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APPLICATION OF HYDROCYCLONE AND UV RADIATION AS A BALLAST WATER TREATMENT METHOD

ABSTRACT

The ballast water exchange methods in open sea are, for the time being, the prevailing procedures accepted by shipowners. However, such methods do not guarantee full efficacy in elimination of allochthonous organisms. Besides, in some navigation zones, in particular in the closed seas, not even the criteria prescribed by international regulations can be fulfilled, i.e. the position of a ship exchanging ballast must be farther than 200Nm from the shore (alternatively 50Nm) at the sea depth exceeding 200m. Numerous research attempts on various treatment methods lead to the conclusion that there is still no scientific opinion on the final choice of methods for wide application on board. The treatment methods, such as hydrocyclone separation in the first stage and UV radiation in the second stage, stand a good chance for application on board. Advantages of such a combined method are in the very application of treatment that can be performed during all stages of ballast water treatment, i.e. loading ballast, voyage in ballast and discharging ballast. In closed seas and on shorter routes the operational advantages of hydrocyclone and UV radiation could be the prevailing factor for application. Within the research on the possible application of ballast water treatment by hydrocyclone and UV radiation, a pilot plant with hydrocyclone cluster and UV device was constructed. The research carried out on the pilot plant installed on board the m/v "Naše more" proved the effectiveness of such ballast water treatment method and offered a new approach in using hydrocyclone for the inactivation of organisms by hydrodynamic forces. This approach has largely increased the efficacy of the device and a new method for utilization of hydrocyclone in ballast water treatment on board has been discovered.

KEY WORDS

ballast water treatment, hydrocyclone, UV radiation, application of method, pilot plant, hydrodynamic forces

1. INTRODUCTION

Presently, ballast water exchange is a procedure well known and applied by all participants in ship-

ping. In order to avoid the introduction of organisms from one port into another, the ship loads ballast in the discharging port and having reached open sea she performs water ballast exchange by loading ballast water from open sea. The ballast water loaded in open sea contains a significantly smaller quantity of organisms and planktons than the one loaded in port. According to scientific recommendations accepted by IMO [1], [2], a distance of over 200Nm from the shore, the depth exceeding 200m, and salinity up to 30‰ are sufficient to avoid habitats rich in organisms. These methods include sequential method, continuous method and dilution method [3]. The relatively low costs of exchange, the possibility of perusal of the existing ballast system on board and the simplicity of the procedure are the main reasons for the acceptance of these methods by the shipowners. Regretfully, due to the impossibility of full exchange of the whole ballast on board these methods cannot provide a satisfactory biological efficacy [4]. Additional major disadvantages of these methods are a lack of the possibility to satisfy the shore distance and minimum depth in closed sea criteria.

The analysis of the ballast water exchange procedure on ships calling the Croatian port of Ploče is shown in Figure 1 and Table 1. The characteristic ports for loading ballast water are shown as well as the possible ideal position for ballast water exchange¹ for ships calling the port of Ploče, i.e. the Adriatic Sea, from those ports.

Having taken into consideration the standing Guidelines for Control and Management of Ships' Ballast Water to Minimize the Transfer of Harmful Aquatic Organisms and Pathogens, (Resolution A.868(20)), also having taken into consideration the possible navigation routes, a zone where it is possible to perform ballast water exchanges has been suggested. The sea depth in the stated area exceeds 200m and the distance from the shore exceeds 50Nm².

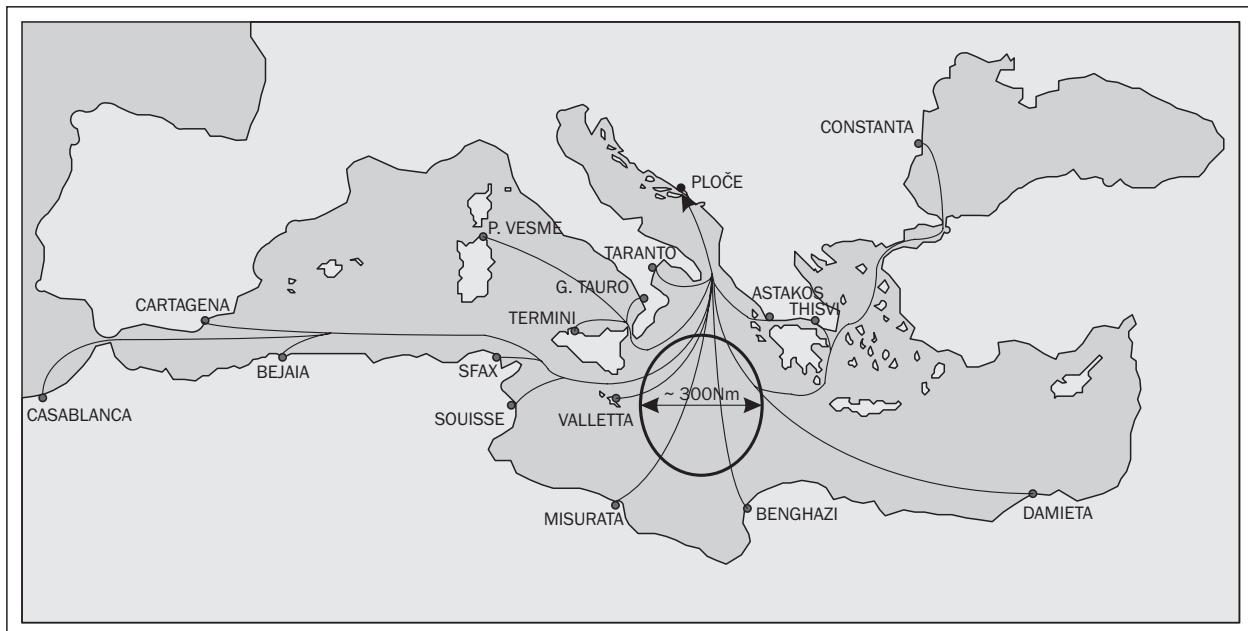


Figure 1 – Characteristic ballast water loading ports and ideal possible position for ballast water exchange in the Mediterranean for ships calling the port of Ploče or the Adriatic Sea

Careful consideration of ideal navigation routes through the suggested exchange area has shown that the navigation routes stretch from ~ 80Nm to ~ 280Nm, although a smaller number of ideal navigation routes still remains out of the suggested exchange zone. The largest number of ballast water discharges into the port of Ploče is done from Handysize bulk carriers. Taking into account the ballast quantities and ballast pumps capacities a full sequential exchange (discharging – loading of tanks) on such vessels can be performed in approximately 16 – 24h on the average. Once the time required for exchange, ship's speed, duration of voyage through a specific exchange zone have been taken into consideration, it is possible to simulate the ballast water exchange scenarios in the suggested zone (*Table 1*).

Table 1 shows possible simulations of the length of navigation route through the suggested exchange zone, ship's speed, possible duration of full sequential

exchange, and the required Nm for the completion of exchange. In most cases it is not possible to perform full exchange in the suggested zone. From *Figure 1* it can be noted that some routes are considerably shorter than the examples given in the Table, while some routes do not pass through the suggested zone at all. The Table refers to sequential exchange only, and the results obtained from continuous exchange would be even less favourable due to longer period of duration of the method. Naturally, when taking into consideration that the ships sail on the shortest possible routes which do not fully comply with the situation in *Figure 1*, the situation is much less favourable, i.e. few ships succeed in performing full exchange within the zone satisfying the exchange criteria.

From the stated definition of the problem the basic scientific hypothesis of this paper is framed: on board ships sailing between ports in closed seas and on relatively shorter voyages the existing ballast wa-

Table 1 – Ballast water exchange scenarios in the suggested zone having taken into consideration the assumed navigation route, ship's speed and duration of exchange

Length of route through exchange zone (Nm)	Ship's speed (knots)	Duration of exchange (h)	Exchange performed after (Nm)	Full exchange in exchange zone
150	11	16	176	No
180	12	16	192	No
280	13	20	260	Yes
200	14	18	252	No
260	14	18	252	Yes
260	15	20	300	No
280	16	20	320	No

Table 2 – Evaluation of ballast water treatment methods

Treatment method	Safety	Biological efficacy	Environmental friendliness
Filtration	4	1	4
Hidrocyclone separation	4	1	4
Centrifugal separation	4	1	4
UV radiation	4	2	3
Ultrasound	3	2	3
Thermal treatment	3	2 - 3 ¹	4
Biocides	2	3	1
Ozonisation	2	1	3
Pulsed plasma	3	N	N
Deoxidation	N	2	3
Coating tanks	3	1	2
Combined methods: hydrocyclone separation/UV radiation	4	3	3

Legend: N – unknown, 1 – unacceptable, 2 – bad, 3 – partly acceptable, 4 – acceptable

¹ 2 for ships on ballast voyages < 10 days, 3 for ships on ballast voyages >10 days

ter exchange methods do not satisfy the set criteria; therefore, it is necessary to set criteria for determining the optimal treatment method, investigate and improve the optimal method, construct a pilot plant and perform tests on board to prove its efficacy.

2. BALLAST WATER TREATMENT METHODS

Due to insufficient biological efficacy of ballast water exchange methods, increasing efforts are being made in search for technologies that would enable efficient inactivation of organisms on board. There are positive indications that ships will be equipped with a ballast water treatment plant. Generally, treatment methods on board can be divided into primary treatment methods, secondary treatment methods which can be physical and chemical, and combined treatment methods. Although many various treatment methods are being tested, this research paper will focus on those methods that are most applicable for use on board. Primary ballast water treatment methods on board are based on filtration, centrifugal and gravitational processes. By treatment of ballast water from liquid stage (fresh or sea water) the solid stage is being eliminated (living and/or nonliving particles). Centrifugal processes take place in a centrifugal field and are based on the assumption that the density of organisms in ballast water on board is higher than the density of the sea. As to the means of creating a centrifugal field, there are dynamic and mechanical centrifugal processes. The dynamic processes utilise the energy of the liquid flow, while in the mechanical processes the engine propulsion energy is utilised. Centrifugal separation can be obtained by mechanical or dynamic process, and hydrocyclone separation is obtained mainly by means of the dynamic energy of a liquid.

Physical methods are acceptable from the safety and environmental viewpoints; however, some of them require major reconstruction and adjustments of the ship's ballast system. These methods are based on the sensitivity of organisms to various external impacts. The efficacy of elimination of organisms depends on the intensity of physical impact and the method applied. Physical treatment methods applicable for use on board are:

1. ultra-violet radiation (UV radiation),
2. methods based on ultrasound,
3. thermal methods.

The basic criteria for the evaluation of a method are the safety of ship and crew, satisfactory efficacy of exchange i.e. biological efficacy and inflicting no harm on the marine environment. The evaluation of the safety criteria and environmentally friendly criteria can be relatively precisely ascertained, but the evaluation of biological efficacy (degree of elimination of allochthonous organisms) is extremely complex since it is influenced by many factors, such as: construction of ballast tanks and ballast system, physical and chemical characteristics of sea water influencing the survival degree of organisms, type of organisms in ballast water, quantity of sediments on the bottom of the tank and many other factors. Nevertheless, on the basis of the research made so far [4], [5], [6], [7], [8] and [9] certain data can be approximated.

Table 2 shows that no treatment method, for the time being, has an acceptable level of biological efficacy. Thermal methods could give satisfactory results, but their disadvantage is that they cannot be applied for all voyage durations. Combined methods such as hydrocyclone separation or filtration as primary treatment and UV radiation as secondary treatment, with

certain improvements, could be accepted as an option for treatment on board.

3. COMBINED TREATMENT METHODS

3.1 Hydrocyclone separation

Hydrocyclone separators have no rotary parts and consist of a conical base (housing) which narrows down at one end. The energy of liquid flow through narrowed cross sections of the hydrocyclone housing is used to form a vortex. The principle of operation is based on the acceleration of particles and the separation of light phase from heavy phase due to different density. Tangential feeding of ballast water under pressure into the upper cylindrical part of hydrocyclone creates centrifugal rotational flow towards the apex (outside vortex). Due to the conical shape of the apex, the vortex slows down and the pressure rises right above the apex outlet, interrupting the laminar flow and reversing its direction, along the axis and upwards, towards the lower pressure area (inside vortex). At that point – in the lower pressure area, the overflow is installed where purified ballast is discharged from the hydrocyclone (Figure 2). The centrifugal force of the vortex drives the organisms and sediments, due to their heavier mass, towards the walls of the hydrocyclone. They slide along the walls and are finally discharged through the apex outlet i.e. sludge outlet. The lighter phase (i.e. purified ballast) due to its smaller mass, remains around the axis and the inside vortex carries it out through the overflow.

The density of sea water and organisms in it differ from one another. For example, the density of dinoflagellate cysts is over 1.1kg/m^3 and consequently they can be separated from the ballast water by hydrocyclones.

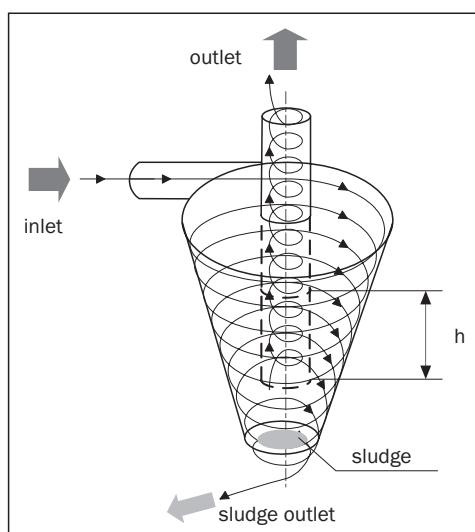


Figure 2 – Process of hydrocyclone separation

The velocity of the hydrocyclone separation process in m/s can be shown as:

$$v_{cikl} = \frac{Q \cdot g \cdot \rho \cdot k_p}{4 \cdot h \cdot \Delta p} [\text{m/s}] \quad (1)$$

where:

Q – flow through hydrocyclone, m^3/s ;

ρ – liquid density, kg/m^3 ;

g – gravitation, m/s^2 ;

k_p – coefficient of pressure drop through hydrocyclone;

h – height of hydrocyclone vortex zone, m;

Δp – pressure drop inside hydrocyclone, Pa.

The initial research of the application of the hydrocyclone separation in the treatment of ballast water on board was made on pilot plants with $55\text{m}^3/\text{h}$ capacity [10]. The results were not promising, since very small efficacy in elimination of organisms was achieved. On an improved hydrocyclone of 5m in length and the capacity of $100\text{m}^3/\text{h}$, and the working inlet pressure of 2 bars the efficacy for cysts Artemie (brine shrimp) was 13.7%, for dinoflagellates Porocentrum minimum and green algae *Tetraselmis* sp. 10 – 30%, while at the same time the elimination of bacteria was negligible [11]. The mentioned efficacy applies to the separation of organisms through heavier phase – sludge outlet.

Although for the time being a higher efficacy of elimination of organisms cannot be achieved by hydrocyclone separation, this method can be adopted as primary treatment instead of filtration. The treatment by filtration causes loss of ballast water flow and loss of time due to the cleaning of filter. On the other hand, hydrocyclones which are without any movable parts have small dimensions, negligible maintenance and low purchase price, seem to be convenient for installation on board. The present technology provides for unit capacities up to $3000\text{m}^3/\text{h}$, which means that hydrocyclones can be directly installed onto ballast pumps on larger ships.

Hydrocyclone separation can enable efficient treatment of ballast water on board in the first treatment stage. The advantages are the reliability, negligible maintenance costs and the possibility of direct installation onto the existing ballast systems on board.

3.2 UV radiation

This method was introduced at the beginning of the previous century when monochromatic UV radiation obtained by low pressure mercury lamp was used to inactivate microorganisms. The devastating impact of UV radiation is used for the analysis of microorganisms in fresh water and waste water as well as in industrial facilities. UV radiation, depending on the dosage used, can be efficient in inactivation of a large number of organisms such as viruses, bacteria, algae, protozoans.

The dosage required for total inactivation is the sum of radiation intensity and period of exposure. It is possible for the exposure of organisms to radiation to cause mutation on the cellular genetic material of organisms (DNA structure). Unit for a dose of UV radiation is expressed by intensity of UV radiation in mW per cm^2 in the exposure period of one s (mWs/cm^2).

UV radiation intensity is far less efficient than the UV dose representing the sum of absorbed photons. For example, a low pressure monochromatic UV lamp can radiate the same UV dose as the polychromatic high pressure lamp if the radiation period of the monochromatic lamp is increased. For disinfection of fresh water FDA³ requires exposure to radiation of each treated volume part of at least 40mWs/cm^2 at the wave length of 254Nm. According to the laboratory research performed, the highest efficacy in inactivation of marine organisms in ballast water is achieved at wave lengths from 250 to 260Nm [7]. UV lamps are filled with gaseous mercury under different pressures, and their shape and dimensions equal those in fluorescent tubes. In the glass body of the tube within the inert gas an electric arch is formed causing evaporation of mercury. Mercury is ionised and emanates UV rays. The lamp is made of special quartz glass that allows radiation from 70 – 90% of the UV rays produced.

Difficulties in operation are caused by turbidity of water generated by the remaining particles present in the ballast system, or dissolved material in the water. Besides the mentioned factors turbidity is caused also by the velocity of the sea water flow in the ballast system (~2 m/s). The particles in the turbid water are normally small (less than 5µm) and difficult to eliminate. Turbid water absorbs light resulting in smaller doses of UV radiation, i.e. shorter exposure of organisms to radiation and reduced inactivation.

Larger particles cause interference of UV rays (while the smaller particles absorb the rays) which prevents penetration of radiation into the water column. Such particles are mostly of higher density than the sea water and can be successfully eliminated by any method of primary ballast water treatment. To check the efficiency of operation within the device, the instal-

lation of a sensor is recommended, which will provide feedback on the radiation intensity. The intensity of UV radiation is automatically adjusted to turbulence in the ballast water, i.e. water conductivity.

The advantage of UV treatment methods on board lies in various possibilities for the installation onto the existing ballast system. UV devices can be efficiently used during ballasting and deballasting of the ship [12]. The utilization of devices during ballast operations significantly improves the efficacy of inactivation because it prevents creation i.e. development of organisms in ballast tanks during ship's voyage in ballast.

3.3 Proposal for application of the combined method (hydrocyclone separation and UV radiation)

Figure 4 shows the proposal for potential installation of the combined method (hydrocyclone and UV radiation) onto ballast systems on board. The ballast water treatment system consists of hydrocyclone separator (primary treatment) and UV device with automatic radiation intensity adjustment.

The treatment system can be directly connected to the existing ballast system on board. The proposal of the system's functional diagram enables ballast treatment during ballasting (loading tanks) as well as during deballasting (discharging tanks). Due to the possibility of survival of organisms during voyage in ballast, while discharging the tanks, there is a possibility for utilization of the UV device without hydrocyclone. Discharging and loading of tanks can be performed even without the utilization of the treatment system.

The devices can operate automatically and unattended by crew thanks to the regulation and safeguard on the very device. The pressure drop is relatively small, and adjustment onto ballast systems is not complicated. The method can be applied on ships with small ballast pump capacities as well as on large tankers. Hydrocyclone separation and UV radiation do not change the physical characteristics of the ballast water, do not produce toxic or any other products making this method environmentally friendly.

4. PILOT PLANT FOR BALLAST WATER TREATMENT

Research of the potential application of ballast water treatment on board at the University of Dubrovnik started by drafting and outfitting a portable lab with specially designed and installed experimental unit. Further research leads to the construction of a ship's pilot plant with hydrocyclone cluster and UV reactor, which was installed on the training-research ship Naše

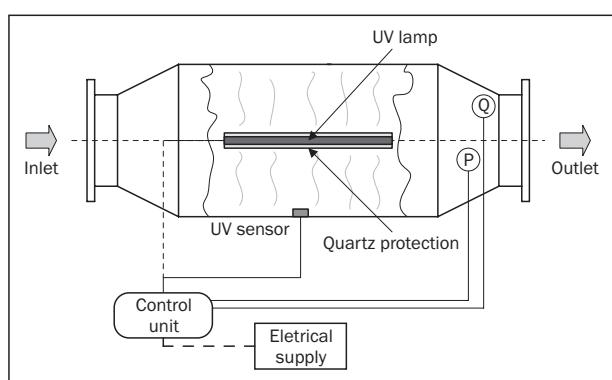


Figure 3 - UV device chamber

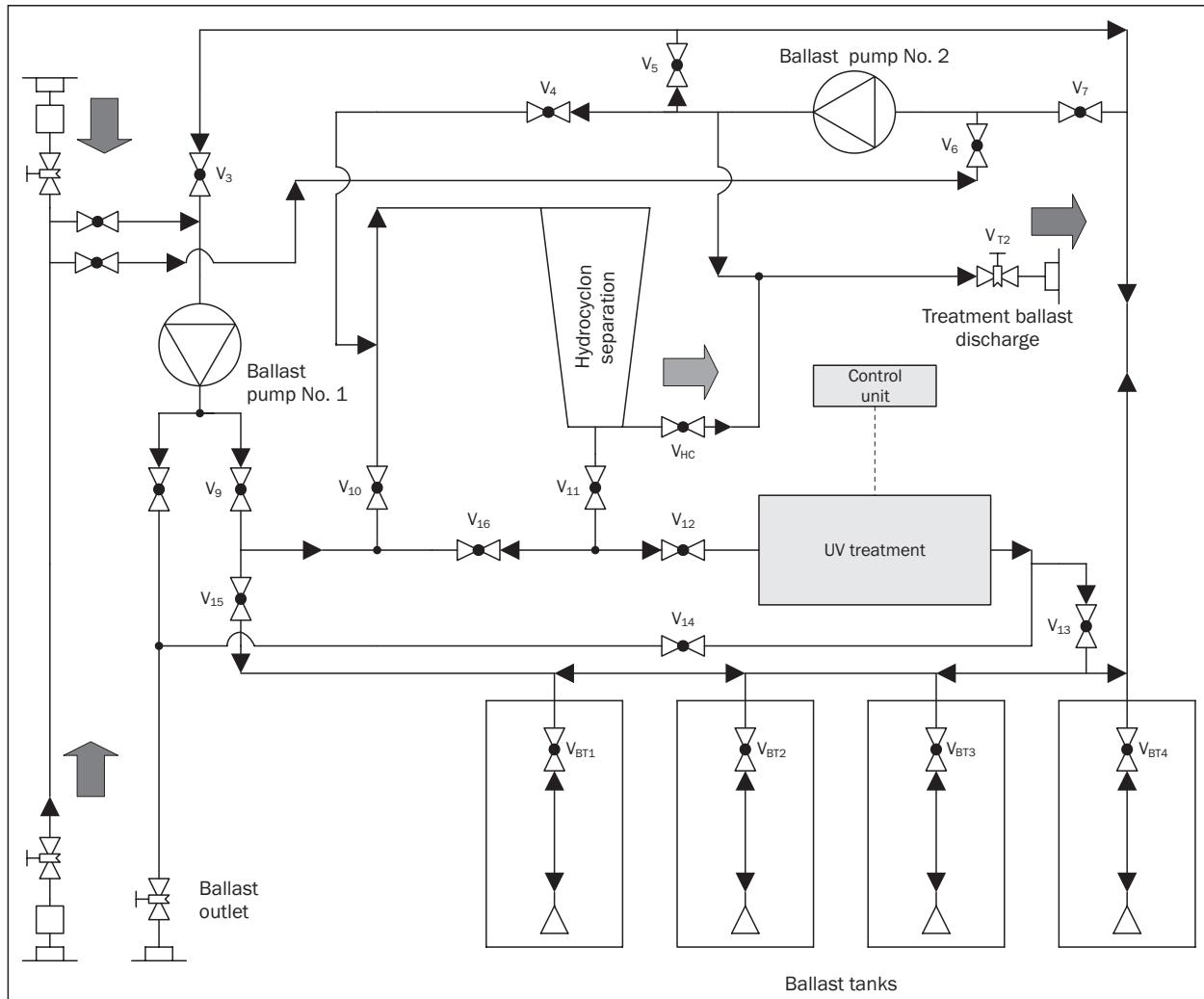


Figure 4 – Proposal for application of the combined method in the existing ballast system on board

more to enable experiments when the ship is in navigation.

The system consists of hydrocyclone cluster containing two series of connected hydrocyclones (6 larger and 12 smaller ones) that can work alternately. Behind the cluster there is a UV device located on the upper deck. The system capacity is adjusted to the ship's centrifugal general service pump ($30\text{m}^3/\text{h}$). According to the conclusions made by IMO Working Group for Ballast and Other Ship's Vectors⁴ in case of testing a pilot plant all tests must be performed on one cubic metre of sea water as a minimum sample. Consequently, it was necessary to install three tanks with a total capacity of 1m^3 located on the middle deck. Located on the lower deck there are 4 concentrators.

The sea pumped by general service pump is fed to tank No. 1 – 1000l and overflows into the concentrator for the analysis of the quantity and structure of organisms in the sea. The entry status having been identified the sea is fed into hydrocyclone cluster. Sludge from the hydrocyclone (heavy phase) is collected into 200l tank, and the treated sea from the hydrocyclone

is first fed into tank 2 – 1000l and then into the concentrator. Next, the sea is fed into hydrocyclone cluster and UV reactor, and tank No. 3 and concentrator. The construction of the system enables separate testing of efficacy of each series of hydrocyclone clusters and combined operation of cluster and UV reactor.

Within the process of testing efficacy of the pilot plant on board a number of experiments have been performed in the Dubrovnik coastal area, Gulf of Šibenik and Omišalj inlet. Figure 6 shows a diagram of research results in the Gulf of Šibenik. The sea was pumped by the general service pump and treated in hydrocyclone cluster through a series of 6 smaller hydrocyclones in three consecutive cycles under pressure of 5.0 bars. In each cycle 10m^3 of sea was treated. The treated 10m^3 was after each cycle concentrated through a plankton filter into a separate canister. This procedure provided samples for each of the three hydrocyclone cycles - HC1 (1, 2 and 3), and samples for each hydrocyclone + UV cycle - HCUV (1, 2 and 3). The average population of zooplankton during the experiment was 31,872 organisms per m^3 of the sea. By hydrocyclone cluster

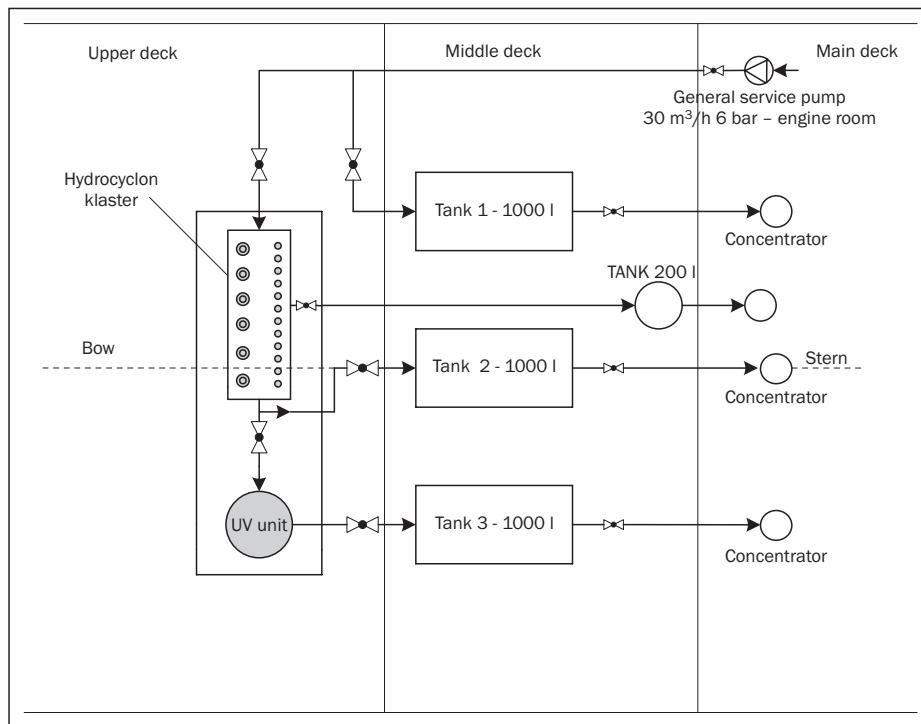


Figure 5 – Diagram of pilot plant for ballast water treatment

approximately 62.69% of organisms were separated (through the apex – sludge outlet). There were 37.31% of admitted organisms on the average (through the overflow – purified water outlet), out of which some 95.3% of organisms was dead. From the population of organisms from the surrounding sea some 1.75% of organisms survived in ship's tanks.

Up to the present, the research made on the application of hydrocyclone in ballast water system treatment on board was focused exclusively on the removal of the heavier phase, i.e. organisms as sludge through

the apex. The mentioned approach resulted in elimination efficacy usually under 50%. The experiments made on the pilot plant showed that a major part of population of organisms was inactivated in the hydrocyclone, and not separated through the heavy phase outlet. Computer simulations revealed that inactivation was caused by the acceleration to which organisms were exposed while passing through the hydrocyclone (Figure 7).

Simulations of flow through hydrocyclone indicated that organisms were exposed not only to high acceleration but also to decompression of 65 bar/s. The results obtained prove that inactivation of plankton organisms by hydrodynamic forces created during sea water flow (ballast water) is possible and very efficient.

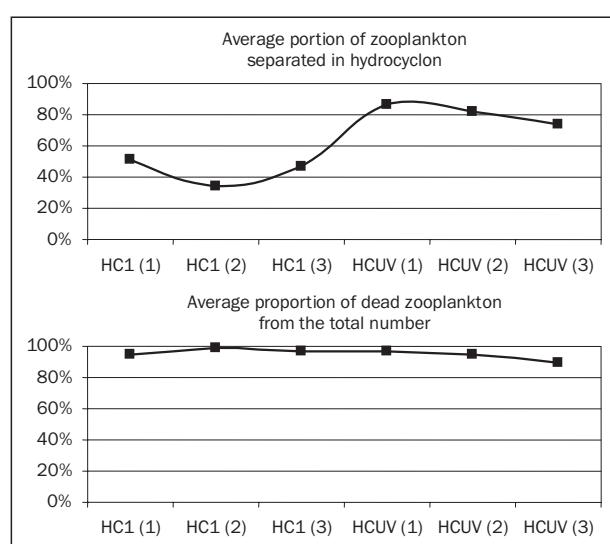


Figure 6 – Diagram of research results in the Gulf of Šibenik

Source: [13]

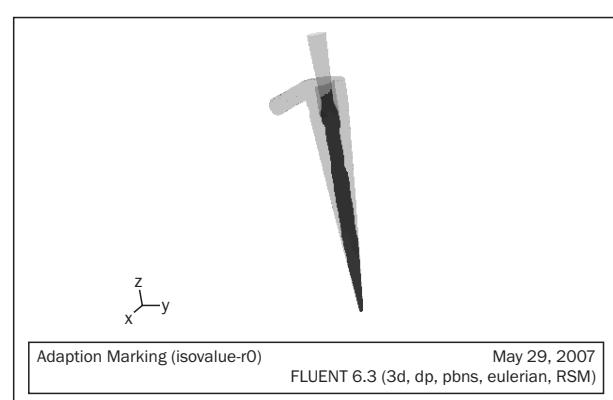


Figure 7 – Simulation of acceleration in hydrocyclone, acceleration shown as black > 5000g

Source: [13]

Namely, each organism has a tolerance limit with respect to value of acceleration and swift almost instant decompression. UV device as secondary, safety component additionally sterilizes the ballast water destroying possibly remaining live microorganisms.

Consequently, on the basis of the obtained results this method of utilization of hydrocyclone has been patented in the State Intellectual Property Office of the Republic of Croatia under the title "Method and Conception of a Ship's Plant for Inactivation of Plankton Organisms in Ballast Water by Hydrodynamic Forces", acronym UNIDU - BWIHD (University of Dubrovnik - Ballast Water Inactivation by Hydrodynamics). The international procedure for registering the patent has been started in order to protect the copyrights on the invention under number PCT/HR2008/000034 and title *Method and a Ship Plant for Inactivation of Planktonic Organisms in Water Ballast by Hydrodynamic Forces*.

6. CONCLUSION

Most of the water ballast treatment methods are still being developed or are in the initial phase of research. The existing ballast water exchange methods will not be able to comply with the strict requirements prescribed by international regulations. In closed sea the operational advantages of the treatment method by hydrocyclone and UV radiation may be crucial for their wider application. By satisfying the existing exchange criteria in the Mediterranean, it is often impossible to perform full ballast water exchange in the exchange zone defined by the criteria given. The treatment system can be efficiently applied on ships sailing on relatively longer voyages outside the closed seas as well.

By combined methods, such as hydrocyclone separation and UV radiation, a satisfactory primary elimination of larger organisms is achieved in the first phase, which leads to higher efficacy of inactivation by application of UV radiation in the second phase. Advantages of such treatment methods lie in the very application of the treatment that can be performed during all phases of ballast water treatment on board.

The research made so far on the application of hydrocyclone separation has been mainly focused on utilization of hydrocyclone as a device for elimination of the heavier phase (organisms) from ballast water and has resulted in a relatively small biological efficacy. Research on the potential application of the combined method of hydrocyclone separation and UV radiation on board has led to the construction of the pilot plant on which hydrocyclones are used not only for the separation but also the inactivation of organisms is accomplished by hydrodynamic forces. In hydrocyclone clusters, consisting of a series of connected hydrocy-

clones the inactivation occurs due to extremely fast acceleration and decompression that the organisms cannot endure. Thus, a new method of utilization of hydrocyclones in ballast water treatment has been found. The efficacy test results have confirmed the main hypothesis of this research work so that further research on the improvement of pilot plant efficacy will be directed onto the application of hydrocyclones operating with acceleration of particles over 10,000g and decompression of 130 bar/s, which is expected to further improve the efficacy of inactivation of organisms in ballast water on board.

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SAŽETAK

PRIMJENA HIDROCIKLONA I UV ZRAČENJA KAO METODE OBRADE VODENOG BALASTA

Metode izmjene vodenog balasta na otvorenom moru su zasada prevladavajući postupak prihvaćen od strane brodara. Međutim takvim metodama se ne može postići potpuna efikasnost odstranjuvanja alohtonih organizama. Pored toga u određenim zonama plovidbe pogotovo u zatvorenim morima ne mogu se ispuniti niti kriteriji koje propisuje međunarodna regulativa, odnosno udaljenosti provedbe izmjene više od 200 Nm od obale (alternativno 50 Nm) i kriterij dubine mora veće od 200 m. Izrazito veliki broj raznih istraživanih metoda obrade navodi na stav kako još nema znanstveno utemeljenog stava o konačnom odabiru metoda koji bi naišle na širu primjenu na brodovima. Metode obrade kao što su hidrociklonska separacija u prvom stupnju i UV zračenje u drugom stupnju imaju značajne izglede za primjenu na brodovima.. Prednosti takve kombinirane metode su u samoj primjeni obrade koja se može obavljati tijekom svih faz postupanja s vodenim balastom, odnosno ukrcaja balasta, putovanja u balastu i iskrcaja balasta. U zatvorenim morima i na kraćim putovanjima operativne prednosti hidrociklona i UV zračenja mogu biti odlučujuće za njihovu primjenu. U sklopu istraživanja moguće primjene obrade vodenog balasta hidrociklonom i UV zračenjem konstruirano je pilot postrojenje s hidrociklonskim klasterom i UV uređajem. Istraživanja obavljena na pilot postrojenju ugrađenom na brodu Naše more dokazala su učinkovitost takve metode obrade vodenog balasta i otkrila novi pristup korištenja hidrociklona za inaktivaciju organizama hidrodinamičkim silama. Takvim pristupom značajno je povećana efikasnost uređaja i otkrivena nova metoda korištenja hidrociklona za obradu vodenog balasta na brodovima.

KLJUČNE RIJEČI

obrada vodenog balasta, hidrociklon, UV zračenje, primjena metode, pilot postrojenje, hidrodinamičke sile

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