Original scientific article

New ballast water treatment system – combination of filtration, hydrocyclone and cavitation tehnologies

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ABSTRACT

Ballast water released from the cargo ships often acts as an inoculation mechanism for a large number of non-indigenous species that can have an important influence on marine ecosystem's change and even devastation.

The IMO's "Convention for the Control and Management of Ships' Ballast Water and Sediments" demands the establishment of ballast water management system which should solve the question of uncontrolled taking and the operations connected to ballast water releasing. Also, it has been planned to complete the transition to ballast water treatment system.

The faculty team work on project which main aim is to examine and develop the principle of technology for ballast water treatment, whose action is based on the use of the combination of filtering technology, hydrocyclone and cavitation.

Until now, the project has proved the possibility of hydrodynamic cavitation appearance inside the hydrocyclone that has been an unexplored phenomenon so far. The next step of the project is to prove hydrodynamic cavitation effectiveness in a joint operation with hydrocyclone which should offer a solution for disabling and removing marine organisms from ballast water.

Key words: Ballast water, convention for the control and management of ships' ballast water and sediments, combination of filtering technology, hydrocyclone and cavitation

Received: 30. 1. 2013
Accepted: 15. 11. 2013

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INTRODUCTION

Ballast water from ships is considered the most important vector of non-indigenous organisms in aquatic ecosystems [1]. The transport of the world's ship ballast water stands at about 12 E9 t per year, and it is estimated that the ship's ballast tanks can transfer at least 10 000 different species of organisms [2].

The ballast water discharged from ships acts as an inoculating mechanism for non-indigenous species such as viruses and bacteria, Dinoflagellate, diatoms and other protists, zooplankton, benthic fish, as well as eggs, spores, seeds, cysts and larvae of various aquatic plants and organisms.

In addition, zooplankton, especially copepods, may be a carrier of pathogenic bacteria, such as *Vibrio cholerae* and *Vibrio alginolyticus* [2].

In February 2004, International Maritime Organization (IMO) adopted a regulation – "Convention for the Control and Management of Ships' Ballast Water and Sediments (Ballast Water Convention)". It regulates the methods of unloading ships' ballast water [3,7].

The convention refers to the reduction in the risk of non-indigenous species from sea ballast waters [4,5,6], and the main aim of the convention is to establish a Ballast Water Management System. The Ballast Water Management System shall solve the problem of uncontrolled intake and operations related to ballast water discharges in the period between 2009 and 2016.

In the future, instead of the existing system of ship's ballast water exchange, a complete transition to a system of ballast water treating is planned, which means that the ship's ballast water will be treated in accordance with standard rules of D-2 Ballast Water Convention before they are discharged into the marine environment [4, 7, 8].

D-2, a ballast water quality standard, requires that in a cubic meter of discharged ballast water should not be more than 10 surviving organisms that are equal as or greater than 50 μm, and in one milliliter should not be more than 10 surviving organisms whose dimensions are between 10 and 50 μm [9].

This standard also refers to the pathogens that represent a potential threat to human health. The standard is governed by the general health standards and sets a maximum number of colony forming units (cfu) per hundred milliliters of water for the three types of chosen indicator microbes, as follows [7, 8]: toxicogenic *Vibrio cholerae* (1 cfu/100 ml, or 1 cfu per gram of zooplanktonic sample, *Escherichia coli* (250 cfu/100 ml) and intestinal enterococci (100 cfu/100 ml).

The treatment of ballast water on ships is carried out by using the technologies that are integrated into the ballast system from the intake through the tanks down to the discharge. Thus the ballast water treatment can be performed during intake or discharge at the inlet/outlet, in the pipes or in the ballast tanks during navigation [10].

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The treatment of ballast water on ships is carried out by using the technologies that are integrated into the ballast system from the intake through the tanks down to the discharge.

According to the IMO Convention, ballast water treatment technologies should be [11, 12,13]: (1) safe, (2) environmentally friendly, (3) feasible, (4) cost-effective, and (5) biologically effective.

Very few of the existing ballast water treatment technologies meet all the five criteria of the IMO Convention. These are, for example [7]: UV irradiation, Ultrasonic treatment, Ozonation, SeaKleen technology, Deoxygenation, Cavitation, etc. Still, not one of these technologies is fully satisfactory. Thus, we decided to combine interdisciplinary experience of our research group to possibly find a new and acceptable solution that will meet the mentioned criteria of the IMO Convention.

The functioning of new technology is based on a combination of filtration, hydrocyclones and cavitation. The aim of experiments is to examine so far unexplored phenomenon of the appearance of hydrodynamic cavitation within the hydrocyclone. They will also try to prove the effectiveness of these combinations of technologies in removing marine organisms from ballast water.

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Filtration is used as the first step and the primary procedure of ballast water treatment in the new system (ship's filter with a grate 8 * 8 mm in diameter). The filtration eliminates organisms and waste of larger dimensions. Filtered water, with a help of the pumps, comes into the hydrocyclone, which uses centrifugal force to separate particles and organisms denser than the water density. They are eliminated through the lower exit of the hydrocyclone.

The functioning of new technology is based on a combination of filtration, hydrocyclones and cavitation.

Hydrocyclones are inertial devices that enable separation or concentration of macrofluids as a suspension due to differences between the inertial forces that manage the movement of suspended substances in a liquid cargo [14]. The basic mechanism of hydrocyclone operation is the swirling flow, which influences the creation of centrifugal force [10, 15]. Sea water and organisms it contains do not have the same density.

Organisms and sediment with a density greater than the density of water are suppressed by the swirling flow towards the wall of the hydrocyclone. They will glide down the wall and at the end of the process they will be ejected through the bottom outlet. The phase with less density, i.e. purified ballast water, remains in the central part, where, affected with the internal vortex, passes through the upper exit [16].

Figure 1 shows appearance and parts of the hydrocyclone device.

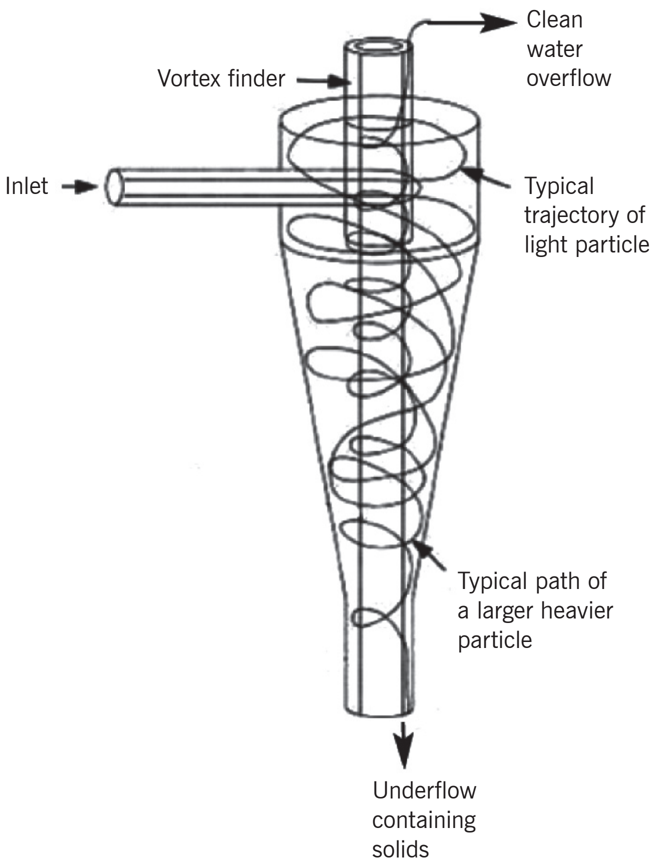

Figure 1:
Appearance and parts of the hydrocyclone device, (Source: Lloyd's Register. Ballast water treatment technology Current status. London, 2010.)

Hydrocyclones are considered to be a sustainable technology for the treatment of ballast water because of the simplicity of use, operation and maintenance, low power consumption, the possibility of working with a high water flow and resulting in a significant reduction of the problems associated with sedimentation in tanks. It is important to mention the fact that they do not have any impact on the health or safety of the ship and its crew.

Cavitation represents the phenomenon of creation, growth and collapse of micro bubbles in a fluid. When a certain volume of fluid is exposed to a sufficiently low pressure, the fluid can burst and form a cavity (cavitation) [17]. Soon after this burst, the vapour collapses back into the fluid - in this phase very high pressures and temperatures may be achieved on a micro scale.

The effects of hydrodynamic cavitation on chemical/physical processes and transformations are particularly investigated in the past decade [18]. The main reason for the development of hydrodynamic cavitation is a variation of pressure in the fluid flow, whereby vapor cavities can be formed anywhere in the liquid flow [19].

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So far, hydrodynamic cavitation has been successfully applied for water disinfection, enzyme recovery and waste water treatment [20, 21]. Hydrodynamic cavitation can be scaled up for operation on very large scale, especially as required for ballast water treatment [17].

Our idea is that hydrodynamic cavitation within the hydrocyclone should destroy the remaining organisms, i.e. the organisms whose density is equal as or less than the density of water and have escaped the centrifugal separation in the hydrocyclone. This step would also be the third (final) phase of operation of the new device for the ballast water treatment.

Until now, the use of these technologies for the ballast water treatment has been relatively well known and researched, one by one. Also, the combination of filtration and hydrocyclone technology is well known, and the application of these technologies in removing marine organisms from ballast water achieves high efficiency. But until now there are no reports on the proposed combination of filtration, hydrocyclone and hydrodynamic cavitation.

What is most important is the fact that the technologies proved their environmental acceptability; they are safe and economical without harmful chemical reactions or consequences to humans and environment.

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Sedna's system is one of the ballast water treatment systems that uses a combination of hydrocyclones and fine filtration (50 μm), together with a chemical agent Paraclean Ocean [22]. This ballast water treatment system has shown 98 % efficiency.

The technologies which have also combined in their work the use of hydrocyclones and filtration, and which, at the same time, meet the regulation D-2 of the IMO Ballast Water Convention are: ERMA FIRST S.A [23] (a combination of hydrocyclone, filtration and electrolytic cell for the extraction of chlorine to destroy the remaining organisms) and Hamworthy Greenship B.V. (a combination of hydrocyclone, filtration and electrolytic chlorination) [24].

Although successful application of a combination of filtration and hydrocyclones in the ballast water treatment has been scientifically proved up to now, the fundamental problem of existing technologies is the last stage of technology operation. It has always involved the use of chemicals which means the increase of risk for humans and environment.

Although successful application of a combination of filtration and hydrocyclones in the ballast water treatment has been scientifically proved up to now, the fundamental problem of existing technologies is the last stage of technology operation.

Also, the use of chemicals further increases the overall cost of technology. There is a risk of corrosion or other harmful impacts on materials, and there is a need for specific additional training of the crew on handling the technology.

The foreseen characteristics of our proposed new ballast water treatment technology are:

– No harmful effects on the environment
– Cost of technology (low power consumption, the use of relatively cheap materials, ease of maintenance, ease of handling)
– Low cost of purchase and device installation
– Universality of application in relation to the size and purpose of the ship, and the capacity of ballast tanks

- Relatively short time of treatment with new technology
- High percentage of efficiency in operating the technology
- No risk of corrosion
- Does not release toxic compounds and it is not hazardous in reaction with other substances
- Adjustable technology in terms of space (does not take up a large area)

METHODS

Description of laboratory pilot device

The pilot device consisted of a chamber, integrated by the cylindrical and conical parts (Figure 1). The cylindrical part of the chamber was made of Plexiglas material due to experimental needs, while the other parts were made of steel. The hydrocyclone was connected to the centrifugal pump.

The laboratory pilot device consisted of a hydrocyclone whose dimensions are shown in Table 1.

Table 1: Dimensions of laboratory hydrocyclone

Width	18 cm
Length	36 cm
Cone length	32 cm
Cone angle	16°
Pressure	0,5-2 bar

The pilot device was constructed in such a manner that at the entrance of the vortex finder the phenomenon of hydrodynamic cavitation occurred. In order to achieve the best possible effect, in the first experiment, the entrance of the vortex finder, at the inlet section, had two conical mouths. A phenomenon of cavitation occurred at the "K" point of the cone.

In the second cycle of testing, the nozzles with holes of various diameters were set up at the end of the vortex finder (photo 1), while the third cycle of research included experiments with cross-shaped additions to the nozzles with 6 or 8 partitions mounted at the end of the vortex finder or inside the vortex finder. The additions to vortex finder were used as mechanisms for calming down the vortex and increasing the longitudinal speed of the fluid which resulted in increased cavitation.

In the experiments, two variations of vortex calming crosses were used – the first combination used in the experiments was a nozzle with a cross which was placed in the vortex finder of the hydrocyclone, while in the second variation, the cross was placed at the exit of the vortex finder as an inner extension of the vortex finder. The third variation used

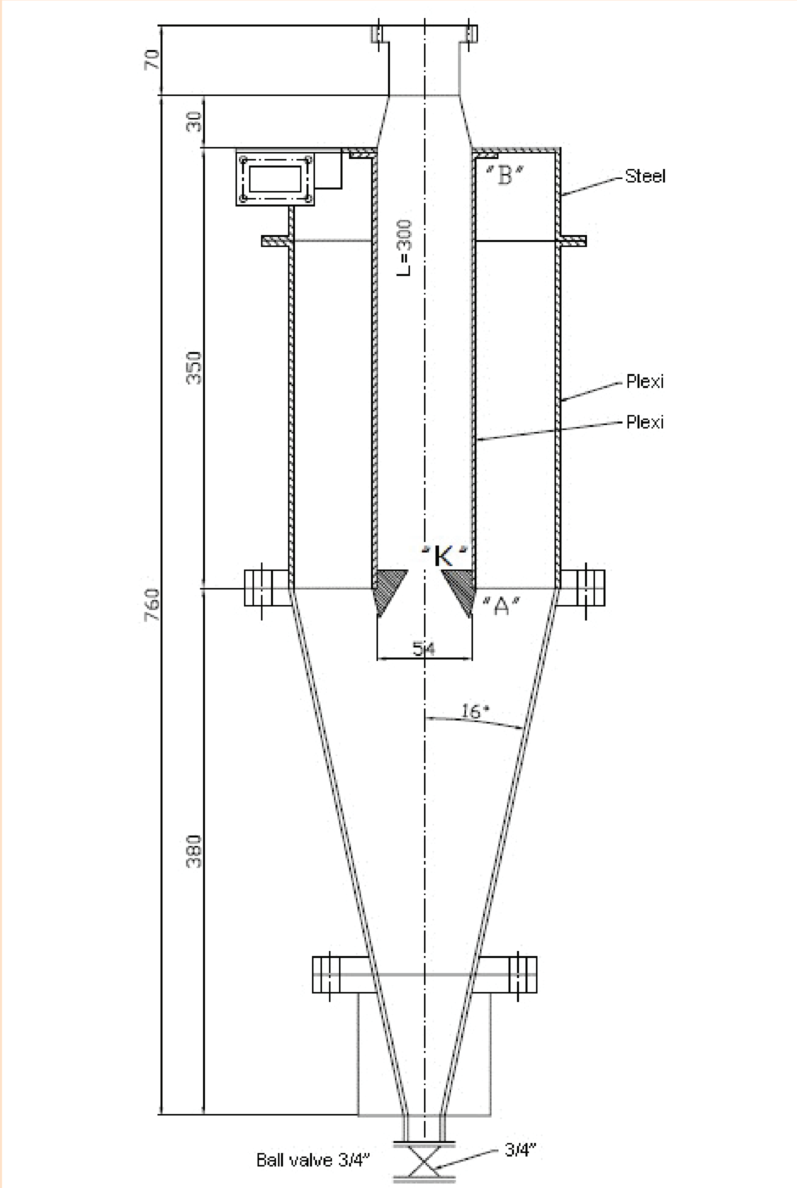

Figure 2:
Schematic representation of the laboratory pilot device

in the experiments implied a combination of the last two mentioned systems.

Namely, the purpose of this segment of the experiment was to demonstrate the theoretical assumption that there was an increase of fluid velocity on the outer end of the vortex finder, which was caused by the placing of obstacles in different diameters, with the aim of creating rapid constrictions.

Photo 1:
The appearance of nozzles for hydrocyclone vortex finder

Therefore, the main goal was to increase the velocity of the fluid on the outer end of the vortex finder, with the aim of decreasing the pressure and, at the same time, creating the conditions for hydrodynamic cavitation occurrence.

The inflow of water into the hydrocyclone had a rectangular cross section, positioned tangentially with respect to the outer surface of the hydrocyclone. The ball valve 3/4" at the bottom (bilge) controlled the flow of waste water (sediments and majority of organisms) on exiting the hydrocyclone and returning them back into the sea.

The methods used and the further development of research

At this stage of research, a pilot device (hydrocyclone) was constructed, and the behavior of water flow within the hydrocyclone was monitored. With the aim of development of hydrodynamic cavitation phenomenon on the vortex finder, the nozzles with 8,12,14,16 and 20 mm diameter were tested, and also one nozzle with 19 holes 4 mm in diameter, and a combination of cross-shaped additions to a nozzle with 6 or 8 compartments that were placed at the end of or inside the vortex finder of the hydrocyclone.

With every change of a nozzle, or a nozzle with addition, the following factors were measured: flow rate, the pressure at the inlet (*p*1), the pressure before reduction (*p*2), the pressure at the entrance of the hydrocyclone (*p*3), the pressure of the hydrocyclone bilge (*p*4), the pressure at the exit of the hydrocyclone (*p*5), the pressure on the outer rim of the hydrocyclone (*p*6), the pressure on the inner rim of the hydrocyclone after the occurrence of hydrodynamic cavitation (*p*7), the pressure at the point of hydrodynamic cavitation (*p*8), the velocity of water in the vortex finder, the speed of water when passing through the nozzle (theoretical value).

The inflow of water into the hydrocyclone had a rectangular cross section, positioned tangentially with respect to the outer surface of the hydrocyclone.

In this phase, the hydrocyclone of corresponding characteristics was constructed, and the behavior of water flow within the hydrocyclone and the occurrence of phenomenon of the hydrodynamic cavitation and fluid motion trajectory were monitored, too.

In the next step of the research, the samples of sea water will be taken and the properties, the content and the presence of certain organisms in the sample before and after the treatment with new technology should be checked.

Further research will be divided into three groups:

1. Treatment of phytoplanktonic species;
2. Treatment of cysts and nauplii
3. Treatment of zooplanktonic species

The next phase of research should focus on checking whether the results obtained during experiments meet the quality standards of ballast water regulation D2, BWP (Ballast Water Performance).

The final step of the research of new ballast water treatment technology will be a trial testing of the effectiveness of the technology on board. The objective of this phase of the project is to examine the previously tested technology in real conditions, when the technology is integrated on the ship.

3. RESULTS AND DISCUSSION

The results of laboratory experiments with a pilot unit, where the nozzles of different diameters as well as the nozzles with combination of additions were used, are shown in the Table 2. Experiments were performed at the air temperatures of 20-21 °C, and the water temperature 19.32 °C.

An explanation for the nozzle and channel shapes:

0 - Normal nozzle with a hole

1 - Nozzle 0 with a cross for the vortex calming down

2 - Nozzle 0 with a cross for the vortex calming down positioned on the vortex finder

3 - Nozzle 1 with a cross for the vortex calming down positioned on the vortex finder

The basic parameter that describes the process of cavitation is a cavitation number. It is calculated by the following equation [26]:

$$\sigma = \frac{p_0 - p_v}{\frac{1}{2}\rho V^2}$$

Where: ρ is the density of the fluid, p_0 characteristic pressure, p_v is the vapor pressure of the liquid, V is a characteristic velocity of the flow.

Table 2: Results obtained from the experiments on a laboratory pilot unit

Nozzle	Form of nozzles and channels	Flow Q0		S nozzle	v nozzle (teoret.)	v outlet pipe	σ (cavit. No.)
ø [mm]		[m³/h]	[l/s]	[x 10^{-3} m²]	[m/s] (teoret.)	[m/s]	
12	0	2,77	0,769	0,113	6,803	0,367	10,187
12	2	2,72	0,755	0,113	6,680	0,361	8,144
12	3	2,62	0,727	0,113	6,434	0,348	10,899
14	0	4,57	1,269	0,154	8,246	0,607	4,927
14	2	4	1,111	0,154	7,217	0,531	5,177
14	3	5,96	1,655	0,154	10,754	0,791	**2,658**
16	0	4,55	1,263	0,201	6,286	0,604	12,142
16	1	5,55	1,541	0,201	7,667	0,737	5,087
16	2	5,4	1,5	0,201	7,460	0,717	6,468
16	3	8,88	2,46	0,201	12,268	1,179	**2,305**
20	1	8,92	2,477	0,314	7,887	1,184	4,539
19x 4	1	8,5	2,361	0,238	9,889	1,129	3,855
19x 4	3	8,34	2,316	0,238	9,702	1,107	3,973

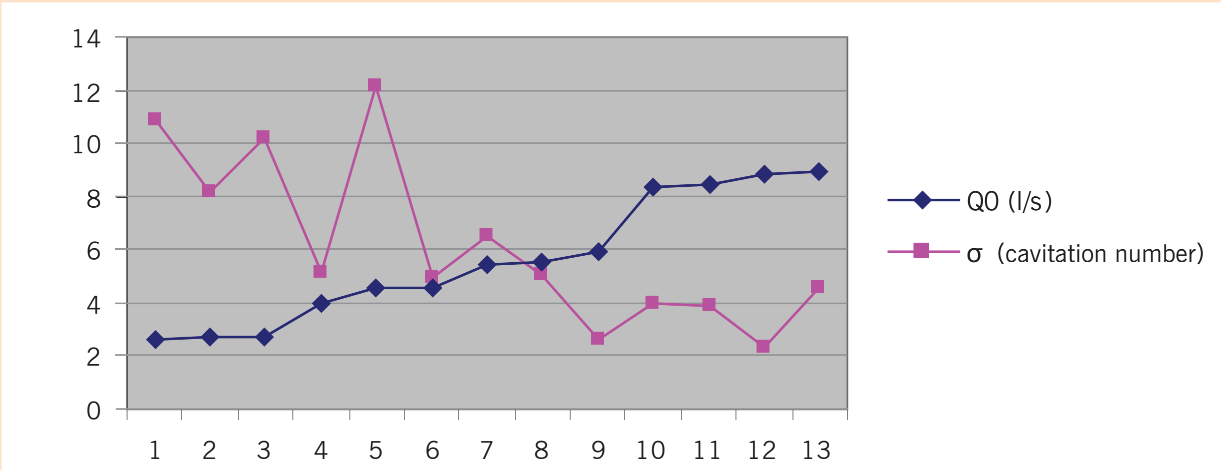

Figure 3:
Dependence of the flow Q_0 (l/s) on cavitation number σ

With the decrease of cavitation number σ the possibility of cavitation occurrence increases. If σ decreases below 2.5, the cavitation will appear. As the mentioned number decreases and approaches number one, cavitation will be getting stronger and stronger. When cavitation number is greater than one, it means that the fluid is resistant to cavitation. When cavitation number is less than one, it means that fluid energy (velocity head and pressure head at constriction) is being taken for the creation of vapor phase and hence cavitation [17].

Figure 2 shows the experimental results that describe the connection of hydrodynamic cavitation and flow in the pilot device. The graph shows the increasing flow in the laboratory hydrocyclone, which consequently influenced the decrease of cavitation number in the pipes (namely, with the increase of the flow rate, the velocity of fluid consequently increases, too). The results showed that the increase of the flow in the hydrocyclone had influenced the increase of the possibility of cavitation occurrence.

As evident from Table 2, the best efficiency (ie the strongest cavitation) was achieved during the usage of the nozzle 16 mm in diameter, and the addition of a cross for the vortex calming down, that was placed on the vortex finder and had a flow rate of 2.47 l / s

Figure 4:
Dependence of cavitation number σ on the diameter of a nozzle

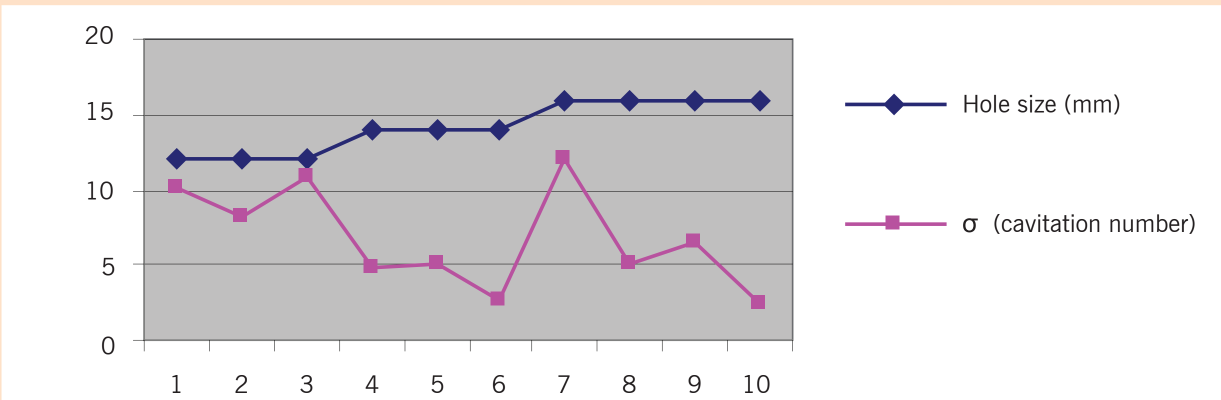

Figure 3 shows the dependence of cavitation number on the diameter of the nozzle mounted on the vortex finder of hydrocyclone. As evident from the graph, the most powerful hydrodynamic cavitation occurred during the usage of a nozzle 16 mm in diameter and with an additional cross for the vortex calming down, set on the vortex finder.

According to the results of the research, a very important effect on the occurrence of cavitation, other than a nozzle diameter, was the determination of proper direction and calming down the water vortex which was executed by using the cross for calming down placed on the vortex finder.

Table 3 and Figure 4 show the theoretical value of losses and pressure drop within a laboratory hydrocyclone for the following flows: 1.39 l / s,

Table 3: Energy losses and pressure drop as a function of changes in the flow of the pilot device

Q0	*d* nozzle	∆v2/2*g*	∆*p*
(l/s)	*(x 10^{-2} m)*	m	bar
1,388	2,5	-0,385	-3,78 E-2
1,388	2	-0,974	- 9,56 E-2
1,388	1,6	-2,412	-2,36 E-1
1,388	1,4	-4,130	-4,05 E-1
1,388	1,2	-7,671	-7,52 E-1
1,388	1,1	-10,875	-1,066
1,388	1	**-15,932**	-1,562
1,666	2,5	-0,555	-5,45 E-2
1,666	2	-1,403	-1,37 E-1
1,666	1,6	-3,473	-3,4 E-1
1,666	1,4	-5,948	-5,83 E-1
1,666	1,2	-11,047	-1,083
1,666	1,1	-15,66	-1,536
1,666	1	**-22,942**	-2,250
1,944	2,5	-0,756	-7,42 E-2
1,944	2	-1,910	-1,87 E-1
1,944	1,6	-4,727	-4,63 E-1
1,944	1,4	- 8,096	-7,94 E-1
1,944	1,2	-15,036	-1,475
1,944	1,1	-21,314	-2,091
1,944	1	-31,227	-3,063
2,222	2,5	-0,988	-9,69 E-2
2,222	2	-2,495	-2,44 E-1
2,222	1,6	-6,174	-6, 05 E-1
2,222	1,4	-10,574	-1,037
2,222	1,2	-19,639	-1,926
2,222	1,1	-27,839	-2,731
2,222	1	**-40,787**	-4,001

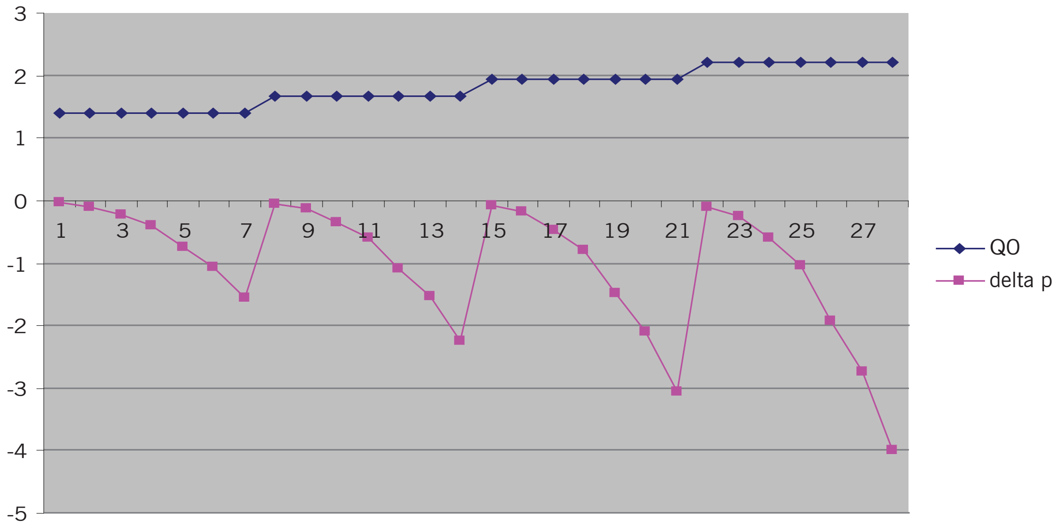

Figure 5:
Dependence of pressure drop on flow rates at different nozzle diameters

1.67 l / s, 1.94 l / s, 2.22 l / s (in the case of experiments with these flows, there was the strongest appearance of hydrodynamic cavitation).

The losses that occurred within the laboratory hydrocyclone increased proportionally with an increasing flow and with a reduction of the nozzle's diameter, as evident from the data given in Table 3. Thus, in these cases, for the smallest nozzle diameter of 0.01 m, (for all the tested flow cases samples), energy losses were the greatest in comparison with other measured flow rates and nozzle diameters.

According to Borda Carnot - equation of losses and pressure drop, depend on the following factors [25]: the density of medium and the square of the change of speed in the system.

According to Figure 4, where the pressure drop dependence on the flow rates of different diameters is shown, the largest pressure drops were noticed in the experiments with a nozzle which had the smallest diameter. This was directly connected with a flow increase. Namely, fluid velocity increases rapidly with the increase of flow and the reduction of the nozzle diameter. There was a sudden pressure drop which was approaching vapor pressure, and it consequently led to the formation of cavitation.

With the aim of the additional reduction of energy losses in further laboratory experiments, one of the possible changes could be the construction change in the structure of the laboratory pilot device.

It has been theoretically proven that if the length of the cylindrical portion (part of plexia) is reduced, than subsequently, for the same used input factors, the losses in pilot hydrocyclone system will be significantly reduced.

Table 4 shows a comparison of losses for the current length of 0.3 m for the cylindrical part of the laboratory hydrocyclone, and if the same was reduced to 0.12 m. Used flow rates were: 1.388 l / s, 1.666 l / s, 1.944 l / s, 2.222 l / s.

4. CONCLUSION

With the aim of achieving a high degree of efficiency in the removal of micro- and macro-organisms from sea water, reducing negative impacts on humans and environment, and satisfying economic criteria, the new ballast water treatment technology has been designed.

The functioning of new technology is based on the use of a combination of mechanical and physical ballast water treatment systems, and the innovation which this technology has brought is the causing of the appearance of otherwise undesirable phenomenon - hydrodynamic cavitation. It has been used for mechanical destruction of marine organisms that survived the previous step, hydrocyclonic treatment.

Former investigations made on the laboratory hydrocyclone have shown the occurrence of hydrodynamic cavitation on the outer edge of the Vortex Finder. Experiments have confirmed the thesis of the interdependence of hydrodynamic cavitation and other parameters such as flow, velocity in the pipe, and the speed in the hydrocyclone vortex finder. The occurrence of the strongest cavitation has been theoretically and experimentally proved during the usage of an addition to hydrocyclone's vortex finder in a shape of a nozzle 16 mm in diameter and a cross for calming down placed on the outer edge of the vortex finder. During the mentioned process, flow rate was 2.47 l/s.

Experiments have confirmed the thesis of the interdependence of hydrodynamic cavitation and other parameters such as flow, velocity in the pipe, and the speed in the hydrocyclone vortex finder.

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