

New, efficient and low-cost technology to separate oil from bilge water

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Abstract— The aim of this study is to present a new technology based on the hydrocyclone concept capable of efficiently and cost effectively separating water and oil from bilge water for vessels below 400 GT. Laboratory tests showed that polluted waters treated by EcoBilge present oil levels of less than 1.7 mg/dm³. This signifies a contaminant concentration which is about 9 times lower than that allowed by MARPOL, representing an overall efficiency rate of above 99.9% and with a purchase price of US\$ 700, low maintenance and zero operating costs.

Keywords— Bilge water; hydrocyclone; EcoBilge; low-cost technology, oil-water separation.

Symbols and abbreviations			
g	Gravity(m/s ²)	r	Radius of the hydrocyclone (m);
v	Fluid tangential velocity (m/s)	k	Ratio of continuous phase viscosity to disperse viscosity phase
V	Sedimentation velocity (m/s)	V_L	Velocity (m/s)
R	Oil particle diameter (m)	R_n	Reynolds number
ρ_{water(1)}	Sea water density (kg/m ³)	v	Kinematic viscosity of fluid (m ² /s)
ρ_{water(2)}	Fresh water density (kg/m ³)	UF	Ultrafiltration
ρ_{oil(1)}	Diesel oil (kg/m ³)	INEA	State environmental institute
ρ_{oil(2)}	Lubricant oil (kg/m ³)	SEA	Secretary of State for the Environment
ρ_{oil(3)}	Hydraulic oil (kg/m ³)	FAO	Food and Agriculture Organization
η	Dynamic viscosity of the continuous phase (Pa.s)	UN	United Nations
L	Length (m)	GEF	Global Environment Facility
GT	Gross tonnage	MARPOL	International Convention for the Prevention of
OWS	Oil-water separator		Pollution from Ship

I. INTRODUCTION

Oil pollution is an environmental problem of increasing importance, in this way, the steady growth of ship traffic requires multilevel studies of its environmental effects. Accidental oil spills from tankers and offshore platforms are the most visible source of oil pollution and several studies in the scientific literature relate to their impact [1-3]. However, few studies report

effects of small but continuous oil release from operational activities such as discharge of untreated bilge water. Since over the run of time they can amount to harmful concentrations and in consideration of an increased ship traffic, the study of these small and continuous oil releases and their possible technical solutions is timely.

Bilge water refers to greasy water which accumulates at the lowest part of a vessel. It is a mixture of seawater and different pollutants such as lubricating oil, cleaning diesel oil, and oily sludge deriving from spills from the engine room [4].

Although environmental pollution of these discharges seem insignificant at first sight, their impact is high: Firstly, these boats can size up to 120 feet (40 meters), which should still be considered comparably “big”. Secondly, they have access to nature protected areas, which are especially important for marine life survival. And thirdly, due to a growing population and increasing wealth standards, the existing number of these type of vessels is rising exponentially around the globe.

Of the total seawater pollution by oil, 10% come from bilge waters [5]. However, when in sheltered environments like nature protected areas, the water pollution can be caused 100% from basement waters. The inshore discharge of these bilge waters causes marine pollution. The oil contamination, particularly getting from anthropogenic activities, genuinely endangers marine biodiversity [6].

There are different problems related to the treatment of bilge water. Firstly, the presence of detergents, surfactants or high suspended solids can cause chemical emulsification of oil with the water. Secondly, inadequate oil removal could be expected with gravity or coalesce systems [7-8].

There are several studies describing complex methods for bilge water treatment, which are intended for the use in vessels above 400 GT: hydrocyclones [9-11], ultrafiltration (UF) method [12-13], wet air oxidation [14-15], electrocoagulation [16-17], UF/photocatalytic oxidation [13,18], biotechnology [19-20], and UF/membrane distillation [21-22].

These water separators (OWS) correspond to the regulations in Annex I of the 1973 International Convention for the Prevention of Pollutions from Ships, which was modified by the Protocol of 1978, and which is today known as MARPOL [23]. Amendments to the Annex I [24] refers to the “prevention of pollution by oil and oily waters” and regulation 14 and 15 order the details about “oil filtering systems” and the “control of discharge of oil”. While for vessels above 400 GT these rules are concise¹, for vessels below 400 GT they leave room for interpretation and therefore, in practice, lead to legal

avoidance of compliance. In this case, ships below 400 GT can travel in two ways: either they treat their bilge water with the same systems as those vessels between 400 and 10.000 GT or they can be equipped to retain on board oil or oily mixtures for subsequent discharge to reception facilities. However, nor does a practical way to retain oil on board exist, if not previously separated from the bilge water, nor the control of proper discharge to reception facilities by the Navy.

This ambiguity in regulation and the lack of control of regulation probably lead to the fact that until now there is no demand on market for any no low-cost and effective bilge treatment system for boats below 400 GT. This again might be the reason why literature on OWSs for vessels of this category can hardly be found. The existing oil-water separators (OWS) are for vessels above 400GT (covered by MARPOL [23]) and are very expensive and complex. There is no OWS equipment used for bilge water on the market that is low-cost and efficient in order to allow for the wide marketing of this equipment.

The MARPOL was not the first protocol created to reduce hydrocarbon sea water contamination. Its precursor was the OILPOL 54 Agreement², which was modified and adopted to other agreements, firstly the 1973 Protocol to prevent contamination by ships and secondly the 1978 Protocol (known as MARPOL 73/78). The MARPOL 73/78 has five appendices, which contained rules applicable to various sources of contamination caused by ships. Based on the 1997 protocol, there are currently six sources of contamination considered in this agreement, all referring to vessels above 400GT.

The aim of the present study is therefore to explore the potential of EcoBilge like an OWS that offers a low cost oil treatment system for vessels like tugs, fisher boats, yachts and sailing ships. In contrast to traditional centrifugal OWS, which work less effectively in in a shipboard environment where the motion of the vessel may agitate the oil–water mixture [4], EcoBilge also works well in shaking environments. To the best of the authors’ knowledge, this is the first effective and low-cost technology that makes bilge water treatment for vessels below 400 GT.

¹Vessels between 400 GT and 10.000 GT should use a filtering system which applies a 15ppm maximum oil level (regulation 14.1) and vessels above 10.000 GT should have an additional monitor and alarm system in place [24].

²This agreement was adopted at an international conference organized by the United Kingdom in 1954. It came into force for international community signatories in 1958.

II. MATERIAL AND METHODS

2.1. Problem

In the past few years, petroleum hydrocarbon pollution has become one of the most serious global concerns, due to its toxicity to microorganisms as well as to higher forms of life including humans [25-27]. Whilst operational discharges from ships like bilge pumping have been controlled for vessels above 400 GT, like tankers, those below 400 GT still commonly operate without any treatment system.

Alarming is, that the problem is apparently little discussed by stakeholders. like politicians, environmentalists and scientists, because its symptoms are effectively hidden from public awareness. Since discharging bilge water into the sea is a basic requirement for vessels, but until now no low-cost and effective bilge treatment system is on the market, oily water necessarily is pumped into the sea and creates fine oil layers on the water surface around the vessel. It is by a common practice among seaman of vessels below 400 GT to add detergent to the water surface since this binds oil with water molecules and drowns the oil to the bottom of the sea. Therefore, the problem of untreated bilge water is even doubled: now marine water is not only polluted by oil, but also by detergent, without anyone even noticing.

The drawback of this lack of technological solution and legislative control is twofold. Firstly, even boats below 400 GT can still be quite big, since these can have a size of up to 120 feet and can include tugs which haul cruisers, professional fishing or tourist transportation boats and private sport boats like yachts and sailing ships. Secondly, these boats, in opposition to tankers, have access to and navigate the most sensitive ecosystems, which increases the problematic even more. These ecosystems function as “marine cradles” where biodiversity of the sea has its start and their oil pollution can lead to severe consequences for marine sea life as a whole.

2.2. Technical description

EcoBilge's functioning is based on sedimentation separating oil from bilge water. The equipment has applied for a patent in Brazil on July 14th, 2015, with the filing number: BR 102015016842-0 A2.

In the absence of surfactants, this is the simplest method of separating heterogeneous liquid mixtures, such as water and oil. It is based on the density difference and the solubility of its components and its efficiency depends on a stable unshaking environment. Due to its hermeticity, EcoBilge makes the sedimentation process also possible

in an unstable environment, like the shaking of a boat on seawater.

Water is a polar substance and oil is a nonpolar substance. Therefore they tend not to dissolve well in each other, generating a phase separation which results in a heterogeneous solution. However, there are also substances that possess polar and nonpolar characteristics simultaneously. These can be surfactants like soaps and detergents and they have the property of forming micellar structures.

According to Cao and Li [28], surfactants that combine high viscosity of a polymer with an interfacial property of a conventional surfactant, reduce the tension in oil-water interfaces and enhance the viscosity of an aqueous solution, enabling in turn the solubility of substances with different polarities. In other words, if detergent is added to the bilge, oil and seawater will be dissolved and an effective sedimentation process by EcoBilge is negatively affected.

The basic conception of EcoBilge is a cylindrical tank that induces laminar flow to the fluid that needs sedimentation. A hydrocyclone is generated within the equipment in order to separate oil from water with the aid of gravity. In this case, the denser water goes to the bottom of the EcoBilge tank and the oil rises to the glass dome.

EcoBilge's entrance tube is connected to the vessel's bilge pump and its exit tube is connected to the vessel's hull. At the top, a controller valve allows for the collection of residual oil. The EcoBilge water outlet flow is 20% less than the rated bilge water pump nominal flow due to the increased EcoBilge internal pressure. The fluid is injected centrally into the upper third of the tank via a V-shaped diffuser whose vanes create a hydrocyclone. A perforated plate is installed above the bottom of the equipment and shields the internal entrance of the exit tube from a water flux that only concentrates on the tubes entrance. By this, the water flux is maintained uniform and laminar from the top of the equipment until its bottom.

Cyclones, i.e., stationary mechanical devices that use centrifugal force to separate oil from water, have been extensively used in both heavy and light industrial applications [29-31]. Within the hydrocyclone, the terminal oil flow will be towards the direction of the EcoBilge axis. As the oil approaches the axis, the radius of rotation decreases causing the fluid rotation speed, and consequently the centripetal acceleration, to rise. This increase of terminal velocity results in an overall decrease of sedimentation time.

If sedimentation velocity is greater than the EcoBilge inlet laminar flow velocity, the sedimentation process is efficient. Thus, it is important that the velocity of oil sedimentation in water is quicker than the velocity of laminar flow. The Hadamard-Rybczynski equation [32] is presented in the literature and refers to a liquid-liquid system in which the sedimentation of a drop in a liquid is described. This equation is obtained through the analytical solution of the momentum transfer equations for the inside and outside velocity fields during the settling of an isolated drop [33].

Since the most significant field force that acts in EcoBilge is centrifugal force, the Hadamard-Rybczynski equation remains valid. However, we need to replace the acceleration of gravity (g) with the centripetal acceleration (v^2/r). The resulting velocity of sedimentation is given by Equation 1.

$$V_s = \frac{[R^2 \cdot (\sum_{i=1}^2 \rho_{water(i)} - \sum_{j=1}^3 \rho_{oil(j)}) \cdot (v^2/r)]}{18 \cdot \eta} \cdot \frac{1+k}{1+2/3 \cdot k} \quad (1)$$

Where:

V = sedimentation velocity (m/s);

R = oil particle diameter (m);

$\rho_{water(1)}$ = sea water density (kg/m³);

$\rho_{water(2)}$ = fresh water density (kg/m³);

$\rho_{oil(1)}$ = diesel oil (kg/m³);

$\rho_{oil(2)}$ = lubricant oil (kg/m³);

$\rho_{oil(3)}$ = hydraulic oil (kg/m³);

v = fluid tangential velocity (m/s);

r = radius of the hydrocyclone (m);

η = dynamic viscosity of the continuous phase (Pa.s);

k =

ratio of continuous phase viscosity to disperse viscosity phase .

The velocity of laminar flow generated by the bilge pump within the EcoBilge feed hose is given by Equation 2.

$$V_L = \frac{R_n \cdot v}{L} \quad (2)$$

Where:

V_L = velocity (m/s);

R_n = Reynolds number;

v = kinematic viscosity of fluid (m²/s);

L = length (m).

2.3. Operating Method

EcoBilge comes in four models to operate in different boat and bilge sizes: EcoBilge 30, EcoBilge 50, EcoBilge 100 and EcoBilge 200 (Table 1).

Table 1: Technical specifications of the different EcoBilge models.

Equipment model	Internal volume (L)	Bilge pump flow (GPH)	Inlet and outlet pipe diameter (In)	Sale price (US\$)	Vessel (GT)
EcoBilge 30	30	[600,1000]	3/4"	700	[1,15]
EcoBilge 50	50	[1000,2000]	1"	700	[15,50]
EcoBilge 100	100	[2000,3500]	1 1/2"	Not Available	(50,150)
EcoBilge 200	200	[3500,6000]	2"	Not Available	[150,400]

These models only differ in volume. Their operating protocol and internal geometry remain the same. Figure 1 and 2 display a schematic view of EcoBilge.

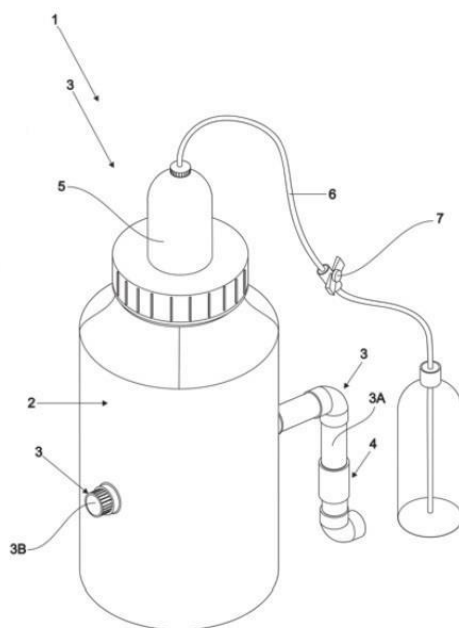


Fig. 1: Perspective view of EcoBilge.

Source: Own elaboration.

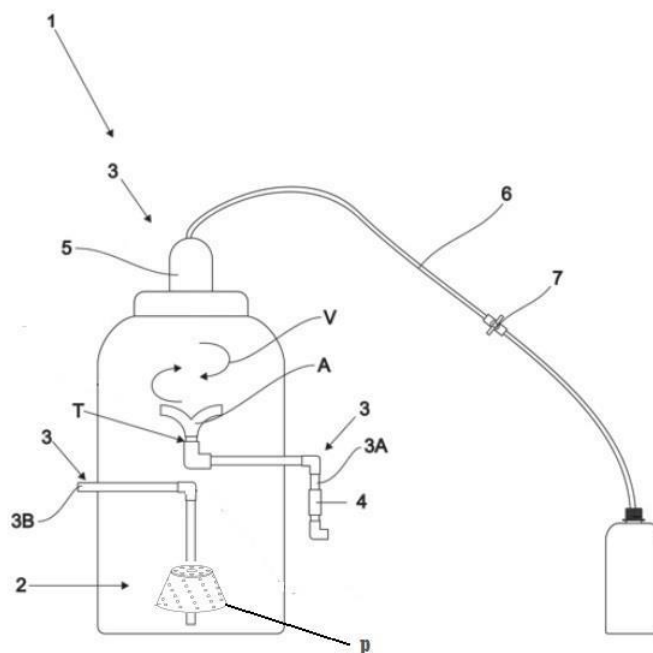


Fig. 2: Schematic sectional view of EcoBilge.

Source: Own elaboration.

Where:

(1) Marine water and oil separating equipment (EcoBilge);

(2) Internal reservoir;

(3) Pipe that connects the pump to the EcoBilge;

(3A) Inlet pipe in the internal reservoir;

(3B) Outlet pipe in the internal reservoir;

(4) Check valve to block return of captured fluid;

(5) Transparent oil accumulator dome;

(6) Transparent dome drain;

(7) Oil drain tap;

(A) Water;

- (P) Perforated plate to improve water distribution in tank;
- (T) Hydrocyclone generated by the diffuser fins;
- (V) Vortex generated by hydrocyclone;

To start the EcoBilge operation, the bilge pump must be activated by the operator as part of the daily routine of the boat. It does not matter if oil is identified in the bilge or not. In case oil particles were in the bilge water, these will accumulate now in the oil accumulation cup of EcoBilge. Since this cup is made out of translucent material, the operator can now identify the oil and is able to retrieve it for proper disposal. Lastly, the treated and clean bilge water is pumped back into the sea.

The operation cost of the equipment is very low due to two reasons. Firstly, its internal set-up is static, so abrasion is low and maintenance on a regular basis is not needed. Secondly, EcoBilge can be operated in a passive form, meaning that no additional bilge pump has to be installed for its operation. However, it was not yet possible to determine its exact life span, since all installed kits are intact since their first operation. The first prototype (Figure 3) was installed five years ago and until today, no maintenance or replacement became necessary nor does it seem to be necessary in the foreseeable future.



Fig. 3: Current EcoBilge prototype

2.4. Laboratory testing

To evaluate the efficiency of EcoBilge, laboratory tests were performed using the methodologies established by the rules indicated in the “Standard Methods for the Examination of Water and Wastewater 22nd ed.

American Public Health Association. USA, 2012 APHA/AWWA/WPCF” [33]. The tests were made by the private laboratory “Qualy Lab. environmental analyzes Co., Ltd.” from Rio de Janeiro, Brazil (certificate number IN027218, INEA³ registration: UN005709/55.11.30). They comply with the same standards that INEA, Brazilian’s State Environmental Institute, requires from treatment systems used by companies that are considered oily water generators (Law n° 6.938 and ordinance n° 3.942)⁴.

Parameter of evaluation was the concentration of oils in the samples. These samples were collected directly from the outside part of EcoBilge’s outlet pipe valve and laboratory tests were performed on the same day. The composition of bilge water entails diesel fuel, lubricating oil, hydraulic oil, NaCl, Na₂SO₄, KCl, MgCl₂ and CaCl₂, as indicated in Table 2.

Table 2: Composition of bilge water.

Parameter	Value
(a) Bilge water composition	
Diesel fuel (mg/ dm ³)	1140
Lubricating oil (mg/ dm ³)	1355
Hydraulic oil (mg/ dm ³)	120
(b) Synthetic seawater composition	
NaCl (g/ dm ³)	21.91
Na ₂ SO ₄ (g/ dm ³)	3.37
KCl (g/ dm ³)	0.73
MgCl ₂ (g/ dm ³)	4.34
CaCl ₂ (g/ dm ³)	1.14

After sample collection, soluble metal soaps needed to be hydrolyzed through acidification. Then the liquid sample goes through a filtration process to separate the oils from solid or viscous grease that is present in the sample. The hydrocarbons separated by filtration are removed through a Soxhlet and a solvent. After evaporation of the solvent the remaining residue will be

³The State Environmental Institute (INEA) was created by the Rio de Janeiro State Government (Law n° 5.101) in October 4th, 2007, under special autarchic regime and linked to the Secretary of State for the Environment (SEA), with the task of implementing environmental policies, water resources and forestry resources adopted by the Executive and Legislative branches of the State.

⁴The document containing the related information about Law n° 6.938 and ordinance n° 3.942, can be accessed at the link: http://www.inea.rj.gov.br/wp-content/uploads/2019/03/baseLegal_4a-edicao_INTERATIVO.pdf (in portuguese).

weighed to determine its oil and grease content. Volatilized compounds at or below 103° C will be lost after filter drying.

According to MARPOL [23], discharge of effluents is acceptable if the amount of oil does not exceed 15 mg/dm³. In laboratory tests regarding EcoBilge's performance the total oil level in the sample was below 1.7 mg/dm³, which represents an efficiency above 99.9% and signifies that contaminant concentration

is approximately 9 times lower than that allowed by MARPOL.

2.5. Case study

Ilha Grande Bay (Main port: Angra dos Reis, State of Rio de Janeiro, Brazil, 23°00'44.06"S/44°26'48.27"W) is the first place where EcoBilge was implemented. With an area of around 3,100 km², the bay comprises many fjords and 189 islands of varying sizes. Local climate is tropical wet [34]. Figure 4 indicates its geographic location.

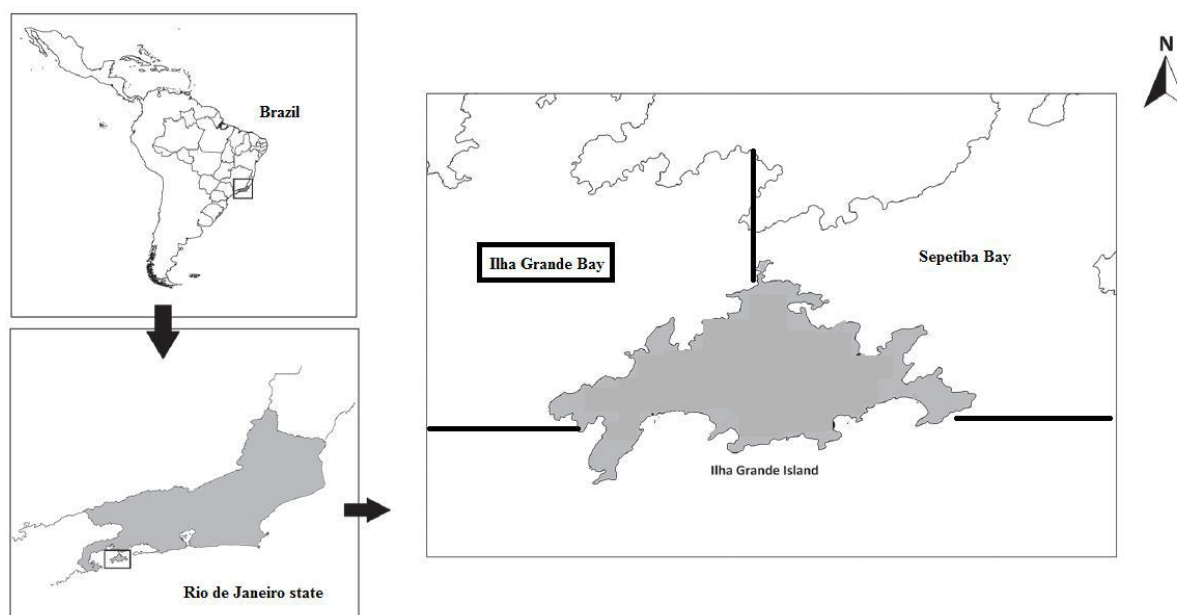


Fig.4: Location of Ilha grande Bay

Source: Adapted from Rocha et al. (2018).

Brazilian Navy declares that Angra dos Reis has about 11.000 registered vessels which are below 400 GT. Five treatment systems have been installed and run successfully in this region since 2015, preventing an estimated total of 26 liters of oil from being spilled into the sea. EcoBilge has the capacity to combat oil spilling of two causes, smaller but chronic oil leakages of motors, and accidental major oil losses. For each of these two situations, the following case studies are presented:

- (a) *Oil leakages of engines: "Sea Quest", a 13 meter sport dive boat with 15 GT.*

In 2015, EcoBilge was installed in the "Sea Quest" which in 2015 presented various sources of oil leakages in the motor, but remained in operation for another six months until the motor could be removed for final reparations. In that time, EcoBilge captured 300 ml of oil per month, totaling 1.8 litres of oil prevented to be spilled into the sea.

- (b) *Accidental major oil losses: "Maravilhosa", a 23 meter schooner with 30 GT.*

This type of pollution is related to one of the most common types of accidents in the boat industry. The "Maravilhosa" schooner, suffered major oil spills during a sightseeing tour on February 15th in 2016. In this accident, the EcoBilge managed to drain 3 liters of oil during the day, preventing it from being spilled into the sea.

III. DISCUSSION

EcoBilge was one out of ten winners of a UN project called BIG 2050 in 2017. This project is the result of a cooperation between the Brazilian Secretariat of State for the Environment (SEA) and the United Nations Food and Agriculture Organization (FAO) and was funded by the Global Environment Facility (GEF). BIG 2050 had the objective of ensuring the conservation and sustainable use of Ilha Grande Bay and its terrestrial and marine biodiversity. In the project's letter of invitation the

problematic of small chronic oil leakages has been explicitly addressed and a public call for innovative solutions has been made.

In sight of traffic of vessels in Ilha Grande Bay and the alarming example of Guanabara Bay's pollution in Rio de Janeiro, which during the Olympic Games 2016 gained major criticism in the international media, key representatives of Angra dos Reis government became concerned about potential problems of oil contamination for their sensitive marine ecosystem. They took action and created the Ordinance Nr. 10912 in 2018, requiring the mandatory use of marine OWS's in boat bilges within the limits of their bay.

In a first stage, the ordinance is targeting only tourist excursion boats with gross tonnage over 20 GT, which signifies a capacity of above 50, but which excludes any other type of vessel that remains below the 400 GT mark. In a second stage, other boat categories will be targeted, with the objective that bilge treatment systems of all vessels below 400GT will be regulated in Ilha Grande Bay in the future.

Although EcoBilge has originally been designed for marine use in bilge water treatment, it is possible to adapt it for usage in the industrial sector, too. For example, the sustainability director of BrasFels, a Brazilian branch of the global leading shipyard Keppel, which was functioning in Angra dos Reis between 2000 and 2018, showed interest in using EcoBilge in 2017 for vessels that are either being repaired or constructed in their facilities [35].

In order to maintain the seawater around the shipyard free from oil pollution, the standard method until February 2018 was to hire a truck that extracts the oily bilge water from these vessels and transport it to a stationary treatment system, where the water is cleaned onshore. BrasFels applies this method once a week, paying approximately 2.250 Dollar per transport, summing up to 9000 Dollar per month. Astonishing is, that this company represents one of the leading marine companies globally, which means, that a simple bilge water treatment system like EcoBilge probably is not known or used in any of their shipyards around the world, and hence most probably also in no other shipyard of its kind. Therefore, using EcoBilge's new method would drastically cheapen operation costs of the shipyard industry as a whole.

In such an industrial environment, a slightly different installation set-up of the equipment would be possible, which would turn EcoBilge even more efficient. In opposition to a navigating boat, in a shipyard an operator is on site that exclusively monitors the water treatment process. In this case, a self-priming pump could

be installed at the exit of the equipment, forcing the system to operate with negative pressure.

The weakness of the proposed technology is that it reduces its efficiency once oil is dissolved in the water, which happens when the bilge water comes into contact with surfactants like detergent. However, this characteristic is common to all water and oil separators that make use of hydrocyclones. For this reason, it is important to avoid any contact of the bilge water with surfactants to guarantee product efficiency.

Nevertheless, the strengths of the equipment outweigh its weaknesses. Firstly, the technology stands out from an economic point of view: both its acquisition and maintenance costs are very low and no added operating expenses are necessary. Secondly, it has a market advantage, since there is no comparable equipment on the market that is equally efficient in treating bilge water in vessels of the targeted range, between 15 and 400 GT.

IV. CONCLUSION

The study showed that the presented technology for marine water and oil separation has a very high efficiency, 9 times lower than the Maximum Concentration Limit described by MARPOL (the content of oil does not exceed 15 mg/dm³). In addition to its attested efficiency, EcoBilge has the support of the UN, SEA, GEF, FAO, INEA and Angra dos Reis City Hall.

A major hindrance to the consolidation of this new technology is the lack of an appropriate legislation, since MARPOL's regulations for vessels below 400 GT do not require the use of OWS's. Although there is an ordinance in the city of Angra dos Reis that suggests the use of EcoBilge or other efficient technology to treat this type of oil discharge, the awareness of this problem in the form of legislation should be broader, encompassing other regions within, and other countries outside of Brazil. Thus, it is essential that stakeholders look more closely at the environmental problems caused by pollution from bilge water of vessels below 400 GT.

Currently, EcoBilge is being refined and other application scenarios for the proposed technology are being studied with the help of Federal Center of Technological Education of Rio de Janeiro (CEFET/Angra dos Reis).

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