DETERMINATION OF THE REMOTION PERCENTAGE OF BARNACLE BIOFOULING FROM MARINE STEEL PLATES USING STEEL BRUSH FOR CLEANING USING A TEST BENCH

Rodrigo Souza Guedes
Federal University of Ouro Preto, Morro do Cruzeiro, Ouro Preto, Brazil
rodrigo.guedes@aluno.ufop.edu.br

Luana Alves do Carmo
Federal University of Ouro Preto, Morro do Cruzeiro, Ouro Preto, Brazil
luana.carmo1@aluno.ufop.edu.br

Philip von Pritzelwitz
Institude of Technology Vale, Morro do Cruzeiro, Ouro Preto, Brazil
philip.pritzelwitz@itv.org

Vinicius Carvalho Teles
Federal University of Ouro Preto, Morro do Cruzeiro, Ouro Preto, Brazil
Vinicius Carvalho Teles

Ana Letícia Pilz de Castro
Federal University of Ouro Preto, Morro do Cruzeiro, Ouro Preto, Brazil
luana.carmo1@aluno.ufop.edu.br

Paulo Henrique Vieira Magalhães
Federal University of Ouro Preto, Morro do Cruzeiro, Ouro Preto, Brazil
paulo.magalhaes@ufop.edu.br

Abstract. Barnacle encrustation in ships has been frequently reported as one of the main causes of the increase in drag force between hull and water. To preserve the hull and to decrease the energetic expense, is common and obligatory to execute periodic hull cleaning . There are several hull cleaning methods, such as manual or mechanical cleanliness, each method has it owns applications and particularities. This work has as its objective, to identify if the tool steel brush is efficient for execute the barnacle fouling cleanliness. First of all the naval carbon steel test plates was submitted to a professional hull painting. Subsequently, the plates were submerged so that barnacle fouling started to grow. Every 30 days, a group of plates was removed, to assess the efficiency of the steel brush at different fouling stages. After these plates were removed, it were all moved to the laboratory, where they were tested at differents rotary speeds. It was possible to determine the percentage of cleanliness, the percentage of paint stripping and the percentage of remaining fouling. The results shows that the steel brush was efficient, removing a great amount fouling of the area where the tool acted.

1. INTRODUCTION

Barnacles are encrusting crustaceans of hard substrates, According to Davis *et al.* (2011), some species have wide geographic distribution, wide environmental tolerance and have been considered as exotic and invasive species across all continents (Farrapeira (2010)). According to Vrouwenvelder *et al.* (2010), the encrusting ability and the shells,combined with planktonic larval dispersal in most species (via ballast water), allows barnacles with adaptive tools to invade and encrust in diverse environments. The barnacle ability to chemically and physically hampers vessel maintenance and therefore, it has generated high costs, including diving team for ship hull cleaning. Thus, the incrustation of barnacles on ships has been frequently reported as one of the main difficulties in reducing friction in the hull of ships (Kim *et al.* (2009)). In the researched literature, there are no data on the efficiency of the different types of tools used for cleaning ship hulls. Therefore, these data are restricted only to companies that perform this type of cleaning and to ship owners. The

purpose of underwater hull cleaning is to remove fouling and regain propulsion efficiency. An added benefit from cleaning anti-fouling coatings is to restore or rejuvenate the effectiveness of the antifouling paint. The underwater cleaning process, therefore, should remove all traces of biological fouling.(Navy (2006))

2. OBJECTIVES

The main objective of this work is to evaluate the efficiency of the steel brush tool for barnacle remotion in ship hulls.

The specific objectives are to determine the best operating speed of the steel brush tool and validate if the built test bench works for this application.

3. THEORICAL FUNDAMENTS

The objective of this review is to consolidate a cluster of information of useful relevance regarding the understanding of current and emerging technologies available for cleaning, and with this, to identify general methodological categories. These categories are the focus for developing test requirements. According to Morrisey and Woods (2015), current cleaning technologies follow two broad approaches:

- Removal of material from the hull (with or more commonly, without waste capture);
- Treatments that kill biofouling organisms "in situ" and rely on the vessel's subsequent movement through the water to remove dead biofouling from the hull.

This work will only address the methods of removing material from the hull.

The categories and subcategories of in-water cleaning methods identified by the review are: manual technologies (remove organisms by hand; cleaning by hand with non-motorized brushes, scrapers and mops), mechanical technologies (motorized brush) .

The simplest technology is manual cleaning, using soft pads, mops, hand scrapers or brushes ("hand technologies"). This is often the primary cleaning method for smaller vessels operating under very different biofouling management regimes than for larger commercial vessels. For the purposes of this study, techniques that remove fouling from the hull using electrical, hydraulic or pneumatic tools are termed "mechanical technologies".

3.1 Manual technologies

Manual technologies involve manual removal of organisms directly. This method has been used, for example, in the management of fouling on ship hulls and fixed structures in ports. As the method relies on divers visually detecting target organisms, effectiveness is influenced by the clarity of the water and the amount of biofouling present.

Hand scrubbing is the most common barnacle removal method for commercial vessels Floerl *et al.* (2010). The types of tools used depend on the amount and type of biofouling and the type of antifouling coating applied. Plastic or metal brushes or scrapers are used for heavier fouling or hard coatings. Manual cleaning can also be used on larger ships to remove fouling from areas that cannot be reached by brush carts, ROVs (Remotely Operated Vehicles) and other larger equipment. Numerous brush manufacturers offer a variety of hand tools as depicted in figure 1.

Figure 1. Examples of manual tools for cleaning ship hulls

3.2 Mechanical Technologies - Motorized Brushes

Traditionally, removal techniques for larger vessels use brushes in contact with the hull surface and/or biofouling layer to remove biofouling. Brush material varies with the type of scale to be removed: nylon or polypropylene for silt, algae and soft organisms; harder plastics, steel brushes or abrasive sponges to remove hard and chalky organisms (Flemming *et al.* (1998)).

Brush-based cleaning ranges from small handheld devices to diver-controlled (but usually self-propelled) brush carts and autonomous remotely operated vehicles (ROVs).

3.2.1 Handheld devices (1)

They are used by divers to clean smaller vessels, confined areas (niche areas) from the hulls of larger ships and to polish propellers. They can be actuated hydraulically (via the support vessel's hydraulic system or via pumped seawater) or pneumatically, and can be equipped with various brush types (eg silicone, polypropylene, nylon or steel), cutting blades or pads abrasives. Some portable devices can be operated manually from the surface of the water, without the need for divers.

3.2.2 Diver-operated brush carts (2)

Diver-operated brush carriages are larger versions of hand-held devices. They usually have a propulsion system that moves them underwater. The diver only has to control the direction of the brush carriage. This is the most used method for larger vessels. Like hand-held devices, brush carriages also vary the brush material according to the material of the ship's hull and the amount of biofouling.

3.2.3 Robot-operated brush carts (3)

They are autonomous devices that attach to the ship's hull through suction created by the flow of water through the cleaning head or by magnets(Iborra *et al.* (2010)). The great advantage of using robot-operated brush carts is that a diver is not required to perform the service, which was not possible with portable devices and diver-operated brush carts.

Usually robot-operated brush cars are remotely controlled in a control room via cameras. They vary in size, ranging from small prototypes to large robots for cleaning industrial ships.

Figure 2 illustrates mechanical hull cleaning technologies. In the left: Handheld devices, in center: diver-operated brush carts, in the right: robot-operated brush carts.
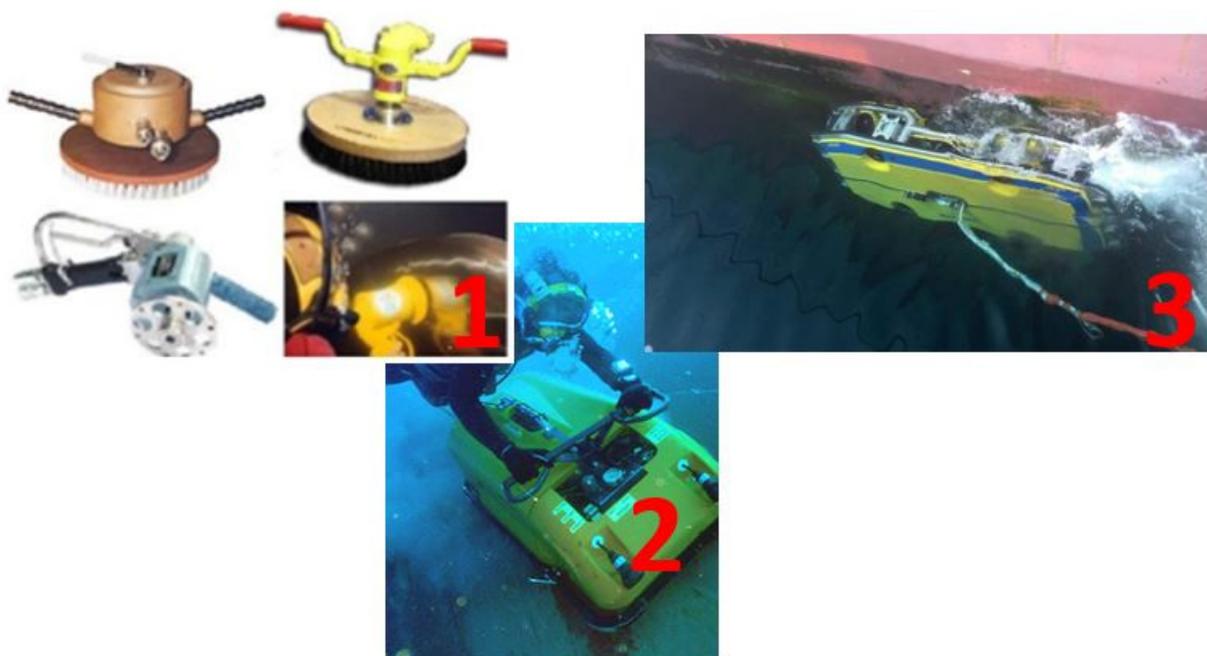

Figure 2. Mechanical tecnologies for ship's hull cleaning

4. MATERIALS AND METHODS

To determine the efficiency of the steel brush, it was necessary to develop the entire environment so that the cleaning of the ship's hull could be simulated. The corresponding steps are described in this section.

4.1 Used tool

The tool that was tested is a steel brush with a diameter of 100mm and a bristle height of 6mm, for cleaning work and removing rust, solder residues, removing paints and other elements present on the surface. According to the brush manufacturer, it is ideal for cleaning flat surfaces, removing paint and oxidation, removing scale and weld spatter, medium and heavy level grinding.

The rotating steel brush used can be seen in figure 3.

Figure 3. Rotary steel brush used in the test

4.2 Test plates submersion preparation

The plates to be encrustated by barnacles were deposited on piers of the Hydrography and Navigation Directorate - DNH, located in Bahia de Guanabara (Niterói, RJ). In biological terms, Guanabara Bay is considered a eutrophic environment, due to the high concentration of nutrients from domestic and industrial effluents. In addition, it is also a highly "aggressive" area in relation to biofouling, due to the high concentration of larvae of these organisms in the water column throughout the year, causing great fixation and growth of them in submerged structures unprotected from antifouling paints . The Admiral Paulo Moreira Studies Institute (IEAPM) was responsible for the submersion of the plates. 29 (twenty nine) plates were submerged for barnacles encrustation. The plates were made of naval carbon steel (ASTM 131), with MSG16 gauge, measuring 25x20cm and 1.5mm thick.

After application of the antifouling paint and identification of the plates, they were placed in stainless steel structures as follows: 8 plates were randomly fixed to each structure. Once installed, the structures were submerged at depths between 1.5 and 2 meters. Thus, the plates were able to receive sufficient light incidence for the growth of algae, which are among the main organisms observed in the incrustations present on the hulls of vessels operating in marine and/or estuarine environments. Figure 4 illustrates what the test plate looked like after being encrustated. In the figure the test plate is ready for the cleaning test.

Every 30 days, a group of plates was removed to assess the tool's efficiency for each level of inlay. The 30-day period was chosen empirically, as it is from this time that the boards begin to reach levels of barnacle encrustation, which it is possible to clean. Four removals were carried out, which made it possible to carry out tests at 4 different biofouling levels. The total submersion time of the plates from the last withdrawal was 131 days.

Figure 4. Structure for submersion of test plates

4.3 Test bench

It is a structure built to test different ship hull cleaning tools. It is basically composed of 1 main motor, responsible for providing rotation to the tool under test. 1 rack motor that has the function of moving the reservoir perpendicularly to the rotating tool. 1 reservoir that has the function of fixing the inlaid plate for testing and storing water for the test to be carried out submerged.

The workbench is operated by a control panel, specially designed for this purpose. The control panel has 2 frequency inverters that vary the speed of the tool and the rack, so that different cleaning conditions are simulated, sometimes with the tool at low speed, sometimes with the tool at high speed, to compare speeds and efficiencies . The test bench also has a data acquisition system where through an analog current signal (4-20mA) it is possible to acquire the tool speed and the tool motor current. Figure 5 shows the cleaning test bench (left) and the control panel (right).
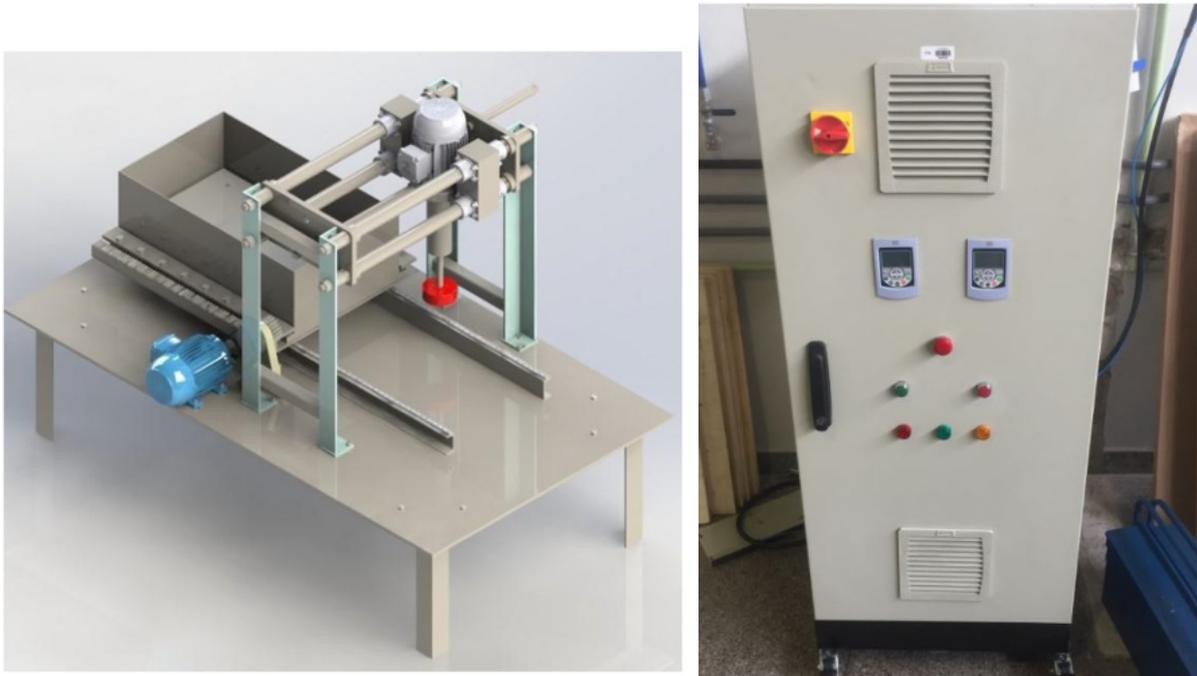
Figure 5. Test bench your control panel

4.4 Cleaning procedure

As illustrated in figure 6, a linear movement with constant velocity is performed along the plate. At the right end the lowest cleaning speed (899 RPM) is performed, at the center range the intermediate speed (1350 RPM) and at the left end the highest test speed (1765 RPM). Afterwards, two more speeds were used: 560 RPM and 1035 RPM, which were tested with the horizontal plate, the right side being the lower speed and the left side the higher speed. The tool passes through the plate only once. Due to the size of the plate and the size of the tool, each plate can be subjected to 3 tests, at 3 different speeds.
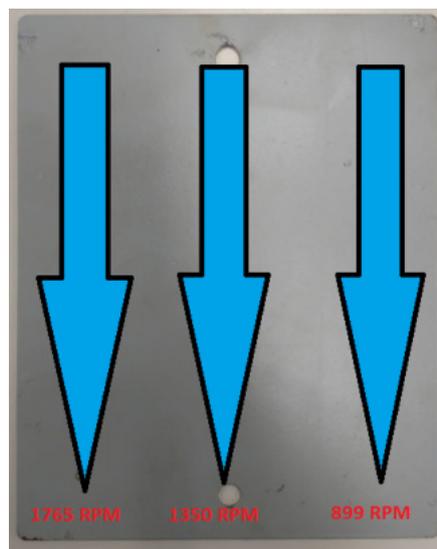

Figure 6. Cleaning Movement x Rotation - Steel Brush

4.5 Tool cleaning efficiency analysis

To define the tool's efficiency and be able to compare them with each other. It was necessary to define:
1. % cleaned (desired);
2. % paint stripping (not desired);
3. % remaining barnacles (not desired);
   To analyze these parameters, the ImageJ software was used. This software identifies the color differences in an

image, resulting in a percentage corresponding to the area of interest color within the total area of the image. able to provide a reliable result regarding the areas of interest. For this reason, it was necessary to prepare the images prior to analysis.

Overall efficiency was calculated by averaging % cleaned surface for all speeds. The overall cleaning efficiency was calculated using the equation below:

$$\frac{\sum\limits_{n=1}^{n=29} x_n}{29}$$

Where, x_n is the % cleaned in test n.

4.5.1 Images preparation

The images preperation was carried out in the graphics software: *Adobe Photoshop* and *Preview App for Mac*. The images received black ink over the other inlays to facilitate their identification by the software *ImageJ*. The bisses were considered as a clean area by the tool and, therefore, were colored with the ink color of the plate. Once prepared, the images were cut in a rectangular format covering the largest possible operating area of the tool and opened in the software. To obtain the percentage, the tool *"Threshold"* was used, adjusting its filter to the maximum position (255) in both adjustment bars. The area obtained in red corresponds to the desired percentage (in this case % of the remaining barnacles), after which the process was repeated to obtain the percentage of the other desired areas of interest. Figure 7 illustrates the process of preparing the image and obtaining the tool's efficiency.
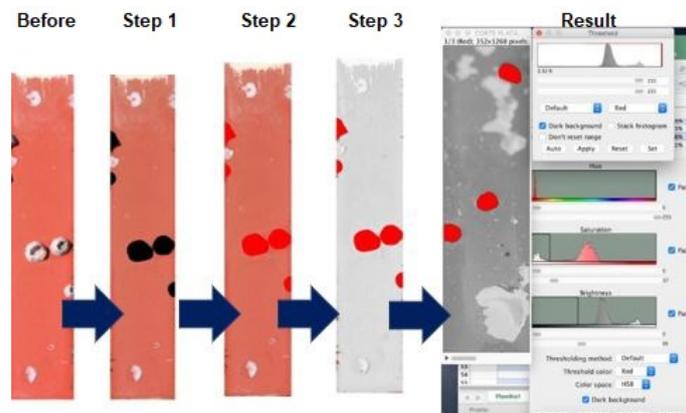

Figure 7. Image treatment process to obtain tool efficiency

5. RESULTS AND DISCUSSION

5.1 Qualitative analysis

Figure 8 represents the cleaning of plates using the steel brush tool. When carrying out a qualitative and visual analysis, it can be seen that, in general, the wire brush was efficient, removing most of the biofouling present in the tool's work area. Analyzing the figure, we see: In the upper left corner - Plate with a good degree of cleanliness, practically all bioincrustations removed, but with a high degree of damage to the paintwork. Damage caused by misalignment on the board. In the upper right corner - Plate with a good degree of cleanliness and with a low degree of damage to the paint, but some barnacles remaining, this was due to the high speed with which the tool moved along the plate. In the lower left corner - Plate with a good degree of cleaning, but with a high degree of damage to the paint, it is observed that the damage to the plate is shaped like the base of the biofoulings and it is concluded that the damage to the paint was caused by the lack of fixing the paint to the plate, not directly by the tool. In the lower right corner - Plate with a high degree of cleanliness and low degree of damage to the paint, it is considered the ideal process, carried out at constant speed and adequate rotation.

Figure 8. Placas após procedimento

5.2 Quantitative analysis

Table 1 presents the data obtained during the 29 tests performed using the steel brush tool.

Table 1. Address map of monitored variables

Test Number	% Cleaned	% Paint stripping	%CRemaining barnacles	Tool	Speed
1	84,39%	4,05%	11,56%	steel brush	560
2	32,85%	60,78%	6,37%	steel brush	560
3	56,59%	43,41%	0,00%	steel brush	560
4	68,29%	31,71%	0,00%	steel brush	560
5	37,61%	59,09%	3,30%	steel brush	560
6	95,23%	2,63%	2,14%	steel brush	899
7	79,06%	18,92%	2,02%	steel brush	899
8	80,94%	11,84%	7,22%	steel brush	899
9	99,53%	0,00%	0,47%	steel brush	899
10	92,51%	2,87%	4,62%	steel brush	1050
11	64,31%	33,08%	2,61%	steel brush	1050
12	74,50%	0,49%	25,01%	steel brush	1050
13	69,85%	30,15%	0,00%	steel brush	1050
14	97,37%	0,00%	2,63%	steel brush	1350
15	88,71%	2,87%	8,42%	steel brush	1350
16	84,54%	2,13%	13,33%	steel brush	1350
17	94,80%	0,00%	5,20%	steel brush	1350
18	25,13%	64,88%	9,99%	steel brush	1350
19	86,32%	6,67%	7,01%	steel brush	1350
20	85,79%	1,44%	12,77%	steel brush	1350
21	12,32%	87,68%	0,00%	steel brush	1350
22	97,16%	0,63%	2,21%	steel brush	1765
23	84,17%	15,83%	0,00%	steel brush	1765
24	69,68%	24,77%	5,55%	steel brush	1765
25	69,80%	17,82%	12,38%	steel brush	1765
26	89,69%	10,02%	0,29%	steel brush	1765
27	61,10%	31,35%	7,55%	steel brush	1765
28	82,12%	7,78%	10,10%	steel brush	1765
29	24,37%	74,78%	0,85%	steel brush	1765

5.2.1 Overall cleaning efficiency

Some tests photos were dark and made it impossible to analyze the software, so there are some speeds with less tests than others. An overall efficiency of 71.77% was obtained. The value is considered sufficient to affirm that the wire brush is efficient for cleaning barnacles on ship's hulls. As further tests are carried out and the optimal operating parameters such as tool speed, applied force, etc. are discovered, paint damage will be avoided and efficiency will increase.

Table 2. Overall cleaning efficiency

% Cleaned	Standard deviation
71,77%	0,24

5.3 Cleaning efficiency by speed

Efficiency by speed was calculated by averaging the % cleaned surface for each speed separately. A graph relating the % cleanliness of each and the speed used is shown in Figure 9:
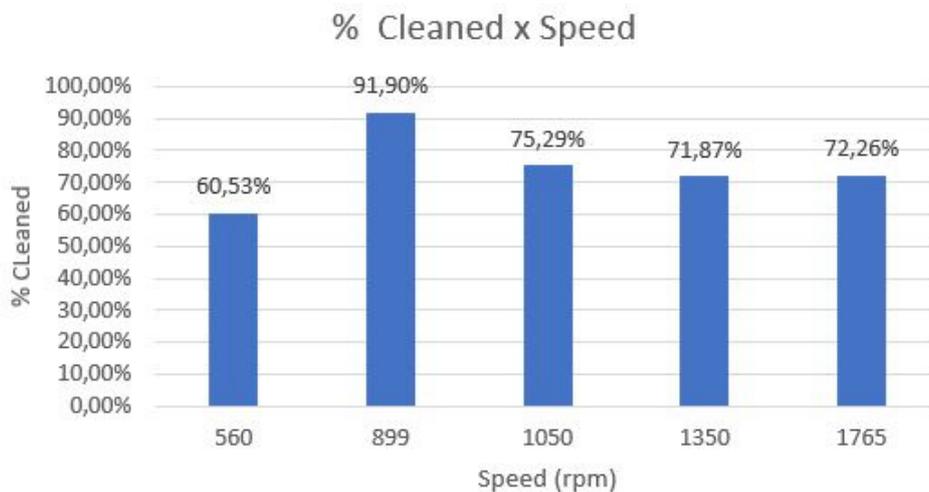

Figure 9. Efficiencies by speed comparison chart

Considering the rotations used: 1765 RPM, 1350 RPM, 1050 RPM, 899 RPM and 560 RPM, it is concluded that both have a good degree of cleanliness and are able to remove all parts of the barnacles, but in most of the tests there was significant paint damage. The rotation with the highest efficiency was 899 RPM with an average % cleaning of 91.9%. Then three speeds had % clean very close, 1050 RPM with % clean average of 75.29 , 1765 with 72.26%. and 1350 RPM achieved an average % clean of 71.87%. The speed that got the worst results was 560 RPM, with % cleaning average of 60.53.

6. CONCLUSIONS

It is concluded that, in general, the higher the rotation speed, the lower the tool efficiency. Thus, it is more advantageous to use lower speeds, but very slow speeds, as was the case in the test at 560 RPM, produce a lot of torque and end up by ripping a larger quantity (more than at higher speeds) of paint, decreasing the efficiency of the tool according to the concepts proposed in this work. It is important to emphasize that regardless of the speed, the tool cannot remain stationary in the same position for more than 5 seconds, as it damages the painting work. Ideally, the movement should be linear and constant.

7. THANKS

8. REFERENCES

Davis, A.R., Targett, N.M., McConnell, O.J. and Young, C.M., 2011. "Epibiosis of Marine Algae and Benthic Invertebrates: Natural Products Chemistry and Other Mechanisms Inhibiting Settlement and Overgrowth". doi: 10.1007/978-3-642-74560-7_4.

Flemming, H.C., Tamachkiarowa, A., Klahre, J. and Schmitt, J., 1998. "Monitoring of fouling and biofouling in technical systems". In *Water Science and Technology*. ISSN 02731223. doi:10.1016/S0273-1223(98)00704-5.

Floerl, O., Peacock, L., Seaward, K. and Inglis, G., 2010. "Review of biosecurity and contaminant risks associated with in-water cleaning. report commissioned by the australia department of agriculture, fisheries and forestry (daff)".

Iborra, A., Pastor, J.A., Alonso, D., Alvarez, B., Ortiz, F.J., Navarro, P.J., Fernández, C. and Suardiaz, J., 2010. "A cost-effective robotic solution for the cleaning of ships' hulls". *Robotica*. ISSN 0263-5747. doi:10.1017/s0263574709005797.

Kim, D., Jung, S., Sohn, J., Kim, H. and Lee, S., 2009. "Biocide application for controlling biofouling of SWRO membranes - an overview". *Desalination*. ISSN 00119164. doi:10.1016/j.desal.2008.01.034.

Morrisey, D. and Woods, C., 2015. "In-water cleaning technologies: Review of information". p. 55.

Navy, U., 2006. "Waterborne underwater hull cleaning of navy ships". *Naval Ships' Technical Manuals*.

Vrouwenvelder, J.S., Kruithof, J.C. and Van Loosdrecht, M.C.M., 2010. "Integrated approach for biofouling control". *Water Science and Technology*. ISSN 02731223. doi:10.2166/wst.2010.747.

9. RESPONSIBILITY NOTICE

The authors are solely responsible for the printed material included in this paper.