al. [14], conducted a simulation analysis of liquid sloshing in a rectangular tank using with/without baffle. According to the author, a baffle reduces relative sloshing amplitudes near the resonant circumstances by increasing physical dissipation in the tank. The behavior of a vehicle's fuel tank's liquid at its free surface under uniform acceleration was examined. Rajamani et al. [15], demonstrates that the amount of fuel in the tank greatly lowers the liquid-free surface displacement amplitude, accelerating the time it takes for the fuel surface to stabilize.

In selecting a skimmer roller, oleophilic and hydrophobic properties are crucial when selecting a material that is suitable for the skimmer roller [16, 17]. Oleophilic material attracts oil and hydrophobic repels water. Thus, it is important to incorporate oleophilic materials for oil suction recovery. Within the spill area, the oil is attracted to a circulating skimmer surface, which collects it. The scrapers then transfer the oil from the skimmer surface to the collection tank by lifting the oil clung to the skimmer surface [6]. Hrushikesh's research led to the selection of disc-shaped polypropylene material as the skimmer since it has oleophilic [18]. Furthermore, even though metal surfaces have been shown to be efficient, oleophilic polymer materials are frequently used as it is inexpensive [19].

It is well known that previous researchers have investigated and reported on liquid sloshing in different applications such as lorries and vessels. To the best of the author's knowledge, however, studies on the implementation of baffle in developing a portable oil spill skimmer's oil tank is still inadequate. Therefore, the objective of this research is to analyze the importance of implementing baffles in the oil tank design to reduce the sloshing impact. CFD simulation was used to investigate the behavior of oil sloshing in the oil tank while accelerating and decelerating. The study of oil sloshing could benefit the industry and research institute because it can help to reduce evaporative emissions, improve fuel efficiency, and prevent damage to fuel tanks.

2.0 METHODOLOGY

The structure of the research begins with a method of analyzing the liquid sloshing and the material selection of the skimmer roller was explained in detail. As for the liquid sloshing analysis, SolidWorks Computational Fluid Dynamic (CFD) simulation was utilized. Furthermore, the method selection of the skimmer roller was conducted to select the best material for the roller.

2.1 Research Framework

The fundamental steps of analyzing the CFD simulation include pre-processor, solution, and postprocessor. Table 1 shows the step-by-step process of the CFD simulation. The pre-processing stage involves setting up the CFD simulation, including defining solid model, gravity, material, boundary conditions, and generating mesh. Solution is where the actual CFD simulation is conducted. The post-processing stage includes analyzing CFD simulation result. The flow field visuals and data extraction can be obtained from this stage.

Table 1: Step-by-step process of the CFD simulation

Pre-processor
1. Define the Solid Model Geometry 2. Select the Element Types 3. Define Gravity Axis and Motion Axis 4. Define Gases and Fluid Types 5. Define Initial Condition and Substance Concentration 6. Global Mesh
Solution
7. Define the Global Goals 8. Select Transient Explorer Parameters 9. Run
Postprocessor
10. Plot, View, and Expert the Results 11. Compare and Verify the Results

2.2 Gravity Axis and Motion Axis

For the simulation, the gravity axis and motion axis must be defined with the appropriate value to produce a result with accurate data. The step-by-step procedure to define gravity and motion axis was as follows:

(i) The gravity of the oil tank must be defined on the y-axis. The value of gravity is -9.81 m2/s as it is constantly pulled by the center of the earth.

(ii) The motion axis, which is the x-axis, is the direction of motion of the oil spill skimmer. The motion was defined as a time variable, as shown in Figure 1. The oil spill skimmer starts from a stationary position. At 2s, the oil spill skimmer begins to move at a speed of 5 m2/s and accelerate uniformly until it reaches 3s. After that, the oil spill skimmer decelerates to 0 m2/s at the 4s. Finally, the oil spill skimmer stops and stays stationary until the 10s.

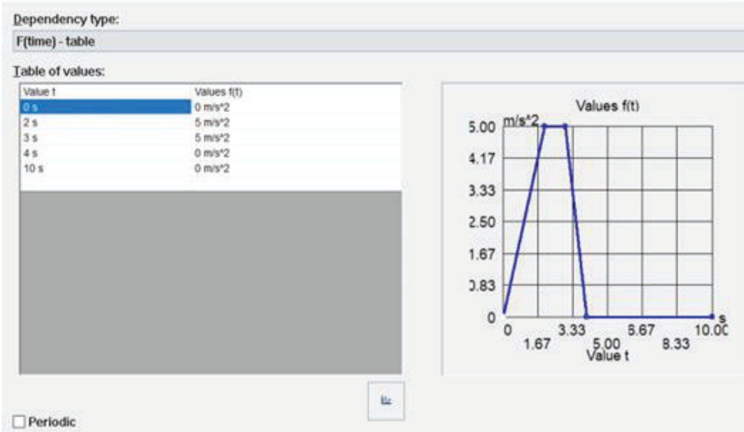


Figure 1: Motion defined in the time variable

2.3 Material Definition

In the gases and fluid types, air and propane are selected as the material in the simulation. Figure 2 shows the selected gases and fluids. The oil tank consists of two main parts: the bottom half is defined as propane (fluid), and the upper half is defined as air (gases). Propane is used as a representative of oil.

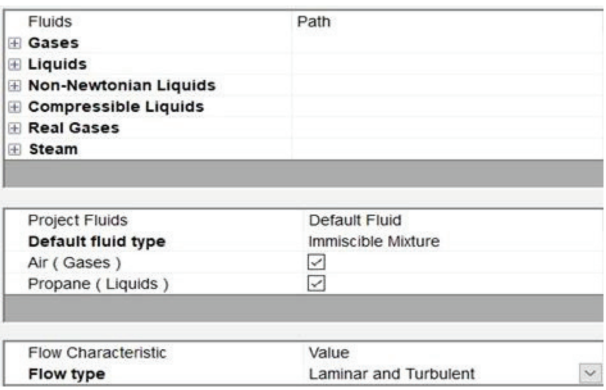
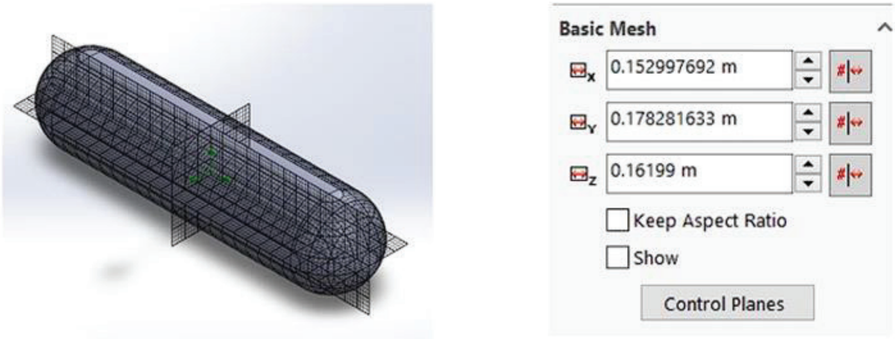


Figure 2: Selected gases and fluids

2.4 Meshing of Geometry

Before running the simulation, meshing must be applied to the design. Meshing is a geometric shape formed over the design to help define the physical shape. The higher the detail of meshing, the higher the data accuracy produced. The parameter set for the meshing in Flow simulation is shown in Figure 3. The higher the meshing refinement, the higher the result accuracy. Figure 3(a) shows the applied mesh on oil tank, meanwhile Figure 3(b) shows the basic mesh.



(a) (b)

Figure 3: (a) Applied mesh on the oil tank, (b) shows the basic mesh of the oil tank

2.5 Material Selection for Skimmer Roller

In order to categorize engineering materials, "groups" such ceramics, metals, natural materials, glasses, polymers, and composites have been created. To determine whether a material is appropriate for a certain product, the initial phase involves gathering information on each material's properties using CES Edu Pack software. The second step was concept screening. If the material is better than the reference, a "+" is given, worse than the reference a "-" is given and similar in reference a "0" is given.

This study analyzed several materials using the screening and scoring method. Polypropylene (PP), stainless steel, polyethylene terephthalate (PET), and polyester (UP) are the materials that were analyzed, as shown in Table 2. All these materials are oleophilic and hydrophobic, which are the main criteria of a skimmer roller. Table 3 shows the screening analysis of the four materials. The screening analysis was conducted to understand and measure the potential of each concept to define the one(s) which should be further progressed in the process. Table 4 shows the concept scoring of the selected material. After specific design concepts have been evolved, concept scoring is used to establish a qualitative hierarchy of design options. The concepts are scored numerically using simple scales relative to a benchmark.

Table 2: Material properties for skimmer roller

Selection Criteria	Polypropylene (PP)	Stainless Steel	Polyethylene terephthalate (PET)	Polyester (UP)
Density (kg/m^3)	890-910	7.61e3-7.83e3	1.29e3-1.39e3	1.04e3-1.4e3
Cost (MYR/kg)	5.61-5.79	12.2-13.	5.32-6.	15.5-17.4
Level of Oleophilic	High	Medium	High	Low
Tensile Strength (MPA)	27.6-41.4	515-1.3e3	51.8-63.	41.4-89.5
Corrosion Resistivity to salt water	High	Low	High	High

Table 3: The screening analysis of the four materials

Selection Criteria	Polypropylene (PP)	Stainless Steel	Polyethylene Terephthalate (PET)	Polyester (UP)
Density	+	-	0	0
Cost	+	0	+	-
Level of Oleophilic	+	0	+	-
Tensile Strength	-	+	0	0
Corrosion Resistivity to salt water	+	-	+	+
Sum of (+)	4	1	3	1
Sum of (0)	0	2	2	2
Sum of (-)	1	2	0	2
Net Score	3	-1	3	-1
Rank	1	3	2	4
Continue	**Yes**	No	**Yes**	No

Table 4: The scoring analysis of the four materials

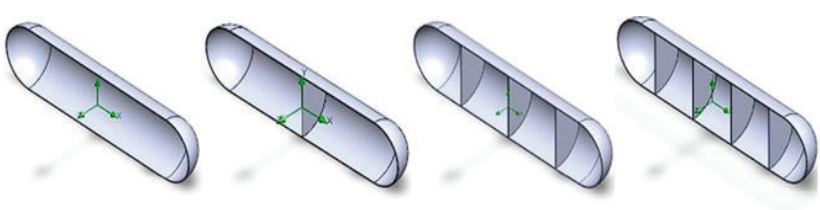
		Polypropylene (PP)		Polyethylene terephthalate (PET)	
Selection Criteria	Weight	Ranking	Weighted Score	Ranking	Weighted Score
Density	20%	4	0.8	2	0.4
Cost	15%	3	0.45	1	0.15
Level of Oleophilic	30%	5	1.5	5	1.5
Tensile Strength	15%	1	0.15	3	0.45
Corrosion Resistivity to salt water	20%	4	0.8	4	0.8
Total Score	100%	3.7		3.3	
Rank		1		2	

The weightage of the selection criteria is based on the user requirement (Table 4). The level of oleophilic is the most important criteria (30%) as the purpose of the skimmer roller is to attract the oil and repel water. Furthermore, the density and corrosion resistivity are weighted as 20% as it has the same importance in order to reduce the weight of the skimmer and to prevent corrosion. In addition, the tensile strength and cost is the least important according to the user requirement. The ranking value of 5 is the most important criteria and 1 is the least important criteria.

Based on the result obtained from the screening and scoring method, Polypropylene (PP) is selected as the best material to be used to develop a skimmer roller (Table 4). Polypropylene (PP) has the lowest density compared to other materials, which is crucial for oil spill skimmer and the cheapest. Stainless steel is not suitable as it possesses the highest density and medium oleophilic level.

3.0 RESULT AND DISCUSSION

The liquid sloshing effect in the oil tank was analyzed using SolidWorks Flow Simulation. The liquid sloshing analysis was conducted by using with and without baffle. A total of four simulations were performed to investigate the importance of implementing a baffle in the oil tank. Figure 4 shows the section view of the oil tank with different conditions. These condition was analyzed to investigate the impact of sloshing on each tank. Thus, the result of each condition was compared and discussed thoroughly.



(a) (b) (c) (d)

Figure 4: Section view of the oil tank with (a) without baffle, (b) one baffle, (c) three baffles and (d) four baffles

3.1 Liquid Sloshing Analysis without Baffle

Figure 5 shows the liquid sloshing effect in the oil tank without using a baffle. The time taken for the sloshing effect begins at 2s and stops at more than 10s. The result shows that the torque value is the highest at 4718.3 Nm (Figure 6(a)). Thus, it creates a pitching and heaving motion which could damage the oil tank's surface. This includes the amount of force exerted when the oil skimmer stops moving. For example, when 4.1 kN of force is exerted on the oil tank, the oil spill skimmer has the tendency to keep moving forward without any command and puts the oil spill skimmer at hazard (Figure 6(b)).

3.2 Liquid Sloshing Analysis with One Baffle

Figure 7 shows the liquid sloshing effect in the oil tank using one baffle. The time taken for the sloshing effect to stop was around 8.416s. The result shows that the torque value is the highest at 1493.4 Nm (Figure 8(a)). Compared to the simulation without a baffle, there is a 68.4% reduction of torque exerted in the oil tank that produces a pitching and heaving effect when implementing one baffle. Thus, it creates a safer environment for the oil tank and oil spill skimmer as compared to the previous simulation. Furthermore, the highest value of the force exerted is 3.8kN which has a 7.32% reduction from the previous simulation. Therefore, less force is exerted on the oil tank when stopping the oil spill skimmer (Figure 8(b)).

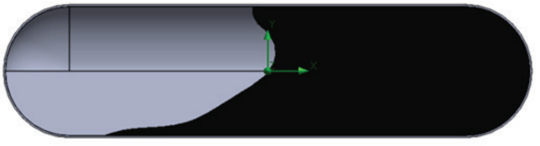
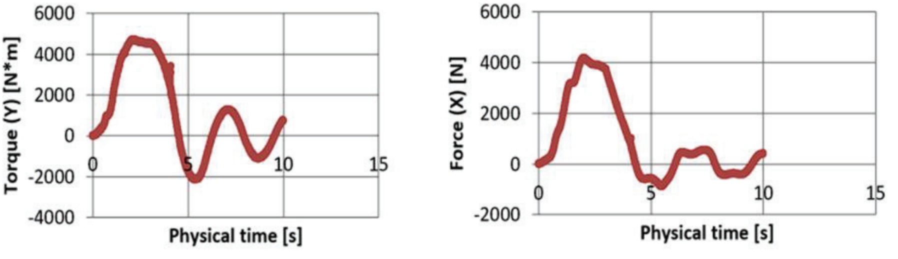


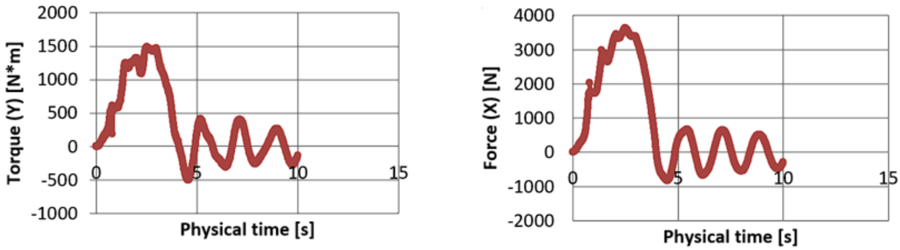
Figure 5: Liquid sloshing effect in the oil tank without using a baffle



(a) (b)

Figure 6: (a) The torque of the sloshing analysis, (b) The x-axis force of the sloshing analysis

Figure 7: Liquid sloshing effect in the oil tank using one baffle



(a) (b)

Figure 8: (a) The torque of the sloshing analysis, (b) The x-axis force of the sloshing analysis

3.3 Liquid Sloshing Analysis with Three Baffle

Figure 9 shows the liquid sloshing effect in the oil tank using three baffles. The sloshing effect starts at the 2s and stops at around 5s. This shows that the baffle helps to stabilize the liquid faster than oil tanks without a baffle. Furthermore, compared to the torque value without and with three baffles, the results show a reduction of 81.12% in torque exertion to the oil tank. The value of torque is 890.78Nm (Figure 10(a)). This proves that implementing several baffles can eliminate the pitching and heaving effect and provide a safer working environment. Moreover, the result shows that the 3.49kN of force exerted on the x-axis was reduced by 14.88% when comparing simulation without baffle. Therefore, lesser force is exerted on the oil tank when stopping the oil spill skimmer (Figure 10(b)).

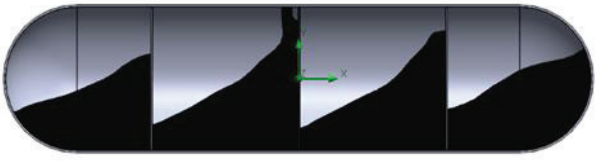
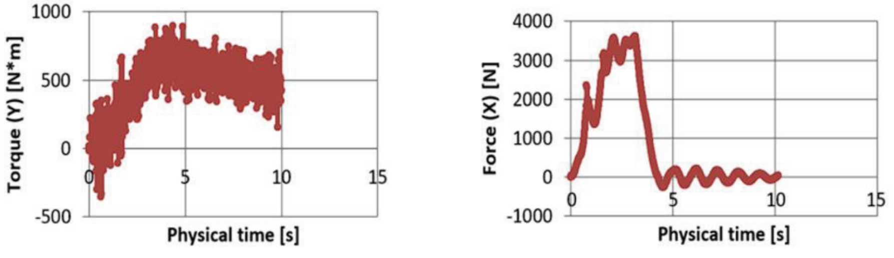


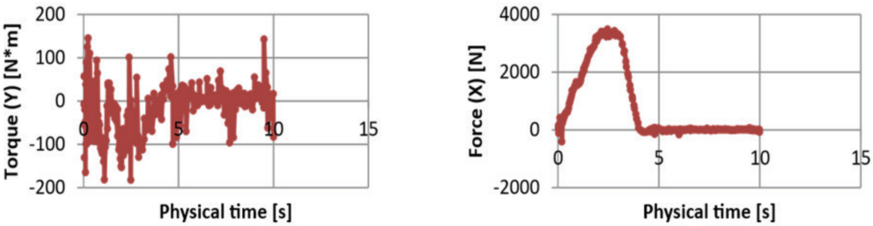
Figure 9: Liquid sloshing effect in the oil tank using one baffle



(a) (b)

Figure 10: (a) The torque of the sloshing analysis, (b) The x-axis force of the sloshing analysis

Another simulation was conducted to identify how many more baffles are needed to further reduce the liquid sloshing effect to the oil tank. Figure 11 shows the simulation result graphs of torque and force. The result shows that designing an oil tank with 4 baffles produces the most significant reduction to the oil tank. The highest torque and force exerted on the oil tank was 145.03Nm and 3486.71N or 3.49kN respectively that is acted upon the oil tank. The reduction of 96.92% in torque compared to an oil tank with no baffles indicates that it is sufficient for the oil tank to be fabricated with only 4 baffles. Despite these research being conducted in different applications; the findings indicate that the implementation of baffle minimizes the liquid sloshing effect accordingly. These findings were strongly supported by several researches conducted in other applications [12], [15], [20]. Moreover, implementing more than four baffles does not add any significant difference since liquid sloshing cannot be eliminated. The force acted on the x-axis has no significant difference when comparing the oil tank with 3 and 4 baffles.



(a) (b)

Figure 11: (a) The torque of the sloshing analysis, (b) The x-axis force of the sloshing analysis

4.0 CONCLUSION

In this research, the analysis of the liquid sloshing effect in the oil tank and the material selection for the skimmer roller were investigated. As a result, it can be concluded that implementing three or more baffles could drastically minimize the torque and the force exerted on the oil tank. Thus, it is important to develop an oil tank with a baffle to minimize the pitching and heaving effect and improve the safety of the oil spill skimmer. The torque and force exerted on the oil tank can be reduced by 97% and 14.88%, respectively, by implementing four baffles. In addition, polypropylene (PP) was selected as the best material for the skimmer roller. It has a high oleophilic level, is lightweight, cost-effective, and has excellent corrosion resistance to salt water.

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AUTHOR CONTRIBUTIONS

R. Ramanathan: Conceptualization, Methodology, Software, Writing-Original Draft Preparation; M.N. Maslan: Data Curation, Validation, Supervision; L. Abdullah: Supervision, Reviewing; M.H.F. Md. Fauadi: Reviewing and Editing; M. Mat Ali: Software, Validation; A.S. Nur Chairat: Writing-Reviewing and Editing.

CONFLICTS OF INTEREST

The manuscript has not been published elsewhere and is not under consideration by other journals. All authors have approved the review, agree with its submission and declare no conflict of interest on the manuscript.

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