ZIBELINE INTERNATIONAL™ PUBLISHING
ISSN: 2523-5664 (Print)
ISSN: 2523-5672 (Online)
CODEN: WCMABD

Water Conservation & Management (WCM)

DOI: http://doi.org/10.26480/wcm.01.2021.53.59

CrossMark

RESEARCH ARTICLE

A STUDY ON SELECTION OF BALLAST WATER TREATMENT TECHNOLOGIES TO MEET BWM 2004 CONVENTION

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ARTICLE DETAILS

Article History:

Received 05 Octrober 2021
Accepted 17 November 2021
Available online 21 November 2021

ABSTRACT

Ballast water is essential for ship operation. However, it also carries potential risks of contamination and disease transmission. The Ballast Water Management Convention (BWMC) was introduced by the International Maritime Organization (IMO) to minimize the transfer of pathogenic microorganisms to ecologically sensitive marine areas, through ballast of ocean-going ships. Therefore, thorough research and analysis of ballast water treatment technologies are essential. This paper summarizes the existing technologies applied for ballast water treatment. These technologies can be port-based or ship-based, with the latter being easier to implement. Particular attention is given to onboard processing methods, which can be classified as physical separation, mechanical or chemical methods. This work describes recent ballast water treatment studies from the scientific and academic communities since the last IMO Convention in 2004, and the treatment methods that have been approved by the IMO substantially and ultimately. We have examined the various methods currently available in scientific means for ballast water treatment and we conclude that standardization of ballast water treatment still has to be done to ensure IMO Standards.

KEYWORDS

Ballast water treatment, Ballast water management, Marine environment, IMO.

1. INTRODUCTION

Economic globalization is an inevitable trend, covering most fields and attracting many countries to participate (Zaucha and Kreiner, 2021; Hoang et al., 2021). In the process of integrating into the world economy, many complex issues are raised, including the field of marine environmental protection (Vo et al., 2021). The transportation of the international shipping fleet is considered the main source of pollution for the marine environment (Karim, 2016; Chu, 2020). Especially in the context of the ongoing Covid-19 pandemic, which has a lot to do with global climate change (Thomas, 2021; Hoang et al., 2021; Olcer et al., 2021). The first threat comes from oil spills due to marine accidents; a few tens to hundreds of tons of oil are poured into the sea from these accidents (Bui and Pham, 2018). Oil spills pollute the marine environment, seriously affecting ecosystems (Nizetic et al., 2021). To deal with oil spills, many different methods can be applied such as (1) Physical methods (recovery by floating buoys (booms) and skimmers), recover oil by using specialized equipment for collecting contaminated material or using absorbent materials); (2) Chemical method (dispersing oil at sea by chemical substances (dispersants, surfactants, coagulants...), burning in place or moving to another location for treatment); (3) biological method (using microbial products that stimulate the growth and development of some oil-degrading microorganisms, the hydrocarbon source of the oil will be used as the sole carbon source, or hydrocarbon degradation products of microorganisms as a source of substrates for the growth of other microorganisms) (Hoang et al., 2018; Hoang and Pham, 2018; Chau, 2018; Tawaha et al., 2018; Huynh et al., 2021).

The second threat comes from emissions from the engines of the ships (Pham and Hoang, 2019). Marine transportations are one of the man-made sources that contribute significantly to air pollution (Pham and Hoang, 2020). According to US government statistics, ships are the main reason responsible for two-thirds of SO_2 emissions in the transportation industry in 2002, the lack of control measures will cause this rate to reach 98% by 2020 (Chau et al., 2020; Cao and Pham, 2019). Diesel engines, especially large marine diesel engines, using low-quality fuel with high sulfur content, when burning with air in the combustion chamber, will create different burning products (Nizetic et al., 2021; Nguyen and Duong, 2020). Due to the serious impact of diesel engine exhaust on human health and many adverse impacts on the living environment, the World Maritime Organization (IMO) has introduced mandatory standards in MARPOL's Annex VI 73/78, revised in 2008, 2010 in order to regulate the content of hazardous substances in the exhaust gases of diesel engine (As, 2009; Tran and Le, 2020; Doan et al., 2021). To meet the requirements of Annex VI, ships can apply the following two methods: (1) Primary method: Direct impact on the combustion space and engine combustion, so the new technologies are developed and applied to improve combustion; (2) Secondary method: impact on exhaust gas (gas after combustion) and technologies applied to treat exhaust gas (Murugesan, 2021; Nayak et al., 2022; Nizetic et al., 2020; Truong et al., 2021; Nizetic et al., 2021; Tran et al., 2020; Al-Tawaha et al., 2019).

With about 90% of global cargo transported by sea, lead to the increased volume of ballast water released into the environment has led to the rising in alien organisms in oceans around the world (Li et al., 2021). To prevent

Quick Response Code	Access this article online	
	Website: www.watconman.org	**DOI:** 10.26480/wcm.01.2021.53.59

Cite The Article: T. H Nguyen, T. H Le, V. V Le, T. M. H Dong (2021). A Study on Selection of Ballast Water Treatment Technologies to Meet BWM 2004 Convention. *Water Conservation & Management, 5(1): 53-59.*

the entry of alien organisms in the ballast water environment transported by ships from other sea areas, affecting the ecosystem, economy, human health and enhancing environmental protection measures, in the maritime domain, IMO ratified the BWM Convention on February 13, 2004, and the Convention met the conditions to enter into force on September 8, 2017 (Outinen, 2021; Nguyen, 2020). Until now, 63 countries with fleets accounting for 68.51% of the world's total tonnage have joined the 2004 BWM Convention. It is a real challenge for shipowners in terms of implementing treatment systems of ballast water management to ensure compliance with the BWM convention 2004 (Nguyen et al., 2021; David et al., 2015).

BWM Convention 2004 stipulates the responsibilities and obligations of member countries in management, of shipowners in controlling and equipping management equipment as well as providing specific indicators on standards of ballast water, is allowed to be discharged into the sea (number and size of marine organisms, plankton, bacteria) ... to protect and ensure ecological and economic safety for living sea species; as well as to not affect or cause damage to its environment, human health, property or other resources of own country or other countries (Lakshmi et al., 2021; Nguyen, 2020). The Ballast Water Management Convention ratified by IMO in 2004 sets out two standards for the treatment and discharge of ballast water on ships, D1 and D2. Standard D1 is for ballast water exchange and specifies the volume of water to be replaced. Standard D2 is used as a reference for the approval of ballast water treatment systems and specifies the level of viable biological organisms remaining in ballast water after it has been treated (Lakshmi et al., 2021; Do et al., 2020). According to the provisions of the BWM Convention 2004, from September 8, 2017, all new ships built (after September 8, 2017) must be equipped with a ballast water management system (Standard D2), ship built before September 8, 2017, can comply with the Convention by implementing a ballast water exchange (Standard D1) or can equip a ballast water management system if desired (Le et al., 2020). However, ships built before September 8, 2017, must be converted to a ballast water management system (Standard D2) after the first renewal inspection of the IOPP certificate after September 8, 2019. By September 8, 2024, all ships are required to use a ballast water management system (D2) (Nguyen et al., 2021; Hassan and El Nemr, 2021).

Ballast water exchange is the replacement of ballast water taken at a port or at the coast where the voyage begins with seawater taken from a far distance (Tran et al., 2021). This process will reduce the risk of organisms being transported to other seas because deep seawater is usually less living organism, and these organisms are often difficult to live in a harbor or coastal environment when they are released to the ocean from ballast water chamber. According to standard D1 of the IMO Ballast Water Management Convention, each ship must replace at least 95% of its ballast water (Ivce et al., 2021). If the ballast water exchange is effectuated by pumping through the ballast water chamber, the ballast water mass is to be pumped through each space at least three times (Tham et al., 2019). Since the exchange of ballast water at sea is subject to weather and sea conditions, therefore, exchange of ballast water is not always possible (Baroiu et al., 2021; Chau et al., 2020). Furthermore, this exchange still has the potential for marine species to remain in the water and can still be harmful if the vessel is draining near shore, especially if the holds are clogged with mud (Van and Anh, 2021). The exchange of ballast water can also make the ship's balance and stability worse (Hyun, 2021; Trinh et al., 2020).

Ballast water exchange in the sea is not considered an ideal method of ballast water management, so efforts are focused on developing methods to treat ballast water. These methods must comply with standard D2 of the IMO Ballast Water Management Convention. Standard D2 states that the treatment and discharge of ballast water should leave only: (1) less than ten organisms 50 micrometers or larger can survive in at least one cubic meter of water; (2) less than ten organisms 50 micrometers or smaller in size and more than or equal to 10 micrometers in at least one cube milliliter of water (Chen et al., 2021; Sayinli et al., 2021). The solutions considered for ballast water treatment today include mechanical, physical, and chemical methods. Each method has different characteristics and features, depending on the evaluation and selection aspects and criteria. Understanding the characteristics of different ballast water treatment technologies will help shipowners make good decisions about choosing the optimal treatment technology (Yondri et al., 2019). The objective of this paper is to present an appropriate selection method for the evaluation, analysis, and comparison between different ballast water treatment technology systems to make a good decision on choosing the most optimal treatment system (Pham, 2019). The best-worst method is used in this work. The evaluation of the objective and subjective weights of the measurement criteria for the effectiveness and convenience of the technology as well as the measures for the combined environmental and ecological impacts has been evaluated to determine the most optimal technology solution.

2. Materials and Methods

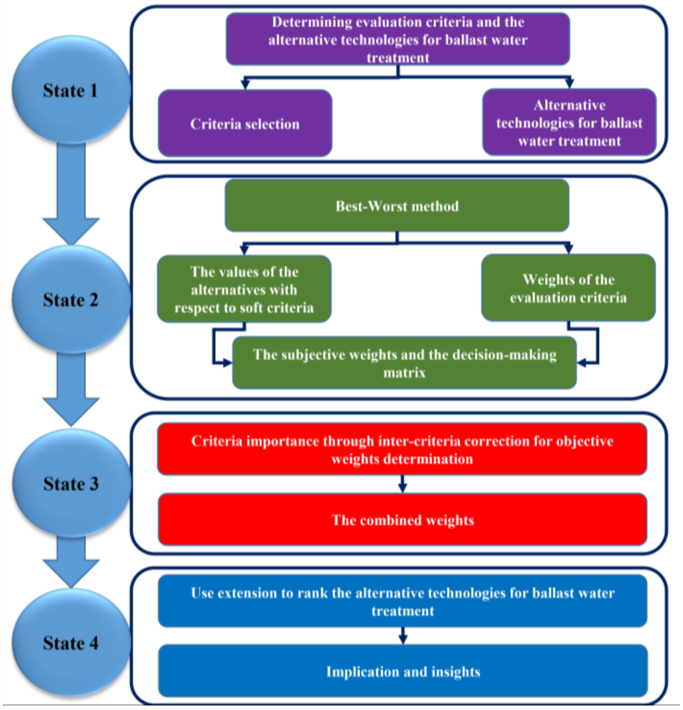


Figure 1: Process of selecting ballast water treatment technology

The process of selecting the best ballast water treatment technology is shown in Figure 1. The process consists of four stages: (1) State 1: determine alternative technologies for ballast water treatment and evaluation criteria. price; (2) State 2: Use the Best-Worst method to determine the relative values of alternative technologies for ballast water treatment for each evaluation criterion and the subjective weight of evaluation criteria; (3) State 3: Using the importance of the criteria through the correlation method between the criteria to find out the subjective weight of the evaluation criteria; (4) State 4: Determine the class of each ballast water treatment technology and rank these technologies.

The weighting methods are underpinned by the criteria importance method through the correlation between the criteria and the best method. In which, the combination of standard deviation and correlation is presented through steps such as normalizing the data, calculating the standard derivative and correlation, and determining the weight of the indicators. Additionally, the best method is described through four steps including determining the best thing, determining the Best-to-Others vector, determining the Others-to-Worst vector, and optimizing the weights of all the criteria. The criteria for selecting a ballast water treatment system consist of capacity, size, equipment volume, and energy consumption.

3. Results and Discussion

3.1 Ballast water treatment methods for meeting the demand of BWM convention 2004

Chemicals can be used to treat ballast water, to prevent the invasion of foreign organisms. The used chemicals must be carefully selected to avoid danger to humans and the environment. There are two types of treatment chemicals used: oxidizing and non-oxidizing (Chong et al., 2021). Oxidizing chemicals are normally used including chlorine, bromine, and iodine (Chu et al., 2021). These chemicals can destroy cell membranes, killing organisms. Ozone gas is also an oxidant used in ballast water treatment (Pham et al., 2021). Ozone is injected into the ballast water to kill organisms. Ozone gas is toxic to the human body, hence, the usage of ozone in ballast water treatment needs to be conducted with caution, and ensured safety (Vu and Nguyen, 2019). A group of non-oxidizing chemicals that affect the metabolism or reproduction of organisms. Most pesticides belong to this group. Glutaraldehyde is an example, that has a very strong effect on organisms and is often used in industries such as sterilization of medical devices (Al-Tawaha et al., 2020).

The advantages of chemical ballast water treatment include (1) The machinery used in the oxidizing process does not require much maintenance. (2) Ozone is effective on various microorganisms (Hoang, 2022). (3) Glutaraldehyde is metabolized quickly when released into the environment to generate CO_2, which is a safe substance. However, this method also includes limitations such as (1) The size of the machinery is limited when installed onboard. (2) When using oxidizing agents, it is very dangerous for sailors while handling this chemical, so it is necessary to train sailors on the safety of oxidizing agents. (3) Ozone cannot remove large organisms. (4) The size of the machine is large and the reaction between Ozone and other components in seawater will form toxic substances that are harmful to the environment (Khalaf et al., 2021).

Table 1: Technological method for ballast water treatment (Tang et al., 2006; Sutherland et al., 2001; Sateikiene and Januteniene, 2012; Nguyen et al., 2020)

Methods	**Filtration**	**Cyclonic separation**	**UV**	**Electrolytic chlorination/ electrolysis**	**Ozonation**	**Coagulation/ flocculation**
Treatment at	Uptake	Uptake	Uptake and discharge	Uptake	Uptake for some systems and at discharge for others	Uptake
Time for lethality	At treatment	At treatment	At treatment	Hours	Up to 15 hours	-
Operations	Pressure drops and reduced flow rate	Pressure drops and reduced flow rate	Increased energy consumption;	Possible consequences on tanks and pipe corrosion;	Possible consequences on tanks and pipe corrosion	Storage tanks for additives are necessary
	-	-	-	Increased energy consumption;	-	-
	-	Minimum maintenance	High maintenance.	High maintenance	-	-
Safety	No safety-related effects	No safety-related effects.	UV light exposure can be harmful	Risk of chemical exposure to the ship's crew	Toxic	-
	-	-	-	The exhaust of hydrogen and chlorination gas generated by electrolysis	-	-
Environments	Reduction of sediments into the ballast tanks;	Reduction of sediments into the ballast tanks;	Efficiency is dependent on water quality;	Effective for a broad range of organisms;	Effective for microorganisms;	Reduction of sediments into the ballast tanks;
	Not effective for microorganisms	Not effective for microorganisms	Effective for microorganisms	Ballast water neutralization before discharge	Ballast water neutralization before discharge	Not effective for microorganisms
	-	-	-	Efficiency is dependent on water quality	Efficiency is dependent on water quality; Air pollution	-

The principle of heat treatment is very simple. Seawater is pumped into the ballast water pipeline and then heated through an exchange with the cooling water on the ship's machinery. After being heated to the required temperature, seawater will be pumped into the ballast water storage compartment (Nizetic et al., 2022). The high temperature of the water may kill the organisms that exist in the ballast water. Treating ballast water with a temperature of around 450^{o}C and maintaining it for a long time can kill large organisms such as fish, but this temperature does not affect microorganisms. This method is not effective for cold seas because it takes a lot of energy to heat the ballast water. Currently, UV light is being used in hospitals and prisons to kill microorganisms and avoid spreading disease. UV lamps have been applied in urban water treatment to replace chlorine treatment. This method is very effective against microorganisms (Chen, 2021). To increase its effectiveness in ballast water treatment, it needs to combine with other methods (Dong, 2020). The disadvantage is that UV rays are not effective when the water contains too much-suspended matter, thus ballast water needs to be filtered before UV treatment. Although there are many proposed methods, none of them are effective in ballast water treatment. UV treatment needs to be combined with filtration that requires filtration of other large materials contained in the ballast water (Ong, 2021).

3.2 JFE BallastAce ballast water treatment technology

Seawater is pumped in from the Kingston valve by the Ballast pump. Seawater passes through the ballast filter and most plankton larger than 50 µm is removed (Kimera ang Nangolo, 2020). The plankton removed here is discharged with the backwash water by the automatic backwash function of the filter into the water body where the ballast water is taken. Disinfectant is injected from the disinfectant pump into the ballast pipe through the nozzle, and the plankton and bacteria passing through the ballast filter are killed and disinfected, shown in Figure 2. Disinfectant is automatically controlled thanks to an automatically set total residual oxidant value (TRO) unit. Disinfectant is injected into the disinfectant and passes through the mixing plate, a strong vortex occurs (Riggio, 2019). This quickly stirs and mixes the disinfectant in the ballast water for a short time, which results in better killing and sterilization (Nayak et al., 2020). Sterilized ballast water is pumped into ballast tanks. Residual oxidants in the ballast water further kill living organisms in the ballast tanks (Pham, 2019; Dong, 2020).

The concentration of TRO (total residual oxidant) remaining in the ballast tank will decrease with time due to autolysis or reaction with reducing agents (ammonia, humic substances, etc) present in the ballast water. Nevertheless, if TRO is left when the ballast water is discharged, it will harm the ecology of the waters where it is discharged, as a result, it needs to be neutralized before discharge (Lee et al., 2019; Wang et al., 2019). The TRO after neutralization is measured by the TRO device to check if it is within the allowable value. The neutralizer (sodium sulfite solution) is pumped from the neutralization pump into the ballast water in the ballast pipe through the nozzle. The neutralizer is vigorously stirred by the mixing plate and transferred (Pham and Hoang, 2020). The remaining oxidant is neutralized inside the pipe. Ballast water is pumped out of the ship by a ballast pump (Zhu et al., 2020).

Ballast water is put into the system and treated and then taken out to the sea immediately, to form the Sea to Sea road. Operate the sterilization pump and operate the neutralization pump to both disinfect and neutralize the amount of reducing agent present in the ballast water and then discharge into the sea (Moreno-Andres, 2018). The neutralizer (sodium sulfite) is pumped from the neutralization pump into the ballast pipe through the nozzle (Figure 4) (Tabatabaei and Aghbashlo, 2020). The disinfectant solution, remaining in the disinfectant solubilizer and disinfectant line, is pumped from the sterilization pump into the ballast pipe (Dong, 2020). The TRO device checks if it is neutral (Van and Anh, 2018). The operation stops automatically when the inside of the device dissolves the disinfectant, which is replaced by clean water (Zhang et al., 2022).

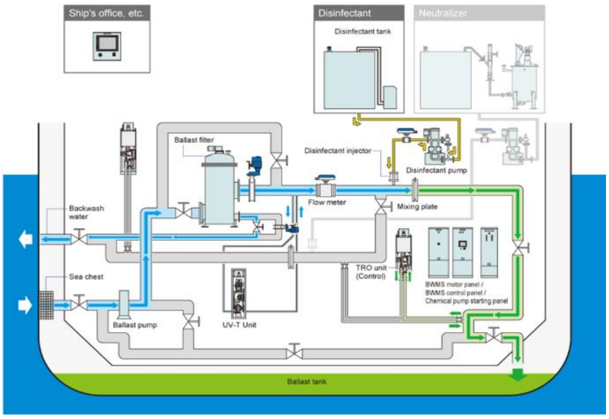


Figure 2: Ballasting process flow by JFE BallastAce (BallastAce, 2021)

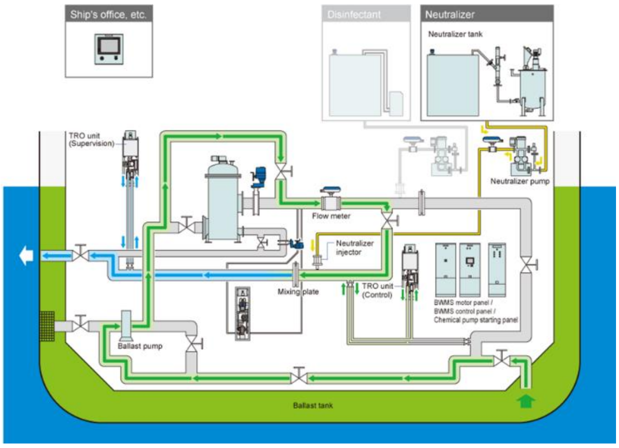


Figure 3: De-Ballasting process flow by JFE BallastAce (BallastAce, 2021)

3.3 LeesGreen ballast water treatment technology

The LeesGreen ballast water treatment system includes equipment such as Filter, UV Reactor, Local Control Unit, Remote Control Unit, Power Cabinets, Electric Valves, Monitoring Devices, Sampling Devices, and Pipelines (Guo et al., 2021). In Figure 4, the LSF series automatic filter is the first step of a system specially designed for the screening of ballast water, featuring fine mesh elements to remove bacteria and particles larger than 50µm in size. The LSF filter applies backflush technology to effectively perform the filtering and cleaning process at the same time (Nguyen and Hoang, 2020). The backflush starts automatically based on the differential pressure of the water inlet and outlet of the filter while continuing to filter with no need for any other on-site manual action (Hess-Erga et al., 2019; Bui et al., 2021).

Ballast water is pumped from the marine vent valve and fed to the filter from the ballast water inlet to the filter (1) (Figure 4). Then it goes through the filter to remove the dirt, a part of the water goes to the upper chamber (6) through the middle upstream pipe (2) to enter the filter number (3). Ballast water flows through the filter elements from the inside out and microorganisms and particles larger than 50 µm in the water are trapped on the filter media of the filters. The purified water will lead to the outlet of the filter (7) and then to the UV Reactor (Dong and Nguyen, 2019). The accumulation of dirt inside the filter mesh increases, leading to a gradual increase in the pressure difference between the ballast water inlet and outlet. When the differential pressure reaches the preset value, then the filter controller will receive an electrical signal from the differential pressure gauge and start the hybrid engine (4). Simultaneously, the reverse discharge arm (5) will be rotated through the ends of both the upper and lower filter tubes. At the same time, the reverse outlet (8) is opened, creating a high axial flow in the filter core and the impurity particles stuck on the inner surface of the filter mesh are pumped out (Subramanian, 2021).

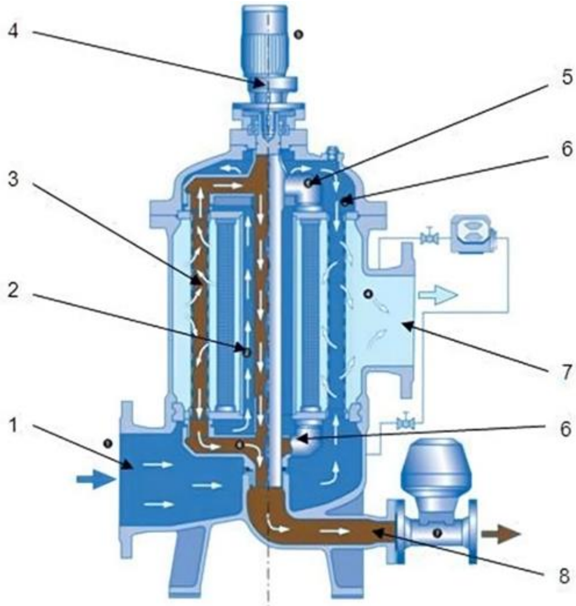
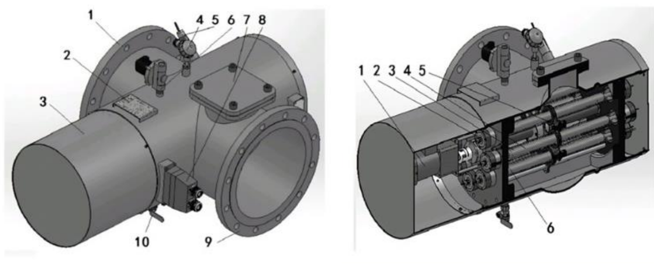


Figure 4: Working principle of LSF Filter (Fuda, 2016)

The main processing takes place inside the UV reactor, where nanometer-sized microorganisms in the water are exposed to UV rays, rendering them harmless (Rivas-Zaballos et al., 2021). UV rays break the DNA chain leading to the destruction of the internal structure (T + T) making microorganisms unable to reproduce. The germicidal range for ultraviolet rays is in the range of 200~300 nm, which is short-wavelength ultraviolet (UVC), shown in Figure 5. No chemicals are added to the process and no toxins are formed. So water is chemically unaffected, has no environmental impact and the process does not affect system corrosion (Bui et al., 2021). Specially designed UV lamps encased in quartz lenses assist in transmitting a wider wave spectrum, providing more UV rays during sterilization (Petersen et al., 2019). The temperature transmitter senses the temperature of the UV lamp and sends the information to the controller. When the lamp temperature reaches 60°C, the controller deactivates the UV reactor. The UV lamp is powered by an adjustable electronic ballast. The irradiation efficiency can be adjusted according to different water conditions. Real-time UV intensity is monitored to determine operational status.



(a) (b)

Figure 5: (a)- External components of UV reactor, (b) - Internal components of UV reactor

LeesGreen BWMS advanced fully automatic system using reverse vortex filter, with highly efficient medium pressure UV radiation technology for the on-line treatment of ship ballast water, depicted in Figure 5. The impurity filtration method plus UV radiation make the filtration highly efficient. The entire system is completely self-contained, so there is no radiation or noise hazard to the crew. The system does not use chemicals, so there is no need to store hazardous substances, and it takes up less space. Because of the above benefits, the system is very safe, reliable, and economical and this low energy usage system responds with energy-saving and environmental protection. The LeesGreen ballast water treatment system has been rigorously tested according to IMO standards and the system has also met all the requirements set forth by the Organization.

4. Conclusion

Vessels are built and designed to move on water and carry goods in very large quantities such as liquid and bulk cargo, containers, machinery, equipment, and even people. When the cruise ship is unloaded or the goods have been returned at the ports required by the customer, water may be used to enter ballast tanks on board ships to achieve the necessary conditions and safety requirements. This helps the ship to change the draft, change the bow and steer of the ship. To provide stability and maneuverability in flight, helping to offset weight changes at different cargo loads due to fuel and water consumption, reduce the ship's center of gravity to ensure the ship is stable while in transit. While ballast water is essential for the safe and efficient shipping operations of ships. However, it can cause serious ecological, economic, and health problems due to the multitude of marine species transported in ballast water. To reduce and prevent environmental pollution caused by the transport of pathogens and harmful aquatic organisms through ballast conventions, the International Convention for the Control and Management of Ballast Water and Sediments (BWM 2004 Convention). This study analyzed and evaluated ballast water control methods with key characteristics of the equipment revealing that: Methods such as mechanical, physical, and chemical are commonly used to meet the standard. BWM 2004 standard D2. The combined ballast water treatment technology solutions have provided the best ballast water treatment efficiency such as a combination of filtration and chemical systems, filtration, and UV systems. The results of the analysis show that the JFE BallastAce and LeesGreen BWMS ballast water treatment technologies are recommended for use on ships to meet BWM 2004 regulations.

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