

# Analysis of Ballast Water Treatment Technologies on Ships Operating in the Baltic Sea Region

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**Abstract** – The introduction of invasive aquatic species in new environments has been identified as one of the four biggest threats to the world's oceans causing serious threats and harm to both ecology and human health. There is a major exchange of ship's ballast water over longer distances between continents and regional seas, and it has been known for decades that ballast water transfers organisms to new ecosystems, where the strongest, most aggressive and adaptable species can survive and become invasive under favourable conditions. The focus of the research is to study available ballast water control technologies to determine their suitability and effectiveness in the reduction of harmful aquatic organisms and compounds in the Baltic Sea.

**Keywords** – Ballast water, ballast water treatment, Baltic Sea, invasive species.

## I. INTRODUCTION

To ensure the buoyancy, stability and manoeuvrability of ships ballast water is required. As the ships become more technologically advanced and larger, cargo turnover and, consequently, the amount of taken and discharged ballast water increases too. Thus, ship's ballast water and sediments are transferring more harmful organisms [1]. To prevent the spread of such global and environmental problem the International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM 2004) adopted by the International Maritime Organisation (IMO) in 2004 entered into force on September 8, 2017. The aim of BWM 2004 is to govern the process of ballast water exchange and to reduce the risk of invasive aquatic species. On June 20, 2018 the Saeima of the Republic of Latvia passed the law stating that BWM 2004 in Latvia will come into force on January 11, 2019 [2].

Based on the requirements and guidelines stated by BWM 2004, a ballast water and sediment treatment system should be installed on ships by September 8, 2024 latest. In addition, it is important to underline that BWM 2004 does not define specific water treatment technologies. Eventually, shipowners have to make a decision to choose among the technologies that already have stable market position or to choose technology recently introduced to the shipping industry and will eventually take advantage of the obsolete technologies considering the ship specifications, technological solutions, costs and environmentally friendly features [3]. Therefore, the study of evaluation of treatment methods to ship ballast water is relevant.

## II. THE CONTROL AND MANAGEMENT OF SHIP'S BALLAST WATER AND SEDIMENTS

Species are more likely to become established in environments that are similar to those of their origin. The risk of a species introduction is relatively high if the port of loading and the port of

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discharge are ecologically equal. However, if habitats from freshwater and estuarine conditions are transferred to marine areas, the most important factor for species to be introduced is not only the salinity but also climate [4]. Besides, it is estimated that world seaborne trade will increase by 3.8 % in 2018–2023. With total volumes reaching 10.7 billion tons in 2017, it is clear that ballast water intake and discharge will also increase in the future [5]. In order to prevent possible catastrophic consequences caused by harmful aquatic organisms which are introduced by ballast water, the BWM 2004 stipulates two standards for discharged ballast water. The D–1 standard accepts ballast water exchange at least 200 nautical miles from land and at least 200 metres in depth by following methods:

1. sequential – a ballast tank intended for the carriage of ballast water is emptied and then refilled with water to achieve at least a 95 % volumetric exchange;
2. flow-through – replacement ballast water is pumped into a ballast tank intended for the carriage of ballast water, allowing water to flow through overflow or other arrangements;
3. dilution – replacement ballast water is filled through the top of the ballast tank intended for the carriage of ballast water with simultaneous discharge from the bottom at the same flow rate and maintaining a constant level in the tank throughout the ballast exchange operation [6].

The D-2 standard specifies that ships can only discharge ballast water that meets the following criteria:

- < 10 viable organisms per cubic metre which are greater than or equal to 50 micrometres in minimum dimension;
- < 10 viable organisms per millilitre which are between 10 micrometres and 50 micrometres in minimum dimension;
- < 1 colony-forming unit (cfu) per 100 millilitres of Toxicogenic *Vibrio cholerae*;
- < 250 cfu per 100 millilitres of *Escherichia coli* and
- < 100 cfu per 100 millilitres of Intestinal Enterococci [6].

Despite the fact that the Baltic Sea is one of the largest brackish seas, requiring greater species adaptability, besides biodiversity is low because of high salinity for freshwater organisms to live and vice versa, it does not guarantee protection from foreign species [7]. Baltic Marine Environment Protection Commission – Helsinki Commission (HELCOM) and AquaNIS database provides the most comprehensive statistics on the introduction of alien species in the Baltic Sea. The cumulative number of non-indigenous species in the Baltic Sea prior to 1840 to 2016 has reached 132 species of which 61 % are established by shipping and only 39 by other reason than shipping [8].

To perform ballast water exchange Regulation B–4 of IMO G6 Guidelines requires specific depth and distance from the shore as ballast water can only be discharged at least 200 nautical miles from the nearest land and in water at least 200 meters in depth, and if it is not possible – as far as from the nearest land but at least 50 nautical miles from the nearest land and in water at least 200 meters in depth. However, such depth and distance cannot be met anywhere in the Baltic Sea, therefore special areas for water exchange could be designated following the IMO Guidelines G14 [9]. In accordance with Regulation B–4.2 sea areas where the distance from the nearest land or the depth does not meet the parameters, the port State may designate areas where a ship may conduct ballast water exchange [10]. However, HELCOM has concluded that most of the alien species in the Baltic Sea have a wide tolerance in salinity, so it was agreed that ballast water exchange is not a suitable option within the Baltic Sea Region [9], so the only option to comply with BWM 2004 requirements is either port based or shipboard ballast water treatment.

### III. BALLAST WATER TREATMENT TECHNOLOGIES

It is possible to use two main methods to treat ballast water and sediments: physical separation and disinfection. Physical or solid-liquid separation is a process where suspended solid material, in this case the larger suspended microorganisms, are separated from the ballast water, either by

sedimentation when solids settle out by their own weight or by surface filtration when organisms are removed by virtue of the pores in the filtering material being smaller than the size of the particle itself [3]. In the systems already produced on the first stage of mechanical particles' removal filters are designed as pre-treatment to remove organisms and organic particles of more than 50  $\mu\text{m}$ . Significant benefit of filter is the reduction of sediment which can interfere with treatment, e.g., by reducing optical transmission in UV treatment afterwards. Filters used in second stage for mechanical ballast water treatment are commonly rated with a nominal pore size in the range more than 10  $\mu\text{m}$  and up to 50  $\mu\text{m}$  [11]. Hydrocyclone filters on the other hand are hydro-dynamically designed creating centrifugal forces generated by cyclonic flow to separate particles that are denser than water and do not provide a mechanical barrier to stop particles. Hydrocyclones have been used on ballast water treatment systems, but not commonly [3].

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Since both the hydrocyclone and filters are more effective for larger particles to increase the efficiency of the methods, pre-treatment with coagulant can be used before these processes, allowing the water-soluble substance as well as the colloidal particles to be lowered in principle, and the particles collected. Iron or aluminium salts (chlorides, sulphates) are used as coagulants. Aluminium sulphate  $\text{Al}_2(\text{SO}_4)_3 \times 18 \text{H}_2\text{O}$  can be considered as the most commonly used coagulant. When this substance enters the water, an aluminium ion hydrolysis process occurs, resulting in the formation of aluminium hydroxides and its polymers. These substances are poorly soluble and the hydrolysis process consists of a flocculent precipitate – flocculates [12].

Disinfection removes and/or inactivates micro-organisms in two ways. Oxidising biocides are general disinfectants which act by destroying organic structures, such as cell membranes or nucleic acids but non-oxidising biocides interfere with reproductive, neural, or metabolic functions of the organisms. For the destruction of organisms with non-oxidizing biocides, only menadione and vitamin K and its derivatives are used as they produce toxic by-products. Although they are often used in catfish farming and produced synthetically for commercial use, they are also relatively safe to store. For ballast water treatment with oxidising biocide mainly chlorination, electrolysis, ozonation and other methods are used [3].

Electrolysis is based on the partial electrolysis of NaCl which is present in seawater. Seawater flowing through an unseparated electrolytic cell and exiting it creates a mixture of seawater, sodium hypochlorite, hydrogen gas, and hypochlorous acid. Electrolysis of sodium chloride solution (seawater in this case) is the passage of direct current between an anode and a cathode to separate salt and water into their basic elements. Chlorine generated at the anode immediately forms sodium hypochlorite and hypochlorous acid – the water disinfectants [12].

Ozone is considered as more effective disinfectant than chlorine. For disinfection of water, ozone is obtained by injecting clean and cool air in the electric discharge area. The ozone-enriched air is then injected into the water to be cleaned. Both ozonation and electrolysis produce significant oxidizers such as bromine (hypobromic acid and hypobromite,  $\text{HOBr} / \text{OBr}^-$ ) and chlorine (hypochlorous acid and hypochlorite,  $\text{HOCl} / \text{OCl}^-$ ), which are active as a destroyer of organisms. The main drawback of ozonation is that this technology is significantly more expensive than chlorination of water [13].

Hydrodynamic cavitation as physical and chemical effect method is based on creation of high temperature and pressure shock waves in combination with generation of highly reactive hydroxyl radicals. Shock waves cleavage the molecular bonds as well. As a result, the free radicals oxidize into organic pollutants, extreme temperatures or hot spots can also create pyrolysis of the molecules if they are in the vicinity of the collapsing cavity [14].

It has been proved that light is not only able to disinfect and detoxify, but also to speed up the process with a catalyst or semiconductor called photocatalysis. Photocatalysis is a chemical reaction

induced by absorption light by a photocatalyst. With solid photocatalyst, the reaction is activated by absorption of a photon with sufficient energy, i.e. equal or higher than the band-gap energy of the photocatalysts. Various semiconductors such as  $\text{TiO}_2$ ,  $\text{CdO}$ ,  $\text{ZnO}$ ,  $\text{WO}_3$ ,  $\text{CdS}$ ,  $\text{CdSe}$ ,  $\text{GaP}$ ,  $\text{GaAs}$ ,  $\text{ZnS}$ ,  $\text{SnO}_2$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{SrTiO}_3$ ,  $\text{BaTiO}_3$  etc, have been used as photocatalysts. Generally, the best photocatalytic performances are obtained with titanium dioxide as catalyst [15]. Materials used for photocatalysis cannot be toxic, they have to be stable and they must be integrated in thin films to avoid secondary pollution. Pristine  $\text{TiO}_2$  is almost the single material occupying 95 % from 1 billion market of photocatalysis. To activate  $\text{TiO}_2$ , UV light is used, and sunlight contains only 4 % UV.  $\alpha\text{-Fe}_2\text{O}_3/\text{Ca}_2\text{Fe}_2\text{O}_5$  photocatalyst system provides the same oxidation power as  $\text{TiO}_2$  to destroy persistent organic pollution, but our system can be driven by visible light (sunlight) [16], therefore it can be potential disinfectant in ballast water treatment.

#### IV. ANALYSIS OF ASPECTS AFFECTING THE EFFICIENCY OF BALLAST WATER TREATMENT

For shipowners the choice of ballast water and sediment control technology and later the choice of the system is a critical decision, often not fully assessed and in fact based on an assessment of complex factors as they mainly rely on economic grounds. Before considering any treatment method and technology, it is necessary to evaluate the key factors of water quality. The water pumped into a ship's ballast water tanks can vary considerably, and consequently will affect separate ballast water treatment systems in different ways. Specific water characteristics may limit a system's ability to comply in this situation, for example, can lead to consumption of more power. Four water characteristics are particularly important: salinity, temperature, ultraviolet transmittance and pH.

Most ports are exposed to river run-off, which means their average salinity levels are generally lower than that of ocean water and can be impacted by temperature, climate, season and other factors. [17]. Since bromine and chlorine compounds are formed in the ozonation process, the salinity of the water also affects the efficiency of this system. Ozone in saline water decomposes faster than in fresh water, for example, if the salinity is 32 practical salinity units (PSU), then with 2 ppm ozone, it decomposes in 30 seconds, but if the salinity is only 5 PSU, then in 180 seconds, while cavitation, deoxygenation and UV irradiation are those methods that are not affected by salinity [18].

Surface water is warmed by solar radiation decreasing in distance from the equator meaning that the warmest water is located closer to the equator, while the coldest water is found at the poles. This effects on board disinfection because lower water temperatures exponentially increase the amount of energy needed to produce the hypochlorite disinfectant. Optimal water temperature for successful treatment is above 15 °C, with normal low-end temperatures in the range between 10 °C and 17 °C. Water below 10 °C significantly reduces the formation of chlorine, which means preheating is needed to ensure effective compliance of ballast water treatment [17].

Not only UV transmittance but also turbidity impact on treatment process. Dissolved matter in the water causes light intensity to decrease exponentially with distance from the source. While UV transmittance in seawater is generally high, it tends to be lower in coastal waters where it can range from 90 % down to 60 % but can sometimes fall to even 50 % [17].

In ballast water purification systems using chlorination, the efficacy is determined by the pH or temperature of the hydrogen ion concentration. Neutral pH (6.5 to 7.5) produces the maximum amount of hypochlorous acid, but if the pH of the water is too low (pH < 6.0), chlorine will be released as gas, reducing efficiency and increasing corrosion of the machine. If chlorine is added to alkaline water (pH > 8.5), the amount of hypochlorous acid will decrease significantly and the water will not be disinfected. If the pH is too low, water can be buffered with lime ( $\text{CaO}$ ). If the pH is too high, it can be reduced with sulphuric acid ( $\text{H}_2\text{SO}_4$ ). It follows from the above that pH affects the systems undergoing chemical disinfection – chlorination, electrolysis, ozonation and coagulation, and flocculation, while UV irradiation, cavitation and deoxygenation have no effect on pH [18].

## V. CONCLUSIONS

Despite the fact that the Baltic Sea is a saltwater sea with low biodiversity, it is not protected from alien species, as it has been established that the number of alien species introduced as a result of shipping has already reached 132 species, one of the largest indicators of the world's seas. As the requirements of D-1 can only be met in the Baltic Sea in a relatively small area, a transitional period is required under D-2 for the installation of a ballast water and sediment treatment plan, which is an inevitable step to comply with the conventional rules. To achieve the best results the most appropriate system for control of ballast water and sediment includes four combined treatment methods, namely:

1. Filtration by mechanical sieve for removal of larger objects and organisms;
2. Coagulation and flocculation for faster settling of larger organisms and particles in the lower layers of water;
3. Filtration using a membrane filter to remove organisms and particles larger than 50 µm;
4. UV irradiation as disinfection method to destroy the remaining living organisms.

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