Overview on the practical methods of ballast water treatment

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Abstract. This paper showed an overview of the most used ballast water technologies on commercial ships, according to Ballast Water Management Convention adopted by the IMO, in 2004. The Ballast Water Management Convention is applied to all vessels engaged in international voyages that are required to manage their ballast water and sediments to a certain standard, according to a ship – specific ballast water management plan. The aquatic organisms known as invasive or nonindigenous species are introduced into foreign ecosystem by ballast water, causing extensive ecological and economic damages. The approach of this paper is based on the assessment of the management systems ballast water types on board, the factors that influence the treatment systems, the quality of the treatment water as well as the toxicity of the compounds discharged into the environment. Identifying the main ballast water treatment technologies on board commercial ships with their advantages and disadvantages was the main objective of this paper. Nowadays, most of the active substances used during the ballast water treatments are oxidative compounds, that inhibit the spread of invasive species. Furthermore, some treatment systems release in the environment many disinfections by - products that could affect human health and the marine environment at certain concentrations.

1. Introduction

This paper presented an overview of different technologies for ballast water treatment used worldwide, and a thorough research at the most common alternatives.

Ballast water is known as seawater used to maintain the stability and maneuverability of ships when they are being transported without enough weight of loading. Through ballast water a variety of organisms, some of which may be non-native and nuisances in receiving bodies of water are transferred, causing extensive ecological and economic damages. The invasive marine species translocated by ballast water consist of bacteria, protists, dinoflagellate algae, macroalgae, and zooplankton [1, 2]. Spread of non-indigenous organisms caused unwanted economic, ecological and human health impacts [3] that threaten the local ecosystems. Some of these threats could be mentioned: competing with native species for space or food and displacing native species, impacts on aquaculture due to introduced harmful algae blooms, decreasing of the shipping economy and efficiency due to fouling species, human health impacts by introducing of pathogens and toxic species etc. Unlike other forms of pollution (oil spillage), the impact of marine species invasions is irreversible.
To minimize the impact of ballast water on the marine environment, International Maritime Organization has required the adoption of legislative measures, materialized by the Ballast Water Management (BWM) Convention adoption in 2004 and entered in force on 8 September 2017.

The BWM Convention assigned requirements and standards for ballast water management on vessels of any type operating in the aquatic environment, including submersibles, floating craft, floating platforms, floating storage units and floating production, storage and offloading units [4, 5].

The BWM Convention includes two regulations for ballast water management standards to reduce the risk of nonindigenous aquatic organism and pathogen invasions: Regulation D-1 looks at the ballast water exchange (BWE) standard, and Regulation D-2 provides the ballast water performance standard for the discharge of organism from ships. The type approval procedure itself is defined in Regulation D-3 and clarified in IMO technical guidelines. IMO is expected to impose tighter regulation on ballast water discharges, so that the development of more efficient ballast water treatment process is required. Under the Convention, all ships in international traffic are required to manage their ballast water and sediments to a certain standard, according to a ship-specific ballast water management plan. All ships have to carry a ballast water record book and an international ballast water management certificate [6].

BWE is not a completely effective solution to minimize the spread of invasive aquatic organisms and is filled by the ballast water performance standard (BWS). BWS identifies numbers of organisms with various sizes and concentrations of indicator microbes in ballast water that Ballast Water Management Standards are required to achieve prior to discharge. Moreover, all ships are required to implement a Ballast Water and Sediments Management Plan, carry a Ballast Water Record Book, and follow specific ballast water management practices.

These regulations are implemented by IMO through 15 guidelines (G1 – G15) of the BWM Convention, in order to achieve consistency in the approval process.

In accordance with these guidelines, G9 and G10 especially and due to the complexity and multidisciplinary nature of this threat environment within ships ballast water, our paper aims to identify new methods and technologies used on the board ships.

Therefore, G9 is provided as a safeguard for the sustainable use of active substances and preparations for their utilization in BWMS concerning ship safety, human health and the aquatic environment, while G10 is approached to the development of new ballast water treatment technologies [7].

Depending on the geographical area of ship voyage and the physical-chemical characteristics of sea water, as well as the type of organisms that are present, the ballast water treatment technologies on ship board are different.

In order to remove, render harmless, or minimize the uptake or discharge of harmful aquatic organisms and pathogens within ballast water, the ballast water management adopted various mechanical, physical, chemical and biological processes, either on their own or in combination.

2. Ballast water treatment technologies

Over the time, various ballast water treatment technologies have been investigated, including mechanical, physical and chemical removal methods [8, 9, 10].

From the point of view of removal mechanical methods, filtration, dilution, sedimentation and flotation methods, coagulation-flocculation and ballast water exchange in Open Ocean were used. Thermal treatment, cooling treatment, ultraviolet irradiation, Gamma irradiation, ultra-sonics or microwave radiation, rapid pressure changes, de-oxygenation, electrical and magnetic fields are known as physical removal methods and carried out in the ballast water treatments.

Among the chemical removal methods, on the board ship are applied: chlorination or electrochlorination, ozone treatment, advanced electrocatalytic oxidation or pH adjustment. In despite of their advantages, the chemical methods of ballast water treatments have two major issues that need to be addressed. First of all is referred to power consumption that generated high total residual oxidants (TRO) concentration at lower salinities [11]. The second problem is due to ballast water treatments
that used high TRO concentrations, more than 10 ppm, during ballasting procedure in order to kill or suppress the growth of organisms inside ballast tanks [12].

This paper highlighted some of the methods and technologies currently used on board the ship to treat ballast water, according to IMO legislation, with the advantages and disadvantages of each of them.

2.1. Biocides treatment

Biocides treatment (peracetic acid, hydrogen peroxide, chlorine dioxide, monochloramine etc) could also present physical requirements, such as increased corrosion risk or modifications in tank coatings. When sterilization treatment involves active substances (biocides), many authorities require verification of compatibility between the chemicals and the materials used in the ballast and chemical supply piping. Before installing treatment systems with biocides, it is also necessary to check the paints used in the ballast tanks and their effects on anodes.

Moreover, both holding time and total residual oxidants (TRO) should be considered [13]. According to Lloyd's Register (2007), Peraclean or Seakleen are used in three ballast water treatment technologies (Hyde marine, Hamman and DNV Maritime Solutions) [14]. Biocides are usually shipped and stored in the form of a concentrated solid or liquid, so they can easily be stored onboard a ship. Also, the specific type of biocide must be known and chosen very carefully to avoid injury of humans or the marine environment.

Efficiency of the used treatment methods can vary according to conditions in ballast water, such as salinity, pH, temperature, UV transmission and total dissolved substances. Physical-chemical water parameters may limit the capacity of a ballast water treatment system or lead to high energy consumption.

2.2. UV radiation

UV radiation is a physical method used for disinfection of ballast water with minimum UV transmittance at a wavelength of 254 nm [4, 5]. The treatment is applied both ballast water uptake and ballast water discharge (ballasting/de-ballasting operations), consisting of mechanical filtration and UV treatment (fig. 1) [15].

![Figure 1 UV irradiation treatment of ballast water [15]](image-url)

In UV treatment, the cell membranes of microorganisms are disrupted by inducing DNA modifications, killing or making them unviable in ballast water. As disadvantages of this treatment are both high energy costs and inefficient method for waters with high turbidity values [4,5]. Moreover,
this method is inefficient at killing algae in large volumes and UV lamps need to be cleaned periodically [16, 17].

2.3. **Electrochemical oxidation**

Electrochemical oxidation consists in the application of a continuous current to electrodes, with generation of free radicals of hydroxyl (*OH) in the water molecules. Hydroxyl radicals are powerful oxidants that oxidize organic contaminants by destroying cell membranes of bacteria and algae in ballast water. This mechanism is possible due to direct oxidation of hydroxyl radicals from ballast water on anode surface. At electrodes are formed oxidants as chlorine (Cl₂), hypochlorous acid/hypochlorite (HOCl/OCl⁻), hydrogen peroxide/ozone (H₂O₂/O₃) by following reactions:

\[
\begin{align*}
2\text{Cl}^- & \rightarrow \text{Cl}_2 + 2e^- \\
\text{Cl}_2 + \text{H}_2\text{O} & \rightarrow \text{HOCl} + \text{H}^+ + \text{Cl}^- \\
\text{HOCl} & \rightarrow \text{H}^+ + \text{OCl}^- \\
\text{H}_2\text{O} & \rightarrow *\text{OH} + \text{H}^+ + e^- \\
2 *\text{OH} & \rightarrow \text{H}_2\text{O}_2 \\
\text{H}_2\text{O}_2 & \rightarrow \text{O}_2 + 2\text{H}^+ + 2e^- \\
\text{O}_2 + *\text{O} & \rightarrow \text{O}_3
\end{align*}
\]

On the board ship the treatment system is consist of a disk-type filter system (used for mechanical separation to 40 to 45 microns) and an electro-chemical system with electrodes for high oxygen potential that produces powerful disinfectants such as hydroxyl radicals on the electrode surface.

The advantages of this method are: low energy consumption, fast sterilization speed, bacteria are annihilated in one treatment. Moreover, no chemicals or precursor substances are added to the ballast water. This method could be applied to different salinity waters and the chromatic parameters, turbidity, temperature, pH, or water salinity are not affected [5].

2.4. **Electrolytic chlorination**, 

Electro chlorination is the most common chemical disinfection technology used in ballast water treatment systems. Electro chlorination systems usually employ pre-treatment filtration and treat the water once during ballasting (fig. 2).

The seawater is passed through an electrolytic cell, where direct current produces chlorine and hydrogen gases (reactions 8 and 9). The chlorine gas is immediately dissolved in the water to produce the germicides sodium hypochlorite (NaOCl) and bromine hypochlorite (BrOCl), which neutralize microorganisms.

Prior to discharge, it is important to neutralize total residual oxidants (TRO) in the ballast tank, i.e. any residual hypo chlorites that may be present. This is usually done by using treatment with sodium metabisulfite (Na₂S₂O₅) or sodium thiosulfate (Na₂S₂O₃) (reaction 11), in order to stop further reaction.

\[
\begin{align*}
2\text{Cl}^- & \rightarrow \text{Cl}_2 + 2e^- \\
\text{Cl}_2 + \text{H}_2\text{O} & \rightarrow \text{HOCl} + \text{H}^+ + \text{Cl}^- \\
\text{HOCl} & \rightarrow \text{H}^+ + \text{OCl}^- \\
\text{Na}_2\text{S}_2\text{O}_3 + 4\text{HClO} + \text{H}_2\text{O} & \rightarrow 2\text{NaHSO}_4 + 4\text{HCl}
\end{align*}
\]
Figure 2 Electro chlorination of ballast water treatment [19]

Necessity to apply in high-salinity water or the addition of salt, which must be stored on board, in order to be effective in brackish or fresh water, low water temperature that concerns treatment efficiency and a significant power consumption when operating in low-salinity or colder waters are presented as disadvantages of this method. Furthermore, because hydrogen is considered a dangerous gas, safe handling and a special ventilation are required. Cleaning of the electrodes involves acid wash or other external electrode cleaning methods [13].

2.5. Ozon treatment

Ozonation treatment produces ozone by means of either UV light or high-voltage electricity (corona discharge). According to Mitsui technology, ballast water passes through a Venturi throat, which creates a vacuum that pulls the ozone gas into the water [20]. The ozone-treated water is stored in the ballast tank for at least 48 hours to allow for the oxidizing and disinfecting properties of bromate (generated from the reaction of ozone and seawater) to become ineffective. The half-life period of the bromate ion is, on average, 12 hours. The unit then decomposes the oxidants remaining in the ballast water at the time of discharge. The ozone generator contains multiple electrodes which convert a part of oxygen in the gas to ozone. The power supply unit converts the power type from commercial frequency and low voltage to medium frequency and high voltage which is most suitable for ozone generation. A gas/liquid separation unit is employed to prevent ozone that does not react from flowing into the ballast tank [5, 20].

From the chemical point of view, the mechanism could be explained as a result of the oxidation reactions of the ozone and the free hydroxyl radicals formed with the bromide salts of the seawater subjected to treatment.

\[
\begin{align*}
O_3 + Br^- & \rightarrow OBr^- + O_2 & (12) \\
Br^- + H_2O & \rightarrow HOBr + H^+ + 2e^- & (13) \\
Cl^- + H_2O & \rightarrow HOCl + H^+ + 2e^- & (14) \\
HOCl + Br^- & \rightarrow HOBr^- + Cl^- & (15) \\
OCl^- + Br^- & \rightarrow OBr^- + Cl^- & (16)
\end{align*}
\]

Y. Jung et al (2013) showed that seawater contains high levels of bromide ions (Br\(^-\)) which rapidly react with ozone to form a stable oxidant, hypobromite (HOBr/OBr\(^-\)) (reactions 12 and 13) [21]. Seawater electrolysis is also efficient in generating hypochlorite (HOCl/OCI\(^-\)) (reaction 14), a strong
disinfectant, because seawater contains huge amounts of chloride ions (Cl\(^-\)). In seawater, bromide ions are more active and replace those of hypochlorous (reactions 15 and 16) [22].

The advantage of these processes is that oxidants could be generated on board the ship without needing to carry of chemicals. Both hypobromite and hypochlorite are relatively stable and may reside for long periods in darkened ballast tanks, which is advantageous for disinfection control.

3. Implications of using the ballast water technologies on human health

The major amount of ballast water systems uses oxidative substances known as “active substances” on aquatic organisms and pathogens and these generate disinfection by – products (DBPs) in different amounts and concentrations. DBPs are chemical, organic and inorganic substances that could be obtained during a reaction of a disinfectant with naturally present organic matter in the water [23].

The identification of substances, that used in ballast water treatments and which have potential adverse effects, could be pointed out the hazards produced in human health, both ship’s crew and collateral staff, according to G9 requirements [24].

An active substance is defined as “a substance or organism, including a virus or a fungus that has a general or specific action on or against harmful aquatic organisms and pathogens” [24]. By definition, the active substances are the substances responsible of disinfection. The all relevant chemicals are defined as “transformation or reaction products that are produced during or after employment of the ballast water management system in the ballast water or in the receiving environment and that maybe of concern to the ship’s safety, aquatic environment and/or human health” [24]. Hence, for health hazard identification, it is important to identify the disinfection by-products. As a result of the ballast water treatment, obtaining of the disinfection by-product is influenced by the physical-chemical characteristics of the water (pH, temperature), the bromide concentration and the natural organic matter (NOM) content [25, 26, 27].

The bromide content of sea water leads to high concentrations of brominated organic species. Many studies showed that the main DBPs species formed during ballast water treatment were bromoform, dibromochloromethane and di-bromoacetic acid [28, 29, 30]. A study by Herwig et al. (2006) demonstrated that ozone treatment generated bromoform concentrations of up to 145 lg/L but no recoverable bromate [30, 31]. In seawater electrolysis based on disinfection by total residual oxidants (hypobromous acid/hypobromite) the DBPs detected are, among others, trihalomethanes and haloacetic acids [28].

S. Banerji et al., (2012) showed in their study that the ballasting operation can induce to inhalation exposure when the air in the ballast tank, potentially containing toxic gases, is vented [30]. While de – ballasting operation can determine to inhalation exposure from spray drift. Most systems permit the treatment during the ballasting and/or de – ballasting, which can lead to dermal contact and inhalation exposure. Exposure to volatile substances through inhalation can occur during the voyage due to the treated ballast that is stored in the ballast tanks. Maintenance involves tank cleaning (sediment cleaning), tank inspection and type specific work activities, like chemical resupply [30].

Among the risks that could occur during de – ballasting operation are related to exposure of swimmers with treated ballast water, when the beaches bathing areas are located near of harbors with ship traffic. Moreover, if aerosols are generated, the volatile substances could be inhaled or produces.

Another hazard to human health is due to the tendency of some substances that accumulated in the food chain and it can lead to exposure for the people eating these [30]. Therefore, discharging of mutagenic and carcinogenic substances in ocean should be minimized as far as precaution is principle of interested. In order to implement safety measures both health human and marine environment during ballasting and/or de – ballasting operations, these hazards need to be identified.

4. Conclusions

Our paper highlighted the practical realities of ballast water treatments on shipboard, to understand their importance in accordance with IMO legislation.
In selecting a suitable treatment system, the ship type will be the most important measure of choice. For this objective, two groups of ship types are identified: ships with high ballast capacity (tankers and bulkers) and ships with low ballast capacity (containerships, general cargo ships, and cruise ships). It also should be noted that the treatment of ballast water on discharge is very important as well as loading (ballasting/ de – ballasting operations).

The physical-chemical characteristics of water as turbidity, salinity and suspended solids content could influence the efficiency, maintenance or reliability of some treatment technologies. The ship service or trade route may also be important in the treatment system choice. The operating characteristics and requirements of the individual treatment technologies are the second most important set of factors in selecting a proper treatment system, after ship type and service. It is important that the approved ballast water treatment technologies have agreed the IMO D-2 standards.

Analysing the processes of ballast water treatment on the ships, the purpose of this study is to find the best method that would be close to our previous studies. Thereby, the toxicity study of the chitosan solutions at different salinities waters [32] indicates to continue our further studies in the development of ballast water treatment technology on the commercial ships engaged in international voyages, no affecting human health and the environment.

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