**WATER TREATMENT TECHNOLOGY
FOR WATER DEMINERALIZATION**

**Innovative System for Controlling the Treatment
and Disinfection of Sea Ballast Water:
Danube Institute of National University
“Odessa Maritime Academy”**

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Abstract—This study is devoted to the threat to marine ecological safety associated with the presence of invasive alien species (IAS) in the World Ocean, which is among the global problems in today's world. A number of port cities of Ukraine, such as Odessa, Izmail, Kherson, and Mykolaiv, significantly contribute to the pollution of the sea water areas with IAS. Invasive alien species that are present in sea water are supplied together with the latter into ballast tanks (to maintain balance, list, and stability of ships) and end up in the sea even after passing through the ballast cleaning system, thereby securing themselves in certain water areas and ceasing to play the sanitary role; on the contrary, they become pests, i.e., a threat to the World Ocean. There are also IAS examples depending on the countries of the World, i.e., their location. An analytical review of the ballast water management systems most famous all over the world is given, the prospects of their application for disinfection and purification of ballast water and their comparative characteristics are provided. On the basis of strict ballast water quality standard D-2 of the International Maritime Organization (IMO), scientists from the Danube Institute of National University “Odessa Maritime Academy” (Izmail, Ukraine) have proposed and developed experimental innovative equipment for purification and disinfection of water ballast. Ballast water is analyzed on sea vessels entering the Izmail shipyard “Odessa Maritime Academy” for factory repair from various water basins of the World Ocean. All ships entering the factory for repairing are suppliers of ballast water samples. The constructive features of the laboratory facility allow one to study ballast water when the corresponding modules of the system pass at various speeds.

Keywords: ballast water, seawater, invasions, disinfection and treatment system for ballast water, electrohydroshock

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INTRODUCTION

It is known that the most economically advantageous means for moving a large amount of cargo over long distances nowadays are not road and rail, but sea transport (shipping).

Among the topical issues of the world community, pollution of seaports (in Ukraine, these are Odessa, Kherson, and Mykolayiv) occupy an important place, since it is with water that invasive alien species (IAS) are transported. All viruses, including COVID-19, start with a dimension of 80 nm and above. The danger of viruses in ballast water is extremely high and, for that reason, the D-2 standard prescribes the procedure for ballasting and deballasting of seagoing vessels (ballast water collection and discharge is carried out in a 200-mile zone from the shoreline with a keel depth of at least 200 m).

Unfortunately, there are many examples of blatant violations of the proposed procedure prescribed in the new Rules [1], which further strictly regulate the number of bacteria and viruses after disinfection and purification of ballast water. The arrangement of ballast water control in the ports of call of ships is extremely imperfect; as for Ukraine, the Cabinet of Ministers of Ukraine by its decision from August 2019 abolished the control of isolated ballast water of ships during their stay in the internal sea waters of Ukraine.

In addition to IAS, other terms can be used for marine invasions, such as introduced marine pests (Australia and New Zealand), aquatic pests (USA), etc. [2]. Examples of marine invasions are Asian brown algae (*Undaria pinnatifida*), scallop (*Mnemiopsis leidyi*), cholera (*Vibrio cholerae*), toxic algae (*Alexandrium* spp. and *Gymnodinium* spp.), European grass crab, green crab (*Carcinus maenas*), caulerpa, seaweed (*Caulerpa taxifolia*), and round goby (*Neogobius melanostomus*). It is estimated that about 3 to 5 billion tons of ballast water is transported around the world annually by ships, each of which carries from several hundred liters to more than 130 thousand tons of ballast water, dependent on the size and purpose of the ship. The destruction of Iran's fishing industry by the settlement of scallops, the almost complete destruction of commercial fish species in the Black Sea for the same reason, and the colossal problems throughout North America (especially the Great Lakes) due to the invasion of freshwater oysters (*Dreissena polymorpha*) that populate water intakes, navigation facilities, and mooring structures—and thereby complicate their operation—are the most typical examples. In the United States alone, the cost of cleaning engineering structures from mussels was estimated at \$750 million to \$1 billion in the period from 1989 to 2000 [3].

It is known that the entire civilized world fleet is rearming ships at the moment in accordance with the requirements of the D-2 standard. The latest requirements of the International Maritime Organization (IMO) for ballast water discharge will be controlled by special tools, i.e., by notification through direct broadcast from environmental services of ports.

Many countries (including Ukraine) have taken independent measures to limit the intrusion of IAS by certain requirements for the discharge of ballast water into their maritime belts. These targeted measures vary from country to country, so their implementation causes substantial difficulties for ship managers and ship personnel. However, Ukraine did not follow the way implying the electronic control, leaving open the issue of protection against IAS of its territorial waters. Shipping requires uniform rules for the control of ship ballast water in accordance with the requirements of the World Shipping Council [4]. Vessels operating in international waters require, in accordance with all the requirements of D-2, a unified approach to the equipment. Currently, the IMO has not adopted a unified ballast water treatment technology, so the industry faces a dilemma whether to install equipment in accordance with the D-2 standard or to follow the technology approved in accordance with the requirements of the IMO. Thus, the issue of ballast water control has recently become relevant in Ukraine.

We have analyzed the relationship between the already implemented strict IMO requirements (D-2) and the effective measures taken by shipowners to comply with the Rules of this Convention [5]. The Ocean Guard Ballast Water Management System is among the most famous and high-quality technology today, which has received the approval of qualification associations. There are other ballast water management systems, such as offered by Japanese companies Mitsui OSK Lines (MOL), Kure National Coll, Technol, and Babcock-Hitachi KK, U.S. companies Ecochlor, Inc. and Maison Navigation Company, Inc., German company HAMANN AG, etc. [6]. However, the above developments lack research on the environmental safety of ballast water, which would take into account the design and operation of mixed (river–sea) navigation vessels. Company Hyde Guardian (United States) is a leader in the production of ballast water treatment equipment [7]. They produce simple and quite economical automatic control and monitoring systems fully integrated into existing shipboard equipment. For a long time, Hyde Guardian has tested numerous ballast water treatment methods and selected the most satisfactory system that uses porous disk filters.

There is no specific protocol for testing the operation of the ballast water treatment system. General recommendations from IMO have been established and are being evaluated. In addition, test procedures in international practice can be determined by laboratory studies.

In July 2019, the Cabinet of Ministers of Ukraine established an algorithm of actions of the Ukrainian Sea Ports Authority (USPA), which is a State coinspection and sea administration for environmental inspections of ships in ports [8].

In this regard, the Danube Institute of National University “Odessa Maritime Academy” developed an experimental innovative ballast water management system by following the D-2 IMO standard of the National University “Odessa Maritime Academy”.

Table 1. Results of analyses of the water sample taken from the Danube River in the area of the city beach after processing in a laboratory setup

Numerical indices of microflora composition	Analysis methods	Values of numerical indices of microflora composition	Parameters/modes of operation of laboratory setup				
			$v_{1w} = 1.61$	$v_{2w} = 1.1$	$v_{3w} = 0.8$	UV (wavelength 254–260 nm)	O ₃ (8 mg/dm ³)
			m/s				
Water before purification/disinfection ($t_w = 24.4^{\circ}\text{C}$)							
MAFAM	MV 2285-81	1500 CFU/cm ³	–	–	–	–	–
LPEC index	MV 4260-87 P.7.7.4.-018-99	<1800	–	–	–	–	–
Phage index	MUK 2282-81	<125	–	–	–	–	–
Enterococci index	MUK 2282-81	<2300	–	–	–	–	–
Water after purification/disinfection ($t_w = 24.4^{\circ}\text{C}$)							
MAFAM	MV 2285-81 [19]	90 CFU/cm ³	+	–	–	+	+
		50 CFU/cm ³	–	+	–	+	+
		5 CFU/cm ³	–	–	+	+	+
		<700	+	–	–	+	+
LPEC index	MV 4260-87 P.7.7.4.-018-99	<550	–	+	–	+	+
		<300	–	–	+	+	+
		<15	+	–	–	+	+
		<5	–	+	–	+	+
Phage index	MUK 2282-81	0	–	–	+	+	+
		<1800	+	–	–	+	+
		<1200	–	+	–	+	+
		<700	–	–	+	+	+
Enterococci index	MUK 2282-81 [21]	<1800	+	–	–	+	+
		<1200	–	+	–	+	+
		<700	–	–	+	+	+

MAFAM is the total number of microbes; LPEC index is the lactose-positive *Escherichia coli* index.

The aim of this study was to develop an experimental innovative ballast water management system for purification/disinfection of ballast water from IAS in accordance with the D-2 quality standard from IMO.

EXPERIMENTAL TECHNIQUES

The efficiency of the system was studied according to the commonly used sanitary and bacteriological analyses of water for compliance with the requirements of SSR 4630-88 (State Standard of Ukraine) [9]. The latter correlates with the D-2 quality standard for ballast water.

The operating scheme of the innovative water ballast control system was as follows. Iron chelate and sodium hypochlorite enter the ballast tank through the reagent dispenser. For the first time in the practice of ballast water disinfection, we used an electromagnetic effect with a high degree of ultraviolet ionization at wavelengths of 254 to 260 nm [10]. The experiment was performed with alternating pulses with a length of $\tau = 10^{-6}$ μs at an instantaneous pulse power of 50–1000 MW [11–13]. Next, the ballast water enters the coarse filter, and then the preliminarily purified ballast water enters the Venturi tube by means of a ballast pump and a water supply controller, into which ozone is supplied from the ozone generator. The laboratory ballast water management system developed at the Danube Institute of the National University “Odessa Maritime Academy” was equipped with an Ekozon-5AW ozone generator with a capacity of 5 g/h [14].

Next, the ballast water enters the fine filter (self-unloading filter). The flow of ballast water passes in the direction from the base of the housing (hollow shaft) of the self-unloading filter to the peak (top) and thereby ballast water is sprayed on the perforated areas of the filter discs composed of carbon nanotubes.

Table 2. Results of analyses of the Black Sea ballast water after processing in a laboratory setup

Numerical indices of microflora composition	Analysis methods	Values of numerical indices of microflora composition	Parameters/modes of operation of laboratory setup				
			$v_{1w} = 1.6$	$v_{2w} = 1.1$	$v_{3w} = 0.8$	UV (wavelength 254–260 nm)	O ₃ (83 mg/dm ³)
			m/s				
Water before purification/disinfection ($t_w = 26.2^{\circ}\text{C}$)							
MAFAM	MV 2285-81	5000 CFU/cm ³	—	—	—	—	—
LPEC index	MV 4260-87 P.7.7.4.-018-99	<3900	—	—	—	—	—
Phage index	MUK 2282-81	<500	—	—	—	—	—
Enterococci index	MUK 2282-81	<7500	—	—	—	—	—
Water after purification/disinfection ($t_w = 26.2^{\circ}\text{C}$)							
MAFAM	MV 2285-81	3900 CFU/cm ³	+	—	—	+	+
		2100 CFU/cm ³	—	+	—	+	+
		600 CFU/cm ³	—	—	+	+	+
		<3000	+	—	—	+	+
LPEC index	MV 4260-87 P.7.7.4.-018-99	<1900	—	+	—	+	+
		<700	—	—	+	+	+
		<390	+	—	—	+	+
		<250	—	+	—	+	+
Phage index	MUK 2282-81	<90	—	—	+	+	+
		<4200	+	—	—	+	+
		<1800	—	+	—	+	+
		<500	—	—	+	+	+

Ballast water is gradually purified passing the filter discs one after another. At the same time, the flow of ballast water is constantly twisted because of that the filter discs are located on a hollow shaft that is driven by an electric motor (akin to a cyclone, with autonomous operation).

Next, the ballast water enters the UV chamber, in which it is exposed to radiation, and then repeatedly purified ballast water is discharged overboard.

The self-unloading fine filter was based on the marine oil filter from the CJC Company [15], which is used in the circulating system of the main B&WMC-C engine. It was equipped with a filter pack made of carbon nanotubes using graphene. The filter cartridge operates using the reverse osmosis principle.

In a laboratory setup, we have analyzed the water sample taken from the Danube River in the area of the city beach (Table 1).

Ballast water was taken at a depth of 200 m in a 100-mile zone from the shore (ship Asia Opal, bulk carrier, under the flag of Singapore, IMO number 09543885; port of destination Mykolaiv, Ukraine). The D-1 Standard of the IMO Convention controls the replacement of ballast on the high seas under appropriate requirements that allow one to neutralize most potentially dangerous foreign organisms [16].

RESULTS AND DISCUSSION

It is known that the use of ozone as an oxidant when excited by UV light at the maximum absorption band (photolytic ozonation) makes it possible to create devices with a specific energy consumption of 5 to 7 times less than the specific energy consumption when using the reagent separately. In the O₃/UV process, the benefits of using ozone and ultraviolet radiation increase. Upon the irradiation of water containing dissolved ozone, hydroxyl radicals are effectively formed and, at the same time, ozone is completely decomposed. Hydroxyl radicals are particles that have an extremely short lifetime (fractions of a second),

i.e., they are short-lived free radicals, but have the ability to accelerate oxidation processes at the same time. Under their influence, the highly effective disinfection process takes place [17, 18].

According to the data given in Table 1, the amount of mesophilic aerobic and facultative anaerobic microorganisms (MAFAM) in the water sample from the Danube River after purification/disinfection processes decreased from 1500 to 5 CFU/cm³ with a v_{3w} water flow rate of 0.8 m/s, a wavelength of 254–260 nm in the UV chamber, and a O₃ dose of 80 mg/dm³, and the lactose-positive *E. coli* (LPEC) index decreased from 1800 to 300, the phage index decreased from 125 to 0, and the enterococci index decreased from 2300 to 700 under the same conditions. In addition, we studied ballast water from the Black Sea in a laboratory setup (Table 2) at a O₃ dose of 83 mg/dm³ (a tenfold increase in the dose was due to the high antibiotic resistance of IAS in seawater compared to freshwater).

According to the obtained results, the amount of MAFAM after exposure decreased from 5000 to 600 CFU/cm³ with a v_{3w} water flow rate of 0.8 m/s, a wavelength of 254–260 nm in the UV chamber, and a O₃ dose of 80 mg/dm³, and the LPEC index decreased from 3900 to 700, the phage index decreased from 500 to 90, and the enterococci index decreased from 7500 to 500 under the same conditions.

Highly ionizing radiation of UV in combination with ozone create the cytotoxic and carcinogenic effects and have a detrimental effect on living organisms, which is directly associated with the generation of OH radicals during the radiolysis of water. The peculiarity of the influence of OH radicals in the proposed ballast water control system is caused by the sequence of an Ekozon-5AW device and a UV chamber. In the reverse connection sequence, the effect is reduced. This fact has been proven by recent studies on the disinfection of pool water and wastewater [22].

After processing the ballast water, we managed to achieve the main indices satisfying the requirements of the D-2 quality standard from IMO, i.e., no more than ten viable organisms ranging in size from 10 to 50 μm^3 .

Following the requirements of the D-2 standard, the setup can be assembled in a simplified version, i.e., using a UV module with a unique design that allows one to achieve the maximum exposure when ballast water passes through this module. The ozone generator module used enhances the effect of ballast water disinfection, in which the automated control of the module allows one, if necessary, to increase or decrease the concentration of ozone in the water under treatment.

Hence, the inventors assume that almost all viruses and bacteria will be destructed in the device with all its modules; according to the results of experiments, disinfection and purification of ballast water in accordance with the proposed principle of operation of the system to meet the requirements of the D-2 standard will substantially reduce its cost in industrial production. The use of a nanotechnological self-unloading filter allows one to desalinate sea water by the reverse osmosis method with a low operating pressure of 2–4 Pa, which makes the device universal; the perfect design of this device allows one to use it with fast addition of necessary modules in compliance with the specific tasks and needs.

CONCLUSIONS

The versatility of the proposed process of purification/disinfection of ballast water in the laboratory setup to the level of the international rules of the D-2 quality standard from IMO and the fitting of the corona pulse module in further studies ensures almost complete destruction of associated microflora. In the performed studies, the use of two modules (UV and ozonation) for purification/disinfection of the coastal waters of the Danube River and ballast waters of the Black Sea meet the requirements of SSR 4630-88 (State Sanitary Rules) on the sanitary and bacteriological analyses of waters.

The energy consumption of the device is 0.3–0.4 kW/m³. This is quite acceptable for use on the largest ocean vessels, in which the productivity of ballast pumping reaches $Q = 6000 \text{ m}^3/\text{h}$.

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