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Kandidatka:

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RAZVOJ METODE OBDELAVE BALASTNIH VOD NA MORSKIH PLOVILIH S CILJEM ZAŠČITE MORSKIH EKOSISTEMOV PRED VNOSOM TUJERODNIH VRST

Doktorska disertacija štev.: 4/VO

DEVELOPMENT OF THE METHOD FOR BALLAST WATER TREATMENT ON SEA VESSELS FOR THE PROTECTION OF MARINE ECOSYSTEMS FROM THE INTRODUCTION OF ALIEN SPECIES

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Abstract

Ballast water is considered as one of the most important factors of the worldwide transfer of invasive alien species in aquatic ecosystems. With the aim of preventing and stopping the spread of the transfer of invasive organisms in aquatic ecosystems and in accordance with IMO's International Convention for the Control and Management of Ships Ballast Water and Sediments, different systems for ballast water treatment have been developed so far. While existing technologies for ballast water treatment have their own advantages and disadvantages, the application of hydrodynamic cavitation (HC), successfully used technology in many different areas with the aim of destroying the organisms or disinfection, remained insufficiently researched. As a part of the doctoral thesis, the detailed research of possibilities for use of hydrodynamic cavitation in ballast water treatment area was conducted. Based on the experiences with the hydrodynamic cavitation presented in the literature, three new pilot systems whose operation included combination of hydrodynamic cavitation as a main step of the treatment and separation as a pre-treatment phase were constructed. The pilot system which showed the highest effectiveness was chosen for the continuation of the experiments to determine the impact on destroying the selected marine organisms. Biological experiments were performed to evaluate the morphological changes and viability of the representatives of zooplankton (copepods), *Artemia salina* cysts, and the growth potential of marine bacteria after the exposure to the treatment in different duration. The results of the tests confirmed a significant efficiency of the treatment on all tested organisms.

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Ključne besede:	**invazivne vrste, upravljanje z balastnimi vodami, sistemi za obdelavo balastnih voda, Mednarodna konvencija za nadzor in upravljanje z ladijskimi balastnimi vodami in sedimentom, hidrodinamična kavitacija, separacija, zooplankton, morske bakterije**

Izvleček

Balastne vode so eden najpomembnejših dejavnikov prenosa invazivnih tujerodnih vrst v vodnih ekosistemih po svetu. Za preprečevanje in zaustavljanje obsega širjenja invazivnih organizmov v vodnih ekosistemih so se, v skladu z IMO Mednarodno konvencijo za nadzor in ravnanje z ladijskimi balastnimi vodami in sedimenti, doslej razvili že različni sistemi za obdelavo balastnih voda. Ker pa imajo obstoječe tehnologije za obdelavo balastnih voda svoje prednosti in slabosti, se je raziskala še uporabnost hidrodinamične kavitacije, ki je bila doslej sicer uspešno uporabljena že na različnih področjih za uničevanje organizmov ali dezinfekcije. Ker pa še ni dovolj raziskana na področju obdelave balastnih voda, je bila v okviru doktorske disertacije opravljena poglobljena raziskava o možnostih uporabe hidrodinamične kavitacije na tem področju. Na podlagi znanih teorij in izkušenj s hidrodinamično kavitacijo iz razpoložljive literature so bile konstruirane tri nove pilotne naprave, katerih delovanje povezuje proces hidrodinamične kavitacije kot glavnega koraka obdelave, in separacije kot predobdelave balastnih voda. S serijo meritev in opazovanjem intenzivnosti kavitacijskih pojavov je bil poiskan pilotni sistem, ki je pokazal največjo učinkovitost. Na slednjem je potekala druga (biološka) faza poizkusov, v kateri se je določal učinek, tj. obseg poškodovanja izbranih vrst morskih organizmov. Biološki eksperimenti so podali ugotovljene morfološke spremembe in preživetje predstavnikov zooplanktona (kopepodov) in cist *Artemie saline,* ter oceno rastnega potenciala morskih bakterij, ki so bili izpostavljeni različnim časom trajanja obdelave. Rezultati so potrdili veliko učinkovitost razvitega načina obdelave na vseh testiranih organizmih.

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KAZALO PREGLEDNIC

KAZALO SLIK

SEZNAM PRILOG

SYMBOLS

Symbol	**Description**	**Unit**
A	Area	m^2
$Ag\text{-}TiO_2 + O_3$	The combination of silver, ozonation and TiO_2 photocatalysis	
d	Diameter	m
f	Frequency	Hz
g	Gravitational acceleration	m/s^2
h	The elevation	m
H	Head	m
H^+	Hydrogen ions	
H_2O_2	Hydrogen peroxide	
K	Loss factor	
L	The length or the diameter of a fluid	m
$l, l_1, l_2, l_n, \ldots$	Linear values that define size, shape, and location of a body	
L_x	Distance between the nozzles	m
N	Number of working cycles of the pilot system per hour	
Na_2SO_3	Sodium sulphite	
NaClO	Sodium hypochlorite	
O_3	Ozone	
OH^-	Hydroxyl ions	
p	Operating pressure	bar
$p_1, p_2, p_n \ldots$	Characteristic pressures within the pilot systems	bar
P	Energy consumption	W
p_0	Characteristic pressure	Pa
p_v	Vapour pressure of a liquid	Pa
Q	Flow rate	m^3/s
r_0	The radius	m
Re	Reynolds number	
s	The surface tension	J/m^2
S	Surface	m^2
t	The duration of the operation	s
T_{air}	Temperature of the air	C
T_{water}	Temperature of the water	C
TiO_2	Titanium dioxide	
v	Velocity of the fluid	m/s

Symbol	**Description**	**Unit**
V	The volume of the system	L or m^3
v_{nozzle}	Velocity of the water inside the nozzle	m/s
$v_{outlet\ pipe}$	Velocity of the water at the outlet pipe	m/s
We	Weber number	
α	The relative thickness	1/m
β	The flow number	
Δp	Pressure loss	bar
μ	Viscosity of a fluid	kg/m/s
ξ	Loss coefficient	
ρ	Density	kg/m^3
σ	Cavitation number	

ABBREVATIONS

A. salina	*Artemia Salina*
ABS	American Bureau of Shipping
AC	Acoustic cavitation
ANOVA	The Analysis of Variance
AOPs	Advanced oxidation processes
BCP	Bacterial carbon production
BTEX	Benzene, toluene, ethylbenzene, and xylenes
BWM	Ballast Water Management
BWMS	Ballast Water Management System
BWT	Ballast Water Treatment
C3T™	Closed Circuit Cavitation
CFU	Colony forming unit
DAPI	Diamino-2-phenylindole
DBPs	By-products of disinfection
DOM	Dissolved organic matter
E.Coli	*Escherichia Coli*
EPA	US Environmental Protection Agency
GESAMP BWWG	Group of Experts on the Scientific Aspects of Marine Environmental Protection, “Ballast Water Working Group”
HC	Hydrodynamic cavitation
IAS	Invasive alien species
IMO	International Maritime organization
LNG	Liquefied natural gas
Ro-Ro	Roll-on/roll-off ship
SD	Standard deviation
TCA	Trichloroacetic acid
USCG	US Coast Guard
UV	Ultraviolet radiation
V.Cholerae	*Vibrio Cholerae*
VLPs	Virus-like particles
VOS	Venturi Oxygen Stripping

1 INTRODUCTION

"Ballast is any material used to weight and balance an object. It is the additional weight necessary to bring a vessel to a suitable draft and to trim and reduce stresses and improve stability" (Satir, 2008).

Regardless of their size or purpose, all ships carry some ballast (Minchin, 2006). Ballast has a unique role in cargo shipping. When ships are loaded with cargo, they do not need to carry ballast because the cargo provides stability to a ship. However, after the cargo is off-loaded from a ship, ballast must be taken on board (Figure 1).

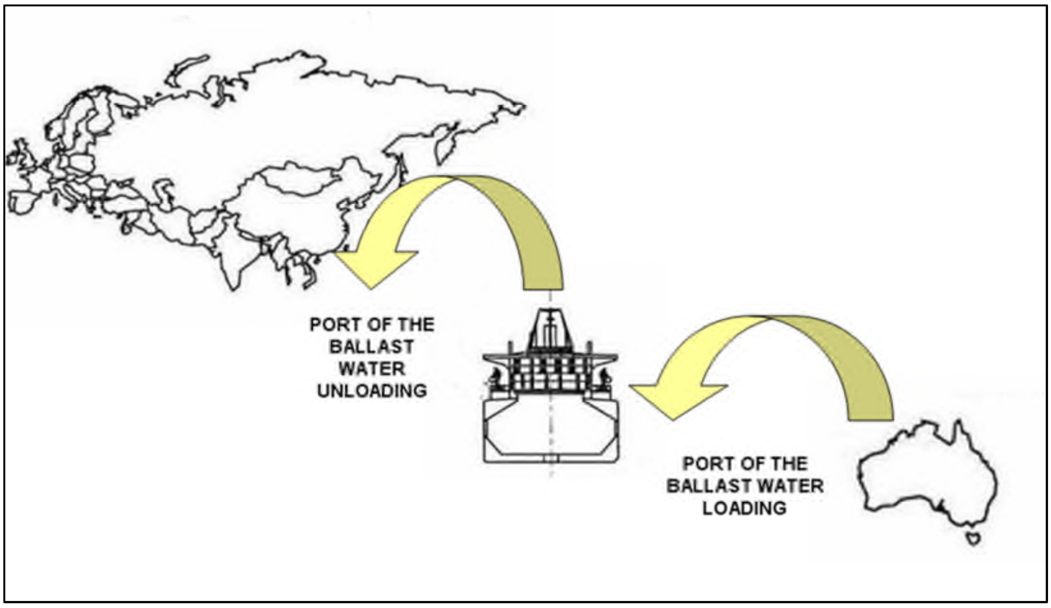


Figure 1: The purpose of ballast water on ships and the routes of loading/discharging of ballast water.
Slika 1: Namen ladijskih balastnih voda in načini njihovega zajemanja/izpuščanja.

The amount of ballast water taken on board of a ship is, according to Ibrahim and El-Naggar (2012), determined by a) safety, b) weather conditions, c) a ship's load and d) its route. Ballast tanks can often vary in size and design which depends on the factors such as size, class or their position on a ship. In most cases, the tanks are situated in different parts of a ship and they are constructed in a way they can be subjected to different environmental conditions (Hewit et al., 2009).

1.1 Problem of ballast water

With over than 90% of share in overall global trade, shipping represents the dominant mode of transport nowadays (Endresen et al., 2004; Hoffmann and Kumar, 2002; IMO, 2012). According to Hua and Hwang (2012), more than 92,000 vessels currently sails different world's waterways. The majority of maritime transport occurs in the northern hemisphere, especially in the areas of the North Atlantic, northern Europe and northern Pacific (Endresen et al., 2003a).

Most ballast water is transported by the following ships (Endresen et al., 2004): dry bulk cargo carriers (39%), oil tankers (37%), general cargo carriers, LNG tankers and chemical tankers (24%), Ro-Ro, and container vessels. For example, just a single large container ship can transport as much as 15,000 t of ballast water.

Today, there are specific regions on the sailing routes of ships which are particularly exposed to huge amounts of exported or imported ballast water. For example, the most critical regions for crude oil carriers in terms of ballast water export are the USA, Europe and Japan, though Middle East, the Caribbean and Africa represent the most critical ports for ballast water import. In the case of bulk vessels, the most critical export regions of ballast water are Asia and Europe while the importing regions represent Asia, Australia and North and South America. (Endresen et al., 2004; Fearnleys, 2000).

Ballast water, hull fouling and aquaculture are considered the most important vectors of the transportation of invasive alien species (IAS) in aquatic ecosystems (Flagella and Abdulla, 2005; Gollasch, 2007). According to Gollasch (2007), the highest amount of IAS in the world is transported by hull fouling and in the European Union by ballast water (Figure 2). The world's ship transport of ballast water stands at about $12x10^9$ t per year. It is estimated that ships’ ballast tanks can globally transfer at least 10.000 different marine species per day (Carlton, 1999; Faimali et al., 2006). For example, the Mediterranean only has 986 invasive species and 12 species were said to be directly introduced by ships (Zenetos et al., 2012). The same number is constantly increasing. It has been estimated that new invasive species come to non-indigenous surrounding every nine days.

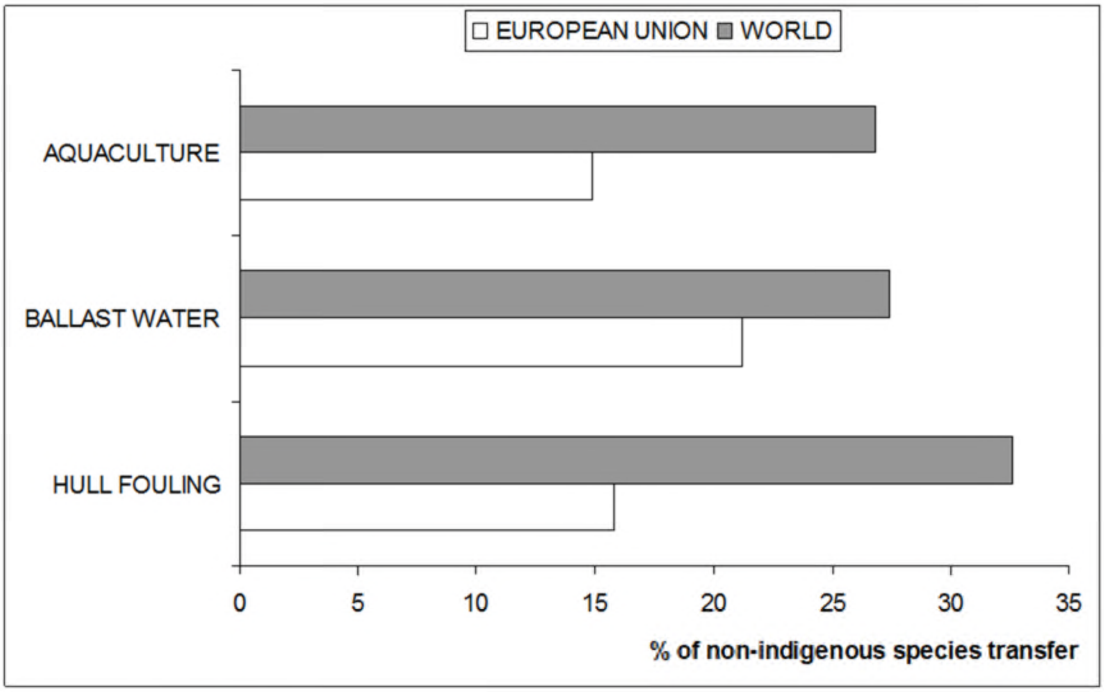


Figure 2: A comparison of invasive alien species' (IAS) transfer caused by hull fouling, ballast water and aquaculture in the world and the European Union expressed in percentage (Gollasch, 2007, modified).
Slika 2: Primerjava prenosov invazivnih tujerodnih vrst (NIS) - z obraščanjem trupa ladij, z balastnimi vodami in vzrejo morskih organizmov v svetu in Evropski uniji, izraženo v odstotkih (prirejeno po Gollasch, 2007).

Damaging effects of the IAS introduced via ballast water are recorded in the seas all over the world (Battle, 2009; Gollasch, 2005), having considerable economic, ecological, and environmental impacts, including the loss of native biological diversity (Battle, 2009; European Commission, 2014). Specifically, in the absence of natural predators, IAS may spread very quickly in non-native habitats. They can displace native organisms in certain areas in the way that they prey on or outmatch native species for both food and habitat. Economic damage occurs when IAS displace the native species important for the food industry or the production of other goods (European Commission, 2014). Consequently, they can negatively affect numerous sectors, such as fisheries, tourism, forestry, agriculture, utilities, water use, natural areas, etc. (Carlton, 1999; Carlton, 2001; Werschkun et al., 2014). The costs of such impacts in the world are estimated to exceed 100 billion US$ per year. Furthermore, the costs arise due to prevention measures such as control, prevention and monitoring, research and education, as well as additional costs of the development of the ballast water treatment systems (Werschkun et al., 2014).

1.2 Development of the systems for ballast water treatment, goals and author's contributions

Current international regulations and recommendations for Ballast Water Management (BWM) were prepared with the aim of controlling and preventing the spread of IAS. The international regulation with the widest global application is IMO's "International Convention for the Control and Management of Ships' Ballast Water and Sediments" (IMO, 2014; ABS, 2014).

Nowadays, very different technologies are used for ballast water treatment, using ultraviolet irradiation, de-oxygenation, heat treatment, ozonation, biocides, acoustic cavitation, and hydrodynamic or acoustic cavitation alone or in combination (Gregg et al., 2009; Holm et al., 2008; IMO, 2014; Liebach et al., 2012; Lloyd's register, 2014; McCollin et al., 2007; Perrins et al., 2006). All of the above listed technologies have advantages and disadvantages: usually environmentally dangerous effects, high installation costs, high energy consumption, complexity, etc.

Despite the fact that hydrodynamic cavitation, which breaks cells of unicellular or multicellular organisms, represents a well-known and widely used method in science, engineering and different industrial processes (Brujan, 2011; Gogate, 2002; Ozonek, 2012; Sawant et al., 2008), the hydrodynamic cavitation process is still insufficiently explored and applied for the ballast water treatment.

Main goals of the doctoral dissertation, as well the author's contributions to ballast water treatment area, are as follows:

a. Explore the possibilities of the use and make a step forward in the application of hydrodynamic cavitation in ballast water treatment
b. To find optimal constructional factors that will result in highly effective hydrodynamic cavitation process in the form of destroying targeted organism species
c. To prove the same or even better effectiveness of the pilot system that uses hydrodynamic treatment in its operation without combining with any active substances compared to the systems for ballast water treatment that use hydrodynamic cavitation in combination with active substances in their operation
d. Develop the system for ballast water treatment whose use will not affect marine ecosystem and living world in it as well as people's health in any way
e. Develop energy efficient and safety acceptable treatment whose characteristics allow adjustment to the limited working conditions required on ships (especially low working pressures which rely on the properties of the ship's pumps).

In consideration of the aims of the doctoral dissertation listed above, the main contribution of the author of this doctoral dissertation supposed to be the performance of a detailed research of application possibilities for hydrodynamic cavitation in ballast water treatment area, as well as quantifying the key treatment parameters that could be used to design a more effective, hydrodynamic cavitation system capable for operation in demanding conditions of ships and high flow rates similar to those on uptake or discharge of ballast water.

1.3 Hypotheses

As the starting point of the doctoral research, we have set the hypotheses whose verity we have wanted to check during the doctoral research. The hypotheses were as follows:

H1: With the use of environmentally friendly and cost-effective technology for ballast water treatment, which includes exclusively the combination of mechanical and physical processes, it is possible to reduce the risk to ships' crew and the environment, and at the same time, achieve the same or higher efficiency in comparison with the technologies that have been used for ballast water treatment so far.

H2: With application of the new technology for ballast water treatment, which will try to remove and return a part of the organisms to their natural habitat immediately during the ballast water loading, the number of organisms which have to be destroyed will considerably decrease. This process should have a positive effect on the preservation of the stability of marine ecosystems.

H3: With a relatively small dimension and spatial flexible systems, it is possible to treat large volumes of ballast water and, at the same time, reach high effectiveness in destruction of organisms, as well a high level of protection of marine ecosystem where the treated water will be returned.

H4: At the entrance to the vortex tube of the hydrocyclone, it is possible to generate the cavitation effect

2 PROBLEM DESCRIPTION

The following chapter describes the most important hazards and brokges related to the transfer of IAS via ballast water on ships, fundamental ways and most effective methods used for controlling and solving the problem of discharging the ballast water. International legal frameworks closely related to the ballast water management are also presented in this chapter. Furthermore, this chapter also contains the advantages, disadvantages and former technologies that use hydrodynamic cavitation as a step of their working process in ballast water treatment.

2.1 Legal frameworks

The international regulations with wide application are IMO’s “International Convention for the Control and Management of Ships’ Ballast Water and Sediments” and the USCG’s “Standards for Living Organisms in Ships’ Ballast Water Discharged in US Waters” (IMO, 2014; ABS, 2014).

2.1.1 International Convention for the Control and Management of Ships’ Ballast Water and Sediments

In February 2004, the International Maritime Organization (IMO) adopted the International Convention for the Control and Management of Ships’ Ballast Water and Sediments (BWM). The BWM convention regulates ways and methods of discharging ballast water from ships (ABS, 2010; Loyd’s Register, 2012). It will enter into force 12 months after the ratification made by a minimum of 30 IMO member states that represent at least 35% of the world’s merchant shipping tonnage. Up to date, 50 IMO member states representing 34.81% of the world’s tonnage have ratified the BWM (IMO, 2016). The primary aim of the convention is to establish a ballast water management system that will solve the problem of uncontrolled intake and operations related to ballast water discharges.

The BWM convention describes two basic methods of ballast water management: Ballast Water Exchange (Regulation D-1) and Ballast Water Treatment (BWT, Regulation D-2). Ballast Water Exchange is a method of ballast water processing in which ships are required to empty ballast tanks and replace ballast coastal water with ocean water (ABS, 2010; Endresen et al., 2004). The Regulation D-1 prescribes the exchange of a minimum of 95% volume of the overall ballast water on ship at least 50 nautical miles from the nearest shore and in waters with a depth of 200 m or more (IMO, 2014; Werschkun et al., 2014).

Ballast water treatment refers to a more complex and effective method for preventing the spreading of IAS. IMO (2004) defines BWT systems as "Prefabricated, commercial-ready treatment systems designed to remove, kill or inactivate organisms that are potentially harmful to human health and receiving ecosystems from ballast water prior to discharge". As a part of Regulation D-2, threshold levels were determined in such a way that they show allowable number of viable organisms and indicator microbes in the ballast water discharged at port (Table 1) (IMO, 2014; Werschkun et al., 2014). When the BWM convention enters into force, threshold levels will become mandatory standards for the discharge of ballast water (Carney et al., 2013; Lloyd's Register, 2014).

Table 1: Allowable number of viable organisms and indicator microbes in the ballast water discharged at port according to Regulation D-2 of BWM Convention (ABS, 2014; Werschkun et al., 2014, modified).

Preglednica 1: Dovoljeno število živih organizmov in indikatorskih mikrobov v balastnih vodah, ki se lahko izpusti v pristanišču, v skladu z Uredbo D-2 BWM konvencije (prirejeno po ABS, 2014; Werschkun et al., 2014).

Size of organism	Regulation (counts per volume)
≥ 50 µm in minimum dimension	<10 per m^3
≥10 µm and < 50 µm in minimum dimension	<10 per mL
Vibrio cholerae	<1 cfu per 100 mL or <1 cfu per 1 g (wet weight) zooplankton samples
Escherichia coli	<250 cfu per 100 mL
Intestinal Enterococci	<100 cfu per 100 mL

*cfu= colony forming unit

The BWM convention determines the approval process of BWT according to the usage of active substances. Systems that use active substances have to go through both the "Procedure for Approval of BWT Systems that Make Use of Active Substances (G9)", and "Guidelines for Approval of Ballast Water Management System (G8)", while systems that do not use any active substance only have to go through "Guidelines for Approval of Ballast Water Management System (G8)" (IMO, 2014b; Joo-won, 2010; Werschkun, 2012).

There are two kinds of possible approvals for fitting systems on board ships: BWTs that use active substances have to go through both the basic approval (pilot scale testing for toxicity) and final approval (land-based and ship test for biological efficiency testing), according to G8 and G9 guidelines. BWTs that do not use active substances only have to go through the final approval according to G8 guidelines. Both systems, with or without the usage of active substances, will obtain Type Approval at the end if the results from the Basic approval report (when applicable) and Final approval report are acceptable. For BWTs that use active substances, additional environmental tests (e.g. corrosion test) are necessary before the BWM is type approved and allowed to be commercialized and installed onboard of a ship (IMO, 2014b; Joo-won, 2010; Werschkun, 2012).

Table 2: The requirements for ballast water treatment (BWT) according to the International Convention for the Control and Management of Ships' Ballast Water and Sediments (ABS, 2011; David and Gollasch, 2008; Lloyd's Register, 2014; IMO, 2014b modified).

Preglednica 2: Zahteve za obdelavo balastnih voda (BWT) v skladu z Mednarodno Konvencijo o omejevanju in ravnanju z ladijskimi balastnimi vodami in sedimenti (prirejeno po ABS, 2011; David and Gollasch, 2008; Lloyd's Register, 2014; IMO, 2014b).

Ballast water capacity (m³) of a ship	**Build date of a ship**	**Date from which BWT is required**
<1.500	Before 2009	First intermediate or renewal survey, whichever occurs first, after the anniversary of the date of delivery of a ship.
<1.500	2009	Entry into force.
<1.500	After 2009	At the date of delivery or at entry into force, whichever is later.
1.500-5.000	Before 2009	First intermediate or renewal survey, whichever occurs first, after the 2014 anniversary date of delivery of a ship.
1.500-5.000	2009	Entry into force.*
1.500-5.000	After 2009	At the date of delivery or at entry into force, whichever is later.
>5.000	Before 2012	First intermediate or renewal survey, whichever occurs first, after the 2016 anniversary date of delivery of a ship.
>5.000	After 2012	At the date of delivery or at entry into force, whichever is later.

The BWM convention categorizes ships into three types (Table 2): according to their size, their total ballast water capacity, and the dates when the BWT becomes mandatory (ABS, 2011; David and Gollasch, 2008; Ruiz et al., 2001). The above-mentioned categorization is regulated by Regulation D-3 of BWM convention.

2.1.2 Other regulations

Ballast water management regulations in the United States are the result of the following rules and regulations: US Environmental Protection Agency (EPA) permits, USCG regulations, and individual state regulations. The final ballast water rule was published in 2012 by the USCG. The most frequent regulations used in the USA are the USCG's "Standards for Living Organisms in Ships' Ballast Water Discharged in US Waters" and California's "The California State Lands Commission Marine Invasive Species Program".

a) *"Standards for Living Organisms in Ships' Ballast Water Discharged in US Waters"*

The USCG supplemented existing BWM regulations with ballast water discharge standards which are equivalent to IMO's BWM Convention. Although the schedule for USCG discharge standards implementation is similar to IMO's BWM Convention schedule, it is not subjected to the ratification. Namely, USCG created a fixed schedule with requirements for ballast water treatment in case of entering US waters. The USCG ballast water regulation entered into force in June 2012 and it is mandatory for all vessels equipped with ballast tanks that enter and operate in the US waters.

b) "The California State Lands Commission Marine Invasive Species Program"

The California State Lands Commission Marine Invasive Species Program is considered the strictest ballast water regulation. It refers to all ships of 300 gross registered tons or more. Currently, all vessels that discharge ballast water in California waters have to carry out ballast water exchange. The requirements related to ballast water exchange depend on the port of origin of the vessel. California developed two kinds of standards for BWT systems, interim and final performance standards. Table 3 presents the allowable number of viable organisms and indicator microbes in the ballast water according to California interim performance standards.

Table 3: Allowable number of viable organisms and indicator microbes in the ballast water according to California interim performance standards (ABS, 2014, modified).

Preglednica 3: Dovoljeno število živih organizmov in indikatorskih mikrobov v balastnih vodah, po začasnih kalifornijskih standardih (prirejeno po ABS, 2014).

Size of organism	Regulation (counts per volume)
≥ 50 μm	No detectable living organisms
10-50 μm	Less than (<) 0.01 living organisms per ml
< 10 μm	Less than 10^3 (1.000) bacteria per 100 ml
	Less than 10^4 living viruses per 100 ml
Escherichia coli	Less than 126 cfu (colony forming units) per 100 ml
Intestinal enterococci	Less than 33 cfu per 100 ml
Toxicogenic *Vibrio cholera*	Less than 1 cfu per 100 ml or
(Human cholera)	Less than 1 cfu per gram of wet weight biological material

Although California State Lands Commission approved a report to the California Legislature, a delay of application of California's interim performance standards was recommended. The final recommended discharge standards are zero detectable living organisms for all organisms listed in Table 3 and they should be mandatory until 1 January 2020.

2.2 Existing methods and technologies for ballast water treatment

The BWT technologies can be integrated into ship's ballast water system at the ballast water intake, discharge, in the pipes or in the ballast water tanks during navigation (Abu-Khader et al., 2011). The mechanisms of living organisms' deactivation in the BWT technologies can be divided into four groups: i) mechanical, ii) physical, iii) chemical, and iv) a combination of the three aforementioned groups (ABS, 2011; Lloyd's Register, 2014; Champ, 2002). The main groups of the BWT technologies available on the market, together with the representative technologies of each group according to IMO, Lloyd's Register, and ABS (ABS, 2011; IMO, 2014b; Lloyd's Register, 2014) are presented in Table 4.

Table 4: Main groups of ballast water treatment technologies and representative technologies of each group (ABS, 2011; IMO, 2014; Lloyd's register, 2014, modified).

Preglednica 4: Glavne skupine tehnologij za obdelavo balastnih voda in reprezentativne tehnologije vsake posamezne skupine (prirejeno po ABS, 2011; IMO, 2014; Lloyd register, 2014).

Ballast water treatment options			
Mechanical systems	**Physical disinfection**	**Chemical treatment**	**Combinations**
Filtration	Ultraviolet irradiation	Electro-chlorination/Electrolysis	Mechanical systems + physical disinfection
Cyclonic separation (hydrocyclones)	Acoustic cavitation with ultrasound	Biocides	Mechanical systems + chemical treatment
Electro-mechanical separation	Deoxygenation	Chlorination	
	Hydrodynamic cavitation	Chloride dioxide	
	Heat treatment	SeaKleen	
		Peraclean Ocean	
		Ozonation	
		Coagulation/ flocculation	
		Chemical reduction (sulphite /bisulphate)	

Mechanical systems, such as filtration or cyclonic separation, are used mainly as a pre-treatment stage, and they can efficiently remove more than 90% of larger particles and organisms (Minchin, 2006) or most particles/organisms with higher density than the seawater. Hydrocyclones represent the inertial devices which, due to their construction, enable separation of particles with densities greater than water. The basic mechanism used by hydrocyclones for their operation is the swirling flow which is formed due to the impact of the centrifugal force (Martínez et al., 2007; Abu-Khader, et al., 2011; Kurtela, et al., 2005). Sea water and organisms it contains do not have the same density, so consequently separation occurs.

With the aim of increasing the effectiveness of the mechanical systems, they are usually combined with other treatment technologies, such as ultraviolet light or heat (Lloyd's Register, 2014; Minchin, 2006).

One of the most commonly used technologies in BWT is ultraviolet irradiation (UV) (30% of recent BWT use UV) (IMO, 2012), which belongs to the physical disinfection category. Even though UV can be very effective in destroying a large number of marine and pathogenic bacteria, microalgae and most zooplankton (Gregg et al., 2009), it is not very useful for the removal of cysts (Liebich et al., 2012; Minchin, 2006). Furthermore, some microorganisms can survive the UV treatment due to enzyme repair systems that repair microbial DNA (Modak, 2008). In addition to UV irradiation, de-oxygenation, heat treatment and hydrodynamic cavitation (HC) are commonly used in BWT. De-oxygenation can be a very favorable option for the damage of several species of zooplankton and phytoplankton if it is combined with chemicals, such as sulphide, or by using the Venturi Oxygen Stripping technology, which rapidly removes almost 95% of dissolved oxygen from ballast water in ballast water tanks (Gregg et al., 2009). The disadvantage of using de-oxygenation for BWT is that some cysts and anaerobic bacteria can survive de-oxygenation process and a completely successful treatment requires lengthy usage of de-oxygenation, which is usually very time-consuming (Gregg et al., 2009; Lloyd’s Register, 2014).

Although the destruction of microorganisms with acoustic cavitation has been used more than 80 years, the usage of acoustic cavitation (AC) or HC in BWT is relatively new and remains insufficiently researched (Gregg et al., 2009; Lloyd’s Register, 2014). In the case of the usage of acoustic cavitation in BWT, zooplankton larger than 100 μm could be reduced by 90%, but acoustic cavitation has shown very low efficiency on phytoplankton and bacterial decrease in abundance (Holm et al., 2008; Mason et al., 2003). In BWT, AC is mostly combined with chemicals whose effect, risks and environmental consequences will be discussed in more details in the following paragraphs.

Most of the recent technologies for BWT use different chemicals alone or in combination with some other technologies. Among various chemicals available on market, the systems that produce free hydroxyl radicals (e.g. the plasma processes for OH^- formation) are preferred over other chemicals (more than 4700 different chemical biocides are used today with the aim of destroying the organisms in oceans and lakes) because they produce fewer or no toxic by-products (Lloyd’s Register, 2014). Each chemical treatment option requires detailed biological, safety and operational efficacy research. Most of the BWT systems use “active substances” as a step of their work. Active substances are defined as ‘‘substances that have a general or specific action on or against harmful aquatic organisms and pathogens’’ (Banerji, 2012; IMO, 2014; Werschkun et al., 2014). The most often used active substances in ballast water treatment are oxidizing agents. These are related to the systems whose composition is based on the usage of chlorine (usually generated by electrolysis of the seawater or from the solutions of hypochlorite stock), ozone, peracetic acid, or chlorine dioxide. The oxidizing agents usually generate by-products of disinfection (DBPs) in different amounts. DBPs were identified for the first time in chlorinated drinking water (Banerji, 2012; Cantor et al., 2010; Werschkun et al., 2014). Because of their high reactivity, strong oxidants are not only reacting with the organisms in the water, but also with numerous other water matrix components (Werschkun et al., 2014). Unfortunately, most of the experiences with chemical reactions in the seawater are, in fact, based on researches with fresh water and some chemicals have not been fully or sufficiently researched in the seawater conditions (Zhang et al., 2013).

Although many different treatment steps in BWT technologies are available on the market, only a combination of two or more different BWT technologies has shown the appropriate removal efficiency of marine organisms from ballast water and, thus, the ability to satisfy standards required by the D-2 standard (IMO, 2014b; Lloyd's Register, 2014). More than 80 BWT system manufacturers with totally 51 IMO type approved systems are identified in the IMO's framework (IMO, 2014b; Lloyd's Register, 2012; Lloyd's Register, 2014). The BWT systems are usually integrated in-line, or in some cases in-tank onboard of the ship (Abu-Khader et al., 2011). Most of the applied systems use treatment during the uptake of ballast water (e.g. systems that use active substances and do not include neutralising agents in their operation), while some systems can treat the ballast water both at the uptake and at the discharge (e.g. UV technologies, systems that use active substances in combination with neutralising agents used immediately before discharge, most of the mechanical methods) while a part of the systems performs the treatment during voyage (systems that use the oxygenation process in their operation) (Lloyd's Register, 2014).

Most of the applied systems use pre-treatment (e.g. filtration or combination of filtration and hydrocyclones). In most of the applied BWT systems, active substances such as sodium hypochlorite are used with the most commonly used electrolysis (electrochlorination) (David and Gollasch, 2012).

2.3 Possible harmful impacts of ballast water to human and ecosystem health

Ballast water discharged from ships acts as an inoculating mechanism for IAS such as viruses and bacteria, dinoflagellates, diatoms, zooplankton, benthic fish, as well as eggs, spores, seeds, cysts and larvae of various marine organisms (Khandeparker and Anil, 2013; Ruiz et al., 2000; Mimura et al., 2005). Some of the most important IAS, with their native area, area of introduction and adverse impacts, are listed in Table 5.

Table 5: The list of the most notable invasive alien species (IAS) in aquatic habitats with native area, area of introduction and adverse impacts (Cvetković et al., 2015).

Preglednica 5: Seznam najpogosteje zaznanih invazivnih tujerodnih vrst (NIS) v vodnih habitatih, z njihovimi avtohtonimi področji, področji vnosa in škodljivimi vplivi (Cvetković et al., 2015).

Group	Organism/Disease	Native range (region/country)	Introduced range (region/country)	Adverse impacts	Sources
BACTERIA	*Vibrio cholerae* (various strains)	Cosmopolitan	Gulf of Mexico; South America	Some cholera epidemics are directly associated with ballast water	(Battle, 2009; IMO 2014a)
ALGAE	Toxic Algae, various species (e.g. *Caulerpa taxifolia, Gymnodinium catenatum, Undaria pinnatifida* (Asian kelp), *Dunaliella tertiolecta, Pyrodinium* sp. *Alexandrium* sp.	Cosmopolitan, different regions	Numerous species have been transferred to non-native regions by ballast waters.	May form harmful blooms (red/brown/green tides); can cause massive kill of marine life (e.g. oxygen depletion, release of mucus and toxins); can affect tourism and recreation due to fouling of beaches; consumption of certain species may cause severe illness or even death of humans and animals	(IMO 2014a)
JELLYFISH	Australian spotted jellyfish *Phyllorhiza punctata*	West Pacific (from Australia to Japan)	Brazil, Caribbean, Hawaii, Mediterranean, Puerto Rico, and parts of the Gulf of Mexico	Fishery loss; net damage, large reduction in harvesting shrimp; predation on bivalve larvae and pelagic fish eggs	(Battle, 2009; Galil et al. 2009; Graham et al. 2003)
	North American Comb Jelly *Mnemiopsis leidyi*	Eastern Seaboard of the Americas	Azov Sea, Black Sea and Caspian Sea	Influence on depleting of zooplankton stocks; causes changes of food web and ecosystem function	(Battle 2009; IMO, 2014a)
STARFISH	North Pacific Seastar *Asterias amurensis*	Northern Pacific	Southern Australia	Consummation of commercially valuable shellfish like oyster, scallop, and clam	(Battle, 2009; IMO, 2014a)
SHELLS	Asian green mussel *Perna viridis*	Asia-Pacific region and Asia	Caribbean, United States Atlantic coast, South Carolina, Japan, South United States	Causes loss for the US oyster fishery; carrier of harmful diseases and parasites; can cause damage to submerged	(Battle 2009; ISSG 2005)

Group	Organism/Disease	Native range (region/country)	Introduced range (region/country)	Adverse impacts	Sources
				structures	
	Conrad's false mussel *Mytilopsis leucophaeata*	Gulf of Mexico, North Americas Atlantic coast	North America and Europe (Belgium, France, Spain, Finland, Netherlands, Wales, Ukraine)	Causes vigorous fouling populations in Belgium, Finland and Netherlands	(Battle 2009; ISSG 2005)
	Zebra Mussel *Dreissena polymorpha*	Eastern Europe (Black Sea)	Northern and Western Europe, including Baltic Sea and Ireland; eastern part of North America	Fouling of all available surfaces; alters native aquatic life; often causes severe changes in habitats, food webs and entire ecosystems	(Battle 2009; IMO, 2014a)
CRABS	Asian shrimp *Palaemon macrodactylus*	East Asia	North-west America and Europe (United Kingdom rivers and estuaries; Belgium; Germany, Netherlands)	Considerable loss of biological diversity; decrease in the abundance of native shrimp population	(Battle 2009; Lavesque et al. 2010)
	Chinese mitten crab *Eriocheir sinensis*	Western Korea and China, in border to the Yellow Sea	Venice lagoon; southern Ireland, southern Wales, British Isles; Baltic Sea, North Sea, and Atlantic coasts	Large influence on food webs due to exporting biomass out of the freshwater ecosystems; Causes significant reduction of native biodiversity; causes damage to dikes and enhance river bank erosion	(Battle 2009; ISSG 2005)
	European Green Crab *Carcinus maenus*	European Atlantic Coast	United States, Southern Australia, Japan and South Africa	Alters native crabs becoming a dominant species in invaded areas; displaces inter-tidal rocky shore ecosystems	(IMO 2014a)
	Fish-hook water flea *Cercopagis pengoi*	Southern Europe, e.g. Black Sea, Caspian Sea, and Azov Sea	Baltic Sea, East Europe, the Great Lakes and the United States Finger Lakes	Clogs fishing gear and nets; reduces zooplanktivorus fish and their larvae	(Battle 2009; ISSG 2005)
FISH	Round Goby *Neogobius melanostomus-*	Asov Sea, Black Sea and Caspian Sea	North America and Baltic Sea	Competes with native fish for food and habitat; preys on their young and eggs	(IMO 2014a)

Figure 3 illustrates the map of the most important coastal eco-regions related to biological invasions from ballast waters and the number of known invasive alien species. It is possible to make a correlation between socio-economic development and levels of shipping. Also, the highest risk of introducing, as well as spreading IAS is consequentially determined by shipping and BWM activities inside the individual ports (Molnar et al., 2008; Challinor et al., 2014).

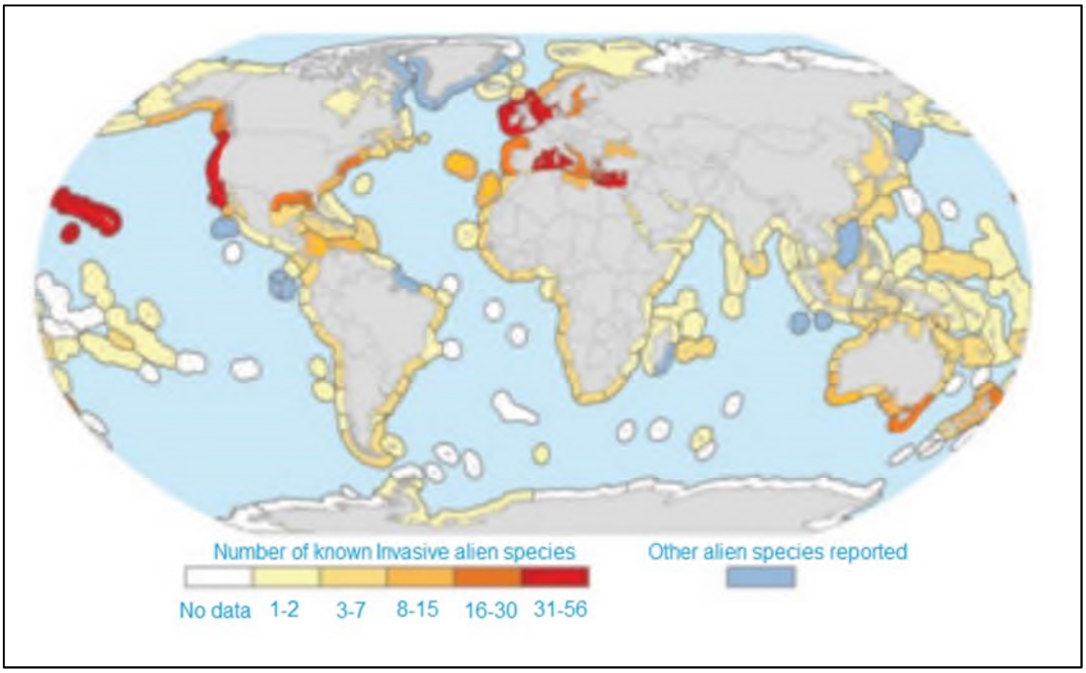


Figure 3: The most important coastal eco-regions related to biological invasions from ballast waters and the number of known invasive alien species (IAS) (Challinor et al., 2014, modified).

Slika 3: Najpomembnejše obalne eko-regije, kjer potekajo biološke invazije z balastnimi vodami in število znanih invazivnih tujerodnih vrst (NIS) (prirejeno po Challinor et al., 2014).

Large Asian ports, Singapore and Hong Kong, are the leading global sites with the highest estimated risk of introduction of IAS, but there is also a large probability of introduction in US ports such as New York and Long Beach (University of Bristol, 2013).

2.3.1 The problem of spreading of invasive microorganisms

Global transport of ballast water represents one of the largest dispersal mechanisms for human pathogens. It is also an important factor for worldwide distribution of microorganisms and at the same time a potential cause of waterborne diseases of plants or animals (Ruiz et al., 2000).

Recent studies, however, report that heterotrophic bacteria and viruses considerably dominate in ballast water tanks (Ruiz et al., 2000; Burkholder et al., 2007; Ma et al., Seiden et al., 2011; Seiden and Rivkin, 2014). A worrying fact is that some of microbes may be pathogenic. Size of bacteria usually ranges between 0.2 to 1 μm, and it has ability to tolerate the various conditions in ballast water tanks in form of spores or other resting stages (Ruiz et al., 2000; Gregg & Hallegraeff, 2007; Khandeparker and Anil, 2013). Their resistance to different harsh conditions can be a reason for their introduction into new environments.

As the IMO's Convention has not yet entered into the force, the ballast water exchange is still the most widely used method of ballast water treatment. This method is not always appropriate due to certain safety issues or geographical limitations. Moreover, ballast water exchange has not always proven to be biologically efficient in certain conditions and limitations. Namely, ballast water exchange is supposedly effective in the reduction of the concentration of some planktonic organisms for 80-95% (Seiden and Rivkin, 2014). Previous research has also shown that with the help of the sea water disinfection it is only possible to reduce the number of bacteria to less than 1% of the initial level. However, three or five days of sea water storage in ballast tanks results in the return of the total return to the starting point concentration.

Ruiz et al. (2000) did research where they measured the concentrations of bacteria, especially the species of bacteria *Vibrio cholerae* O1 and O139, causers of the human epidemic cholera, as well as the number of virus-like particles (VLPs) in the ballast tanks of ships that come to Chesapeake Bay. The results of experiments have shown that *Vibrio cholerae* was found in the plankton samples from all ships' tanks, and both serotypes were noticed in 93% of the ships. Comparing the concentrations of *V. cholerae* O1 and O139, results have shown that the concentration of the *V. cholerae* O1 was considerably higher than that of O139.

Rehnstam-Holm et al. (2010) have monitored the relationship between microalgae (phytoplankton) and *Vibrio* spp. in their mesocosm study. During the experiment, the mesocosms were inoculated with phytoplankton, sediment or plankton and sediment without presence of larger zooplankton. The highest abundances of diatom were noticed with the increase in number of *Vibrio*, in the case of all the mesocosm.

Khandeparker and Anil (2013) have observed epibiotic and symbiotic bacteria in relation with zooplankton, including veliger larvae, barnacle nauplii, and adults of the copepod *Oithona* sp. The results have shown that regardless of the size of the zooplanktonic organism, the smallest one, veliger larvae, had the highest number of present bacteria, while the largest one, barnacle nauplii, had the lowest number of present bacteria. The process of pulverization of bacteria affected the increase in bacterial numbers of e.g. *V. cholera*, *Escherichia coli* and *Streptococcus faecalis*.

Regarding all the facts presented in this paragraph, it is possible to predict a high potential of invasions by microorganisms from ballast water that is in direct correlation with ecological and human risks. The possible solution for the prevention of the invasions of non-indigenous microorganisms is the development of technologies for its reduction, as well as the development of risk based approaches for ballast water treatment.

2.3.2 The problem of by-products formation

Besides the ultraviolet (UV) radiation and electrolysis, many systems that use strong oxidants, such as ozone or chlorine, are used in ballast water treatment. Ozone and chlorine are known for their high reactivity when they react with biomolecules in the cell membranes. The consequence of this reaction is the loss of structural integrity as well as cessation of cellular processes (LeChevallier and Au, 2004; Werschkun et al., 2012).

Systems that use chlorine in ballast water treatment produce halogenated acetic acids, trihalomethanes, and bromate, and in comparison with other areas of use, higher quantities are measured (Banerji, 2012; Werschkun et al., 2014). Ballast water treatment systems that use ozone in their working process generate bromoform in lower concentrations, while they produce higher levels of bromate. Systems whose working process is based on the use of electrolysis often produce trihalomethanes and haloacetic acids (Banerji, 2012; Banerji et al., 2012). Systems which utilize UV radiation in their work usually employ medium pressure lamps, as well as UV-induced advanced oxidation. However, formation of by-product in UV systems is noticed only occasionally and it is evident in small increases in hydrogen peroxide, nitrite, acetic acids and halogenated methanes (Werschkun et al., 2012).

Chemical risks associated with the use of strong oxidants can be divided into two groups: 1) acute effects caused by the action of strong oxidants and 2) long-term effects as consequences of DBPs formation. The concentrations of the total residual oxidant used on board are limited to maximum 0.2 mg/L, which is mostly caused by reaction with some agents (eg. sodium bisulfite or thiosulphate) (Werschkun, 2012; Werschkun et al., 2014). Factors that have direct influence to DBP formation include reaction time, dose of oxidant used, content of organic matter in water, etc. (Liang and Singer, 2003). Formed compounds of DBPs could have serious and far-reaching toxicological consequences for both human health and natural biota. DBPs are often related to severe health risks such as cancer or different reproductive and developmental effects. They are also associated with genotoxic effects such as DNA strand breaks, DNA adducts and induction of micronuclei (Richardson et al., 2007; Lyons et al., 2004; Savitz et al., 2005).

Human and environmental exposure to chemicals used in ballast water treatment is mostly determined by amounts of chemicals discharged after the treatment with the system. Although the amount of active substances used during ballast water treatment by certain system is determined by the regulations, the amount of formed DBP needs to be determined with the help of analytical procedures during testing of the ballast water treatment system. The most common DBP compounds formed in marine waters are brominated compounds such as bromoform, bromate, bromoacetic acid, dibromoacetic acid, tribromoacetic acid, dibromoacetonitrile and dibromochloromethane (Werschkun et al., 2014). Exposure to chemicals from the BWMS could be potentially hazardous for everyone who comes into contact with them; the ship's crew, inspectors or public. Banerji et al. (2012) and the GESAMP BWWG (IMO, 2012) made a list of potential danger and scenarios related to exposure to the chemicals from the BWMS which is shown in Table 6.

Table 6: A list of potential danger and scenarios related to exposure to the chemicals from BWMS (Banerji et al., 2012).

Preglednica 6: Seznam potencialnih nevarnosti in scenarijev, ki so povezani z izpostavljenostjo kemikalijam iz BWMS (prirejeno po Banerji et al., 2012).

Operation	**Kind of activity**	**Exposure scenario**	**Exposure way**
Starting of BWMS	Type specific activities to be documented, e.g. calibration	Type-specific	Dermal, inhalation
Ballasting	Ballasting	Potential exposure to volatile substances from exhaust air	Inhalation
	Treating of ballast water	Type-specific	Dermal, inhalation
	Sampling	Exposure to chemicals in treated ballast water	Dermal, inhalation
Deballasting	Deballasting	Potential exposure from spray drift	Dermal, inhalation
	Treating of ballast water	Type-specific	Dermal, inhalation
	Sampling	Exposure to chemicals in treated ballast water	Dermal, inhalation
Cruising	Storage of treated ballast water	Potential exposure to volatile substances from vapor	Inhalation
	Sampling	Exposure to chemicals in treated ballast water	Dermal, inhalation
Maintenance	Tank cleaning (sediment cleaning)	Exposure to residual water, sediment and vapor of volatile substances in ballast tank	Dermal, inhalation
	Tank inspection Inhalation	Exposure to vapor of volatile substances in ballast tank	Dermal, inhalation
	Type specific: UV: change/cleaning of UV tubes Ozone: filter change, electrode calibration Chemicals: resupply, cleaning of storage	Type specific	Dermal, inhalation

	tanks Electrolysis: washing of filter cartridges, electrode calibration		
Malfunctions	Any of the listed work activities or independent thereof	Leakage, ventilation breakdown	Dermal, inhalation
Accidents	Any of the listed work activities	For example: splashing of chemicals during resupply	Dermal, inhalation
Emergency	Distress and salvage operations	For example: explosion, fire	Dermal, inhalation

Handling ballast water can be divided into five routine unit operations: starting of the treatment system, ballasting, deballasting, cruising and maintenance. Moreover, relevant unexpected situations when the exposure to the chemicals is also possible (e.g. failures, emergency situations or accidents) have to be taken into account.

2.4 Basics of hydrodynamic cavitation

Cavitation is a physical phenomenon that happens at the moment when rapid changes of pressure occur in running water or another fluid (Jyoti and Pandit, 2001; Gogate and Pandit, 2004; Al-Juboori, 2011; Zupanc et al., 2014). At the state of vapour pressure of a fluid, a fluid changes its state from liquid to gas. Shock waves are produced as a consequence of the significant amounts of trapped energy released from the bubble collapsing. Temperatures reach over 5000 K in the center of bubbles, while temperatures in the gas-liquid interface reach over 2000 K (Arrajo et al., 2008; Zupanc et al., 2014). Cavitation noise is one of the most important indicators of cavitation, and it can occur in the frequency range of 100 Hz to 100 kHz as a result of bubble implosions (Brujan, 2011; Ozonek, 2012).

Cavitation can also be very destructive and is generally considered to be an undesirable phenomenon (Knapp et al., 1970). It can affect in a negative way different surfaces, such as ships' propellers, pumps, valves, pipes, etc. (Brennen, 1995; Brujan, 2011) causing erosion, vibrations and noise (Kuiper, 2012; Moussou, 2004).

According to Gogate et al. (2002), Gogate (2005) and Gogate et al. (2007), cavitation can be divided into four basic types:

a. Acoustic cavitation

Pressure variations in the acoustic cavitation are the result of sound waves, usually ultrasound with frequencies between 16 kHz and 100 MHz. Chemical changes that happen due to the passage of sound waves through the system, are usually called sonochemistry.

b. Optic cavitation

Optic cavitation is affected by high intensity light (laser) that causes a rupture of liquid continuum.

c. Particle cavitation

Particle cavitation is generated by a beam of elementary particles, for example, in the case when neutron beam ruptures a liquid, as in the conditions of a bubble chamber.

d. Hydrodynamic cavitation

Hydrodynamic cavitation (HC) is generated by pressure variations due to specially constructed geometry of a system and as a consequence of velocity variation. For example, as a result of the geometry of a system, the alternating changes of pressure and kinetic energy can be produced, which results in the generation of cavities. The geometry for HC generation can be in a form of orifice, venturi, etc. Among the above-mentioned types of cavitation, acoustic and hydrodynamic cavitation have been the most interesting in both academic and industrial field because of its easy operation and generation (Gogate et al., 2001; Gogate, 2002). The emphasis of the thesis will be put on research, development and potential areas of the usage of HC. Despite the fact that HC can be easily generated in different hydraulic systems, the usage of cavitation has been avoided in the past. The reason for HC avoidance was the destructive and corrosive effect of cavitation on directly exposed surfaces. However, in the last decade the efforts have been focused on emphasis and usage of the positive sides of HC. Main factors that affect HC are the physical properties and the thermal state of liquid, impurities in the form of submerged bodies, gaseous impurities dissolved in liquid or other liquid impurities (Brennen, 1995; Cai et al., 2009; Gogate, 2008; Ozonek, 2012). Main effects of cavitation, in relation to the changes taking place within the cavitation bubble (from the moment of its creation to the moment of its implosion), can be divided into two primary groups: 1. physicochemical and 2. mechanical (Ozonek, 2012) (Figure 4).

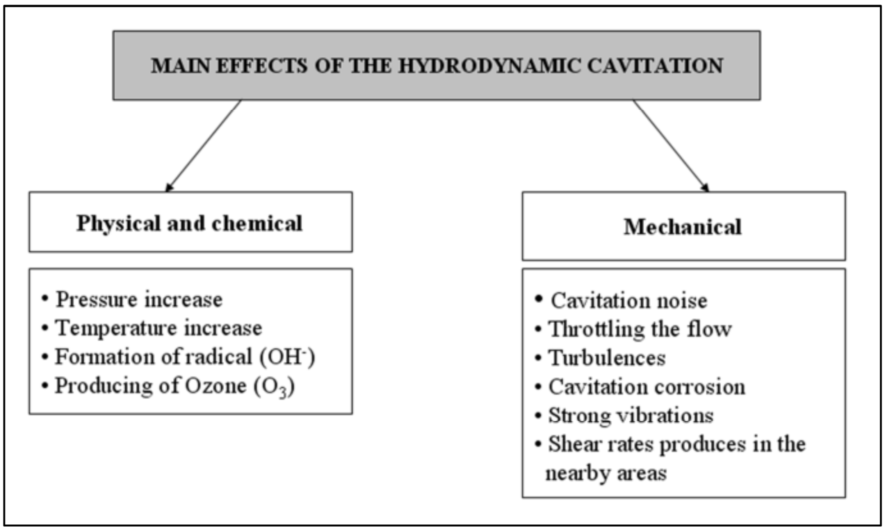


Figure 4: Main effects of hydrodynamic cavitation (Ozonek, 2012, modified).

Slika 4: Glavni učinki hidrodinamične kavitacije (prirejeno po Ozonek, 2012).

HC can affect water's physicochemical and chemical properties, especially concentrations of hydrogen ions (H^+) and hydroxyl ions (OH^-) by the pulsations of resonance bubbles, which can occur with a large amplitude under certain conditions, such as high temperatures of bubbles that exceed 5000 °C, high local pressures, changes of the pH of the medium, and the destruction of cavitation spaces (Viten'ko and Gumnitskii, 2007; Bauer et al., 1958). Among the most notable chemical effects of HC is the formation of OH^-, an unstable radical which can react with its counterparts creating a strong oxidant, hydrogen peroxide (H_2O_2) (Al-Juboori et al., 2010). Viten'ko and Gumnitskii (2007) performed an experiment whose aim was to determine the H_2O_2 formation and its concentration during the treatment of distilled water with HC. The experiments were carried out under constant temperature of the cavitation device (15°C) with the duration of the experiment in 0, 400 and 800 s intervals. At the end of the experiment, the H_2O_2 concentration in distilled water had not exceeded 0.01 mmol/dm³. The formation of the H_2O_2 is directly related to the amount of energy introduced to the system (Viten'ko and Gumnitskii, 2007).

The most prominent mechanical effects of HC are (Al-Juboori et al., 2010) 1. Turbulence, which is a consequence of high-velocity liquid jets; 2. Collision of microorganisms on solid surfaces; 3. Shear rates produced in the nearby areas; and 4. Jets and shock waves formed by the explosion of bubbles. With regards to the physical point of view, there are three basic types of cavitation in water (Ozonek, 2012): 1. **Vaporous cavitation**; 2. **Gas-vapour cavitation**; and 3. **Gaseous cavitation**.

a. Vaporous cavitation represents a process, mainly in homogenous material, associated with changes such as transition from liquid to vapour and vapour to liquid phase. After reaching critical size, bubbles contain mostly vapour. Therefore, diffusion of the gases dissolved in water is blocked. Vaporous cavitation can occur when pressure falls below vapour pressure.

b. Gas-vapour cavitation occurs in bubbles as a result of liquid evaporation and the diffusion of gases, which comes through the phase transition boundary layer from aqueous solution diffuse.
c. Gaseous cavitation may occur when bubbles slowly grow under particular conditions (the magnitude of pressure reduction and the rate of application). Bubbles can be filled by gas rather than vapour. Gaseous cavitation usually appears at the pressures higher or lower than vapour pressure.

According to Pandit et al. (1999) and Gogate (2002), main advantages in the usage of HC are:

a. The reactors that usually work in rigorous conditions can be very easily adapted to ambient conditions,
b. HC presents a cheap and energy efficient method,
c. The requirements related to the performance of equipment are usually simple
d. Scale-up can be relatively easy.

HC can be created with the help of different constructions such as: throttling valve, orifice plate, and venture (Al-Juboori, 2010; Gogate and Pandit, 2011; Mishra and Pelesa, 2006; Qun et al., 2008). In HC, the cell walls of organisms can be broke by high energy bubble creation and their collapse, which creates strong hydrodynamic forces, ultrasonic oscillations or high-frequency noise (Al-Juboori, 2010). Bernoulli’s equation describes the achievement of the effect, with the help of pressure-velocity relationship (Squires et al., 2005). During the water transit through the HC construction, the kinetic energy of a liquid increases at the expense of pressure head (Gogate and Pandit, 2011; Qun et al., 2008). The fluid flow in HC construction is shown in Figure 5.

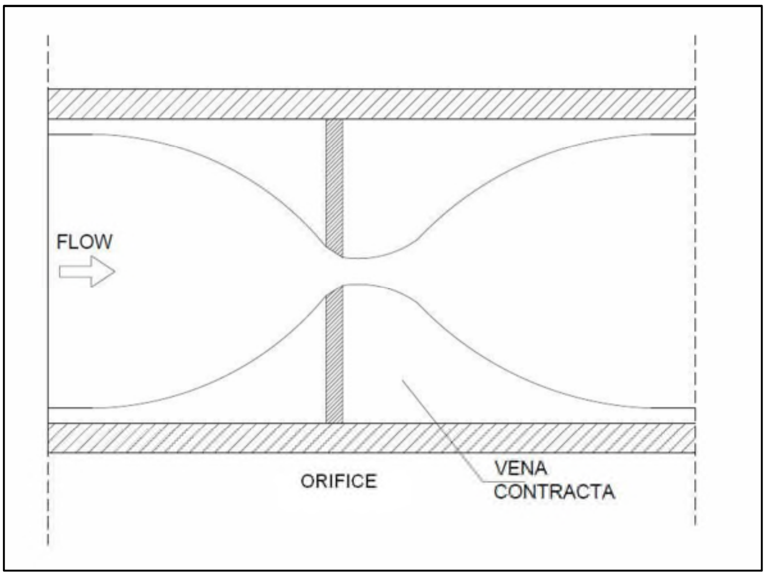


Figure 5: An illustration of the fluid flow in hydrodynamic cavitation construction (Gogate and Pandit, 2011, modified).

Slika 5: Prikaz tokovnih razmer v napravi za hidrodinamično kavitacijo (prirejeno po Gogate in Pandit, 2011).

If the static pressure at a throat achieves a critical value, this point becomes a place of fluid rapture and consequently, a large number of cavities are generated. The cavities collapse with the expansion of the liquid jet; simultaneously, the average velocity reduces while the pressure increases (Gogate et al., 2001; Gogate and Pandit, 2005; Gogate and Pandit, 2011; Mishra and Pelesa, 2006; Qun et al., 2008). Due to local turbulence, a sudden loss of a substantial amount of energy occurs, which is indicated by the permanent pressure drop. Downstream from the construction, an intensive turbulence is generated, and its intensity influences the cavitation intensity (Gogate and Pandit, 2005; Gogate and Pandit, 2011).

According to Gogate (2002), the most important parameters which affect the overall efficiency of HC reactors are:

a. The pressure at the entrance of the system (inlet pressure) or the rotor's speed

Higher operating pressures are preferred, but only to an optimum value (t.i. cavitational inceptive threshold value) and this will depend on the geometry of the system. It is recommended to make an analysis for the critical cavitation of every system which should be based on the available scientific literature.

b. Physicochemical characteristics of liquid and an initial radius of the nuclei

Physicochemical characteristics can very often affect cavitation properties. For example, an increase of the liquid's surface tension could affect an increase of the threshold pressure of cavitation which consequently makes the creation of cavitation more difficult, and therefore the collapse of cavities becomes more violent. Also, the opposite effects of liquid's characteristics could give different possibilities for an optimization. It is also known that physicochemical characteristics of a liquid have a key role in determining an initial size of the nuclei in a liquid and the liquid medium could also have considerable influence on an initial radius of the nuclei.

c. **Overall effect of the construction's geometry on the creation of hydrodynamic cavitation**

The geometry of the construction is a key parameter that affects the number of cavitation events and also the pressure pulse created as a result of the collapse of cavities. Also, it is known that the geometry of the construction has an important effect on the distribution of pressure and the downstream recovery profile of pressure. It is directly related to the active volume of cavitation and has an important effect on the HC reactor.

i) The diameter of the construction used for the creation of cavities inside a liquid

The diameter of the construction has an important influence on cavitation inception number. Namely, cavitation inception number will increase with increasing of the diameter of the hole used in the construction (Yan and Thorpe, 1990). In the case of larger diameter holes cavitation will start at a higher cavitation number. The intensity and the range of cavitation will also increase in the case of the same cavitation number until it reaches the cavitation inception number (Gogate and Pandit, 2000; Gogate, 2002).

ii) Free area available for flow

Numerous studies (Gogate et al., 2001; Senthilkumar et al., 2000; Vichare et al., 2000) have confirmed the thesis that the collapse pressure created as a consequence of the collapse of cavities will decrease with increasing of the free area that is made by the holes of the orifice plates, t.i. lower free areas in *cavitation reactors* will be more suitable for creating strong cavitation than wider free areas.

2.4.1 A comparison of acoustic and hydrodynamic cavitation

In comparison with AC, which is generated due to the passage of ultrasound waves through the medium, HC occurs as a consequence of velocity variation of the liquid flow, and it is caused by the changes in geometry of the path of the flow (Arrajo and Benito, 2008; Gogate and Pandit, 2011; Joty and Pandit, 2001; Moholkar et al., 1999). There are two key parameters that affect the generation and control of the intensity of AC and HC (Moholkar et al., 1999): (i) the intensity and frequency of the ultrasound (AC), and (ii) the recovery pressure in the area downstream of the orifice, as well as the time needed for pressure recovery (HC). Moholkar et al. (1999) made a comparative study of the performances of the AC and HC. The results confirmed an analogy between the intensity of ultrasound in AC and recovery pressure in HC, and between the frequency of the ultrasound in AC and the time of pressure recovery in HC. Different studies have also proven that HC can represent appropriate substitution for AC, due to the generation of identical cavitating conditions (Arrajo and Benito, 2008; Gogate, 2002; Moholkar et al., 1999).

Furthermore, many studies proved that the HC equipment performs better in comparison with the AC equipment (Gogate, 2002; Joty and Pandit, 2011; Moholkar et al., 1999; Chivate and Pandit, 1993; Pandit and Joshi, 1993). For example, the HC equipment is usually far more energy-efficient than the acoustic equipment (the energy-efficiency for different HC equipment varies between 54% and 60%, while the energy-efficiency for different AC equipment varies between 3% and 43%) (Arrajo and Benito, 2008; Chivate and Pandit, 1993; Gogate, 2002; Jyoti and Pandit, 2001; Pandit and Joshi, 1993). In addition to energy-efficiency, the studies also reported other advantages of the HC over the AC (Moholkar et al., 1999; Jyoti and Pandit, 2001): e.g. much simpler equipment, very little need for maintenance, and relatively easy scale-up of process.

2.4.2 The areas of hydrodynamic cavitation usage

HC is commonly used in science and engineering, implied acoustics, biomedicine, dentistry (dental water irrigators), botany, chemistry, hydraulics, different industrial processes, wastewater treatment, ballast water treatment, etc. (Al-Juboori, 2010; Brujan, 2011; Gogate, 2002; Gogate, 2008; Gogate et al., 2009; Ozonek, 2012; Save et al., 1994; Save et al., 1997; Sawant et al., 2008; Zupanc et al., 2010; Qun et al., 2008). There are three main areas of HC usage (Al-Juboori, 2010; Gogate et al., 2009; Gogate et al., 2011; Save et al., 1994; Save et al., 1997; Zupanc et al., 2010): (1) chemical processes, (2) cell disruption and (3) microbial disinfection.

a. **Chemical processes**
   HC is used for the hydrolysis of vegetable oils, depolymerization reactions, the oxidation of toluene with the help of an oxidizing agent in a HC reactor, the degradation of BTEX (benzene, toluene, ethylbenzene, and xylenes) in aqueous solution, the synthesis of biodiesel, the synthesis of nano-scale particles of styrene butadiene rubber, the synthesis of different catalysts that have the shape of nano-sized grains, the paper production from synthetic fibres, the intensification of pulp bleaching processes, the preparation of highly-disperse sizes, and the removal of wastepaper ink (Braeutigam et al., 2009; Gogate and Kabadi, 2009; Gogate and Pandit, 2011).
b. **Cell disruption**

Different mechanisms for the large-scale disruption of microorganisms such as high-speed agitator, high-pressure homogenizers, and bead mills, were used in the past (Geciova et al., 2002; Gogate and Pandit, 2011; Save et al., 1994). Such technologies showed very low energy efficiency, and thus, there appeared a need for the new technologies in the area of cell disruption. HC and AC efficiency for the cell disruption of microorganisms has been researched in many studies (Balasundaram and Pandit, 2001; Farkade et al., 2006; Geciova et al., 2002; Harrison and Pandit, 1992; Save et al., 1997). Engler and Robinson (1981) and Keshavarz et al. (1990) determined that an effective disruption of cell walls with a high-pressure homogenizer is possible due to an impact of the high-velocity jet of suspended cells on a stable surface. Save et al. (1994) proposed the usage of pressure impulses formed by collapsing cavities as a practical option for cell disruption. Doulah (1977) described a mechanism of cell disruption with the help of Kolmogoroff's theory of isotropic turbulence. Balasundaram and Harrison (2011) researched the usage of HC in biopharmaceutical industry, where the ability of HC to release periplasmic products has been described and compared to other conventional methods of cell disruption. Furthermore, the influence of the geometry of an orifice on certain releases of periplasmic products has been shown. HC is a more acceptable option compared with acoustic cavitation with regards to cell disruption because of lower investment costs, easier scale-up and higher energy efficiency (Gogate and Pandit, 2011; Zupanc et al., 2013).

c. **Microbial disinfection**

Acoustic cavitation is a very convenient way of disrupting cell membranes because it causes stress from micro-streaming from stable cavitation (Cerri et al., 2008; Scherba et al., 1991; Yusaf, 2013). It is especially useful in combination with conventional chemical methods as supporting methods, e.g. chlorination, ozonation, hydrogen peroxide, hypochlorite, etc. (Jyoti and Pandit, 2003; Jyoti and Pandit, 2004). It has been established that ultrasound significantly improves the effect of a chemical in disinfection processes (Mason et al., 2003). According to Jyoti and Pandit (2001, 2003, 2004), HC is a more effective technology for microbial disinfection than acoustic cavitation. One considerable advantage of HC over acoustic cavitation is its lower energy consumption. HC is also highly efficient in preventing the further growth of faecal bacteria *E. coli* (Mezule et al., 2010).

HC has been successfully used in wastewater treatment because of its ability to generate high concentrations of oxidizing substances, such as hydroxyl radicals and hydrogen peroxide, while simultaneously generating very high local temperatures, variations of pressures and formats in transient supercritical water (Chakinala et al., 2009; Gogate and Pandit, 2011; Sivakumar and Pandit, 2002). HC is an acceptable tool for the removal of pharmaceutical micro-pollutants from wastewater (Zupanc, 2014) as well as for the removal of algae, especially toxic cyanobacteria, from eutrophic lakes and reservoirs (Xu et al., 2006; Wang et al., 2010). HC can also be used in flotation processes, which are the processes where solid particles, chemicals or ions, biological entities or liquid droplets are separated from the bulk liquid, which is caused by their surface properties (Flint and Burstein, 2000). HC can be used in flotation processes as a means of generating micro-bubbles, since cavitation can accelerate particle-bubble attachment and flotation rates, and it yields a possible solution for the improvement of flotation cell designs (Zhou et al., 2009). Along with the treatment of contaminated wastewater, HC is increasingly used for ballast water treatment. Released energy and shockwaves from cavitation effectively destroy the cells of bacteria, algae, larvae, and other aquatic organisms (Gogate and Pandit, 2011).

2.5 Theoretical background for performing experiments

Many different treatment technologies are applied for BWT, such as ozonation, de-oxygenation, gas super-saturation, electro-ionization, and chemical treatment (Gregg et al., 2009; Oemcke et al., 2005; Perrins et al., 2006; Veldhuis et al., 2006). Although some of the above-listed systems cannot limit the environmentally dangerous effects that could result from their usage (Sawant et al., 2008), the large number of the existing systems for BWT on the market is already considered environmentally friendly because they do not use any active substances in their working process. An example of such technology is the UV irradiation, alone or in combination with some mechanical treatment (Veldhuis et al., 2010; Gregg et al., 2009). However, as it is mentioned in previous chapter, the effectiveness of UV irradiation could sometimes be limited (Gregg et al., 2009; Minchin, 2006; Veldhuis et al., 2010; Wu et al., 2011a; Wu et al., 2011b; Zhang et al., 2014). With the aim of achieving better effectiveness, UV is often combined with different advanced oxidation processes (AOPs), such as TiO_2 (titanium dioxide), O_3 (ozone), Ag–TiO_2 + O_3 (the combination of silver, ozonation and TiO_2 photocatalysis), H_2O_2 (hydrogen peroxide) (Agustina et al.,2005; Zhang et al., 2014; Wu et al., 2011a; Wu et al., 2011b).

Zooplankton can be adequately controlled by acoustic cavitation, while the effect of acoustic cavitation on bacteria and microalgae is uncertain (Gregg, 2009). Moreover, the use of AC in BWT is associated with health and safety issues related to the noise produced by the treatment unit, high energy consumption and problems with hull integrity caused by long lasting exposure to cavitation (Gregg, 2009; Sassi et al., 2005).

Although HC is applied in many different areas, the application of HC in BWT is relatively new (Gregg, 2009). Effective usage of HC in BWT has been proven through several laboratory studies (IMO, 2006a; Kato, 2003; Sawant et al., 2008) and several large-scale applications (IMO, 2006a;

IMO, 2006b; IMO, 2011; IMO, 2013; Lloyd's Register, 2014; Yukihiko, et al., 2011). HC has a vast potential in BWT because of its low energy consumption, low operating costs and no harmful effects on the environment or human health.

2.5.1 Review of lab-scale experiments of hydrodynamic cavitation setups for ballast water treatment

According to our knowledge, there is only few available data on lab-scale HC setups for BWT. In the following paragraphs, a summation of three different lab-scale HC setups is presented (Kato, 2003; IMO, 2006a; Ranade, 2009; Sawant et al., 2008), although they use different research methods and observe different kinds of organisms.

Sawant et al. (2008) used the experimental setup shown in Figure 6 for the destruction of zooplankton of size greater more than 50 μm in ballast water. Different kinds of zooplankton were tested: Decapoda, Copepoda, Cirripedia nauplius, *Favella* (Oligotrichea), larvae of Bivalvia and Gastropoda. Regarding the fact that cavitation can be generated in a centrifugal pump or a partially closed valve, and consequently can destroy the part of live zooplankton, the first group of experiments was performed with fully and partially closed valve with and without the cavitation element (orifice plate). The aim of these experiments was to determine the real number of zooplankton destroyed with the help of the orifice plate. The results of this group of experiments quantified the exact effectiveness of the valve in the generation of HC and the percentage of zooplankton that would be destroyed inside the partially closed valve. The second group of experiments was performed with the addition of the orifice plate with three different open areas (25%, 50% and 75%). The best result, more than 80% of destruction of zooplankton, was achieved with a 75% open area of the orifice plate, a pressure of 3.18 bar and flow rate of 4.68 m^3/h and one pass through the orifice plates. The destruction rate has not been equal in all species of zooplankton. Specifically, while the number of live Decapoda, Copepoda, Cirripedia nauplius and *Favella* was substantially decreased, none of the used conditions had any effect on larvae of Bivalvia and Gastropoda larvae.

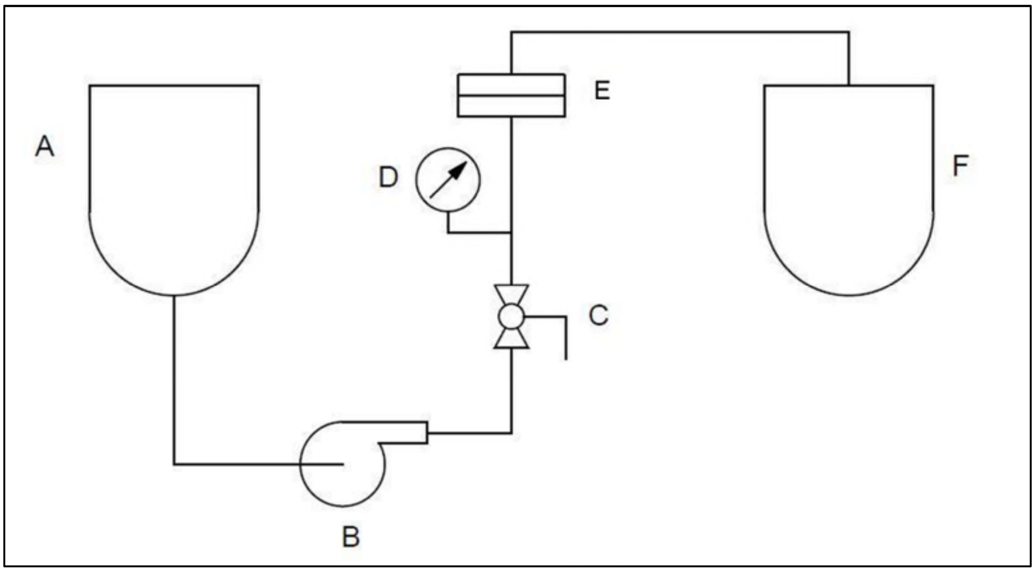


Figure 6: The schematic of a lab-scale hydrodynamic experimental setup for zooplankton destruction; A- Feed tank, B- centrifugal pump 5.6 kW, C- Valve, D- Pressure gauge, E- Orifice plate, F- Collection tank); (Sawant et al., 2008, modified).

Slika 6: Shematski prikaz nastavitev eksperimentalne laboratorijske naprave, ki s hidrodinamično kavitacijo uničuje zooplankton; A - Dovodna posoda, B - centrifugalna črpalka 5,6 kW, C - Ventil, D - Merilnik tlaka, E- Šoba, F- Zbirna posoda, (prirejeno po Sawant et al., 2008).

At the Institute of Chemical Technology Matunga, Mumbai, India (IMO, 2006a; Ranade, 2009), the influence of HC on the marine organisms in ballast water was studied with the help of a system consisting of a pump with capability to develop discharge pressure between 3.92 and 9.8 bar and with a flow-through cavitating device (Figure 7). The flow rate and pressure of liquid through the main line can be regulated by the valves placed on the main line as well as the bypass line. The aim of the experiments was to (1) sterilize ballast water and (2) recover intracellular enzymes with the help of disruption of microbial cells. With the HC device presented on Figure 7, a 57% reduction of zooplankton (size > 50 µm), a 24% reduction of phytoplankton (size > 10 µm) and a 43% reduction of free living bacteria was achieved. In this experiment a flow - through cavitation element with a single hole was used and ballast water passed only once through it. In the experiment, when the ballast water passed ten times through the cavitation chamber with a tangential nozzle expansion angle, a flow rate through the cavitation chamber of 2.95 m^3/h, a flow rate at the entry of vortex diode of 1.67 m/s, and pressure of 6 bar, a 99.9% reduction of zooplankton (size > 50µm), a 94.4% reduction of phytoplankton (size > 10 µm) and a 46% reduction of free living bacteria were achieved.

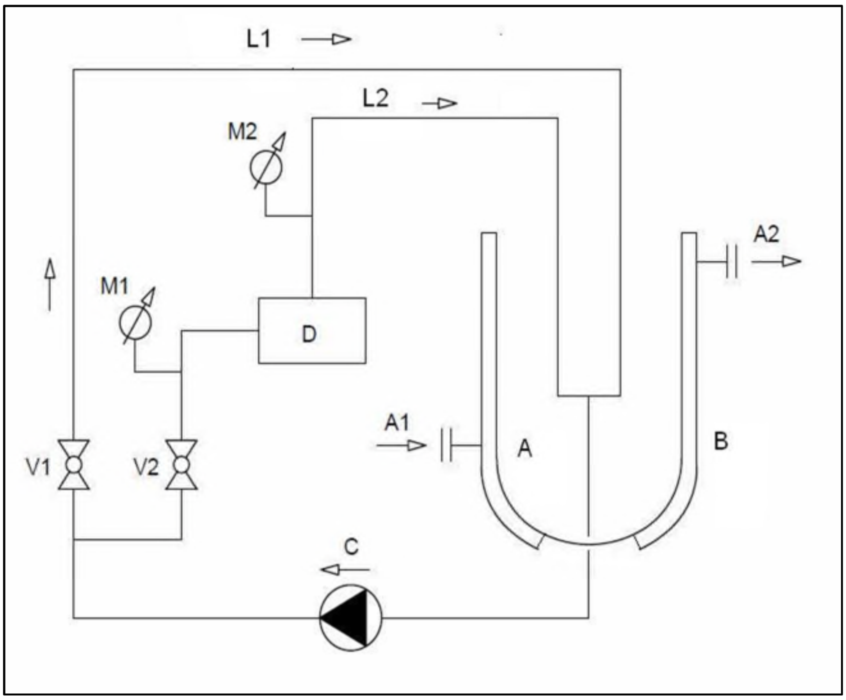


Figure 7: The schematic of a hydrodynamic experimental setup for ballast water treatment developed by the Institute of Chemical Technology Matunga, Mumbai, India; A - Jacket, A1 - Cooling water inlet, A2 - Cooling water outlet, B - Holding tank, C - Centrifugal pump 1.75 kW, D - Vortex diode, M1&M2 - Pressure indicators, V1&V2 - Control valves, L1 - Main line, L2 - Bypass line; (IMO, 2006a and Ranade et al., 2009, modified).

Slika 7: Shematski prikaz eksperimentalne hidrodinamične naprave za obdelavo balastnih voda, razvit na Inštitutu za kemijsko tehnologijo Matunga, Mumbai, Indija (IMO 2006a in Ranade et al 2009, s spremembo); A - Ovoj, A1 - dovod hladilne vode, A2 - Izpust hladilne vode, B - Zadrževalnik, C - Centrifugalna črpalka 1,75 kW, D - Diode vrtinca, M1 & M2 - kazalniki tlaka, V1 in V2 - Regulacijski ventili, L1 - Glavna linija, L2 - linija obvoda (prirejeno po IMO, 2006a in Ranade et al., 2009).

Kato (2003) from Toyo University of Japan performed a research with a loop of a cavitation jet (Figure 8), with the aim of destroying the eggs and the nauplii of the brine shrimp (*Artemia salina*) and the plankton in the water from Toyo's campus lake. Experimental set up consisted of a plunger pump with three cylinders that can produce up to 56 bar of pressure in water, a nozzle with a diameter of 0.4 mm and a water tank with inside pressure lower than atmospheric and which has an effect on the creation of a cavitating jet. The maximum flow rate in the system was 1.13 m^3/h. Sea water passed through the system two times. The results of the experiment show that the pressure of 25 bar completely destroyed the bodies of brine shrimp nauplii, while the pressure of 10 bar also destroyed the brine shrimp although their shape did not change. Even though the study reported that one part of the *A. salina* eggs was successfully destroyed by the loop, the author did not specify the exact percentage of destroyed eggs.

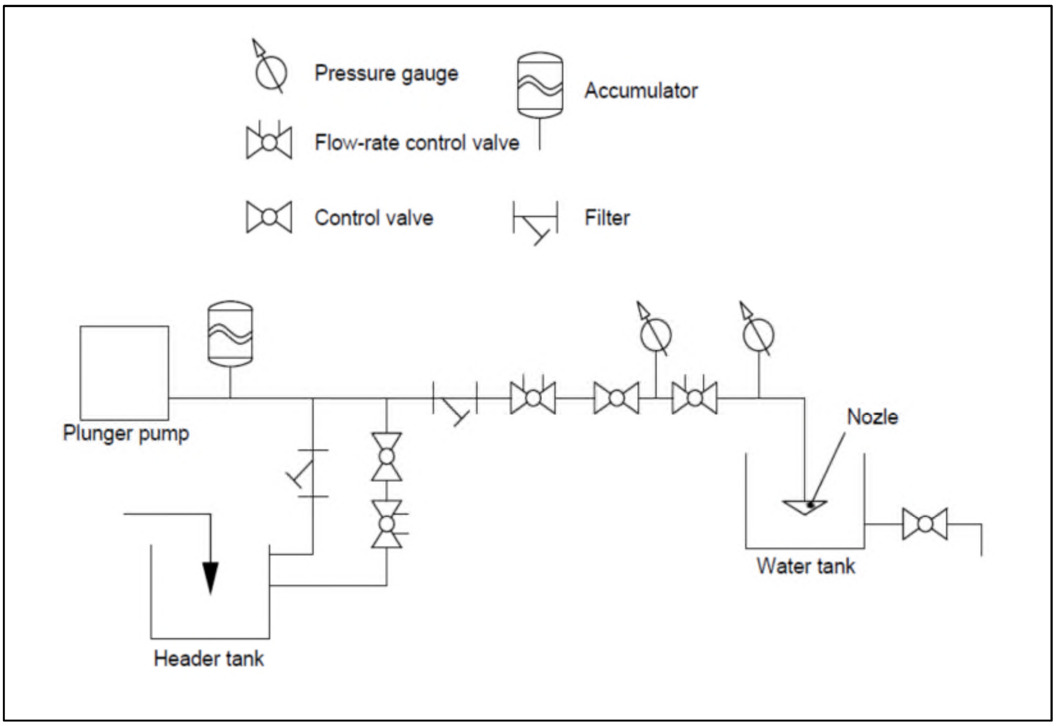


Figure 8: The schematic of the loop of a cavitating jet (Kato, 2003, modified).

Slika 8: Shematski prikaz zanke za kavitirajoči curek (prirejeno po Kato, 2003).

2.5.2 Large-scale hydrodynamic cavitation setups for ballast water treatment

Although 27 of 51 existing type-approved systems for BWT do not use active substances in their operation (IMO, 2013; IMO, 2014d), only four of them use HC in their operation. In all four systems, HC is combined with other technologies. These systems are: (1) JFE Ballast Ace (JFE, 2014; Okamoto, et al., 2010), (2) OceanSaver (Andersen, 2009; Oceansaver, 2014), (3) Fine Ballast OZ (Mitsui, 2014; Ueki et al., 2012), (4) Venturi Oxygen Stripping (VOS) (McNulty, 2005; N.E.I., 2014).

a. **JFE BallastAce** is a ballast water management system (JFE, 2014; Okamoto et al., 2010) consisting of three steps (JFE, 2014; Okamoto et al., 2010; Yukihiko, 2011): (i) mechanical separation (35 µm filtration), (ii) two chemical agents (sodium hypochlorite (NaClO) for disinfection of microorganisms and sodium sulphite (Na_2SO_3) for neutralization of total residual oxidant at the time of discharge of the ballast water, and (iii) Venturi tubes as a mean of generating cavitation. In the JFE Ballast Ace system, HC is used as a main step of the treatment when seawater together with NaClO passes through the Venturi tubes where water mixes strongly with the help of powerful vortices inside the tubes that cause the destruction of the organisms (JFE, 2014; Okamoto et al., 2010). This system meets D-2 Standard of the IMO

Ballast Water Convention for bacteria, phytoplankton, and zooplankton in the summer season with no re-growth of bacteria or algae (IMO, 2006a).

b. **Oceansaver** is a ballast water management system (Andersen, 2009; Carney et al., 2013; Oceansaver, 2014) consisting of three main steps: (i) filtration by a mechanical back-flushing filter, (ii) cavitation in a Closed Circuit Cavitation (C3T™) unit and (iii) supersaturation by nitrogen in combination with the injection of disinfectant produced in an electrodialytic process. The Oceansaver system allows tank control and monitoring of the level of nitrogen and residual oxygen in tanks (Andersen, 2009; IMO, 2006b; IMO, 2011). In the OceanSaver system, HC is used as a main step of the treatment which happens inside a Closed Circuit Cavitation (C3T™) unit induced by intense pressure pulses. HC brokes the cell membrane of the organisms and thus destroys different particles and targeted organisms (Andersen, 2009; Carney et al., 2013; Oceansaver, 2014).

c. **Fine ballast** (Mitsui, 2014; Ueki et al., 2012) is an innovative BWT system that comprises of two steps: (i) cavitation as a result of high shear as a pre-treatment unit, and (ii) ozonation. The main disadvantage of the Fine ballast system is the time of the treatment, as it is necessary for ballast water to be in the treatment tank at least 48 hours to achieve good treatment results. In the Fine Ballast OZ system, HC is used in a pre-treatment phase and it is combined with ozone as the main phase of the treatment. HC is produced as a result of high shear forces inside a “specially designed pipe” system which consists of slit plates (Mitsui, 2014; Ueki et al., 2012).

d. **Venturi Oxygen Stripping** uses inert gas injected into ballast water with the help of a Venturi Injector in order to maintain a low level of dissolved oxygen in the ballast water tank. In this way, ballast water is sterilized, and the requirements of D-2 Standard of the IMO Ballast Water Convention are met. Venturi Oxygen Stripping is also considered to be an efficient technology for the reduction of corrosion in the ballast water tanks (McNulty, 2005; N.E.I., 2014). In the Venturi Oxygen Stripping system, HC is used as a main (first) step of the treatment and it happens in venturi tubes where the inert gas is introduced. Cavitation in venturi tubes destroys targeted organisms (McNulty, 2005; N.E.I. 2014).

Table 7 shows main advantages and disadvantages and the use of active substances in the five above-described type-approved BWT technologies that use HC in their operation. The common characteristic of the four discussed type-approved BWT systems that use HC in their operation is that cavitation is always combined with other treatment processes.

HC does not always have the same role in the process of the treatment. For example, in Fine Ballast OZ cavitation is used as a pre-treatment phase and ozonation is the main treatment step, while in other three systems cavitation is the main treatment step alone (JFE Ballast Ace, OceanSaver, Venturi

Oxygen Stripping) or in combination with various active substances to achieve the complete efficiency of the system (ABS, 2011; Delacroix et al., 2013; Gregg et al., 2009; Joo-won, 2010; Lloyd's Register, 2014). However, application of technologies that use active substances in their operation may cause a potential danger for the crew and the environment (Fisher, 2014; Werschkun et al., 2012). Most of the systems that use HC in their operation operate during the ballast uptake, the only exception is JFE Ballast Ace which operates exclusively during the discharge of the ballast.

All four described systems are designed to work with high flow rates (range from 300 m^3/h for Fine Ballast OZ to 10000 m^3/h for Venturi Oxygen Stripping), but they significantly differ in relevant characteristics, such as the power consumption, costs of the installation and operation, footprint, etc (Lloyd's Register, 2014). The system with the lowest power consumption is JFE Ballast Ace which needs 6.2 kW for a system with 500 m^3/h flow rate (Lloyd's Register, 2014). The system with the highest power consumption requirements is the OceanSaver (59 kW for a 500 m^3/h flow rate) (Lloyd's Register, 2014).

Since detailed data about the costs of installation and operation of the four discussed systems are not available in the literature, complete comparison of the systems considering this criterion is not possible. According to Lloyd's register (2010), besides the basic price of the system, during the decision-making process the operators should also consider factors such as installation and commissioning costs, costs of consumables, training demands, time needed for delivery, supply and fitting system, special docking requirements or modifications on the ship required for the installation of equipment, etc.

During the decision-making process, as a consequence of the often limited space requirements on the ships, the footprint of the BWT system should be considered. The system with the smallest footprint is Venturi Oxygen Stripping (2.7 m^2 for a 500 m^3/h system), while the system with the largest footprint is Fine Ballast OZ (about 15 m^2 for a 500 m^3/h system). The footprint of the OceanSaver system is not comparable with the footprints of other systems, since it consists of a number of components (Lloyd's register, 2010; Lloyd's Register, 2014).

The only type-approved BWT system whose operation includes AC is the OceanGuard produced by Headway Technology Co. (Lloyd's Register, 2014). The footprint for the 500 m^3/h system is 3.5 m^2, and power consumption is 8.5 kW. Although the power consumption for this system is in range with the power consumption of similar systems whose operation includes HC, and AC has shown relatively high efficiency for large-scale disruption of microorganisms as well (Balasundaram and Pandit, 2001; Farkade et al., 2006; Geciova et al., 2002; Harrison and Pandit, 1992; Save et al., 1997), it is hard to make general conclusion about the benefits of the usage of AC in BWT area on the basis of only one type-approved system.

Table 7: Main advantages and disadvantages of the type-approved ballast water treatment (BWT) systems that use hydrodynamic cavitation in their operation.

Preglednica 7: Glavne prednosti in slabosti tipskih, odobrenih sistemov (BWT), ki pri svojem delovanju uporabljajo hidrodinamično kavitacijo.

BWT system	**Active substances**	**Advantages**	**Disadvantages**	**Sources**
JFE Ballast Ace	+	No limitations of voyage length Re-growth of organisms is prevented by residual oxidizing agent	Very complex system Education of crew in handling with the system is necessary	(IMO 2006a, JFE 2014, Lloyd's Register 2012, Okamoto et al. 2010, Yukihiko et al. 2011)
OceanSaver	+	Can operate through whole life span of a ship The system is modular, so it can be compatible with any pumping capacity	Very complex system Relatively high power consumption	(Andersen 2009, IMO 2011, Lloyd's Register 2012, Lloyd's Register 2014, Oceansaver, 2014)
Fine Ballast OZ	+	Disinfection is generated automatically by ozone from the air Place for storage of ozone is not required Chemical agent for ozone production is not required .	Very complex system It produces intense noise Long time of treatment The organisms can be killed only during ballast water loading Education of crew in handling with the system is necessary	(Lloyd's Register 2012, Mitsui 2014, Ueki et al. 2012)
Venturi Oxygen Stripping	-	Reduction of corrosion The system can operate in different conditions (temperature, turbidity, salinity) Storage or handling of chemical agents is not necessary	Education of crew in handling with inert gas is necessary Additional space is required for storage of inert gas	(McNulty 2005, N.E.I. 2014)

In comparison with the UV, one of the most commonly used technologies in BWT, whose basic price for a unit depends on the manufacturer and amounts to about $933.333, the price for the cavitation unit for BWT amounts to about $640.000 (King et al., 2012). Operation costs of the UV technology alone or the UV technology combined with AOPs can be higher in comparison with systems that do not use active substances because of the usage of UV-lamps and rather expensive chemical reactants (Hanzon and Viglia, 1999). In contrast, HC has considerably lower operation costs because neither reactants nor UV are needed for its work (Benito et al., 2005). Energy consumption for the existing systems on the market that use a combination of the UV technology and a filtration ranges between 52 kW for a 500 m^3/h (Ecomarine system) to 107 kW for a 500 m^3/h (Cathelco system) (Lloyd's Register, 2014), while power consumption for most systems that use HC in their operation is much lower (the exception is OceanSaver which needs 59 kW for a 500 m³/h flow rate) (Lloyd's Register, 2014).

2.5.3 Theoretical background for the experiments in the cavitation station at the Hydraulic laboratory of the Faculty of Civil and Geodetic Engineering at Ljubljana University

Parameters measured during the performance of the experiments at the cavitation station in the Hydraulic laboratory of the UL FGG have been analyzed and the key values for the assessment of effectiveness of the pilot systems have been calculated with the help of the equations given in subchapter 2.5.3.1. Moreover, the main conditions and parameters that influence the HC occurrence and intensity are specified in the subchapter 2.5.3.2.

2.5.3.1 Basic parameters of the behavior of the fluid within the pilot system

To describe the basic indicators of fluid behavior within the pilot system, three following equations are important (Andreić, 2014; Mustapić, 2012):

a) A continuity equation

$$Q = vA = v\frac{\pi d^2}{4} = konst. \qquad (1)$$

Where Q (m^3/s) is volumetric flow rate, v (m/s) velocity of the fluid, A (m^2) the cross sectional area of flow and d (m) pipe diameter.

b) Bernoulli equation (for idealistic fluid, without irreversible energy transformations)

$$p + \frac{\rho V^2}{2} + \rho g h = const. \qquad (2)$$

Where p (N/m^2) is the pressure, ρ (kg/m^3) is the density, v (m/s) is the velocity, h (m) is the elevation and g (m/s^2) is the gravitational acceleration.

c) Equation of losses (i.e. irreversible energy transformations)

$$h_{L=}K(\frac{v^2}{2g}) \qquad [-] \qquad (3)$$

Where K is loss factor, v (m/s) is the velocity and g (m/s^2) is the gravitational acceleration.

Number of working cycles of the pilot system per hour, could be counted as follows:

$$N = \frac{Q \,.\, t}{V} \qquad [-] \qquad (4)$$

Where N is the number of working cycles of the pilot system per hour, Q (m^3/s) is volumetric flow rate and V (L or m^3) is the volume of the system and t (s) = 1 hour, ie. the duration of the operation of the system.

Duration of one working cycle of the pilot system could be counted as follows:

$$t = \frac{3600\ s}{N} \qquad [s] \qquad (5)$$

Where t (s) is the duration of one working cycle of the pilot system, 3600s = 1 hour and N is the number of working cycles of the pilot system per hour.

2.5.3.2 The conditions and parameters that influence the hydrodynamic cavitation occurrence and intensity

In the last years, many efforts have been invested in the research of HC, as well as the key conditions and parameters that influence its occurrence and intensity. The cavitation bubbles' creation is directly related to two parameters: change in velocity of the liquid and drop of static pressure. The equation which describes these changes is the Bernoulli equation (Ozonek, 2012; Franc et.al, 2004). It describes the sum of static and dynamic pressures as the constant value. With the increase in the velocity of the fluid, the dynamic pressure will also increase, while the static pressure will simultaneously decrease. At the time when the static pressure achieves the hydrodynamic cavitation threshold, the cavitation bubbles will occur. In the process of the generation of HC, the three deciding factors will have an important role (Ozonek, 2012): the pressure of liquid flow, the velocity of the liquid flow and the shape of the cavitation reactorinduc.

Numerically, the occurrence of cavitation in a liquid is described by the following equation (Ozonek and Lenik, 2011):

$$f\left(\frac{l_1}{l},...,\frac{l_n}{l},K,\mathrm{Re},We\right)=0 \qquad (6)$$

Where: l, l_1, l_2, l_n, … represent linear values that define size, shape, and location of a body, as well as its surface conditions, micro-bubble dimensions and solid particles that form the nucleus of cavitation, while *σ*, *Re*, *We* represent characteristic numbers that describe the cavitation phenomenon (Cavitation, Reynolds and Weber, respectively).

The fundamental parameter that describes the process of cavitation is a cavitation number. It is calculated with the following equation (Jyoti and Pandit, 2001; Ozonek and Lenik ,2011; Sawant et al., 2008):

$$\sigma = \frac{p_0 - p_v}{\frac{1}{2}\rho v^2} \qquad [-] \qquad (7)$$

Where: ρ is the density of a fluid, p_0 characteristic pressure (Pa), p_v is the vapour pressure of a liquid (Pa), and v is the characteristic velocity of a flow (m/s).

With the decrease of cavitation number σ, the possibility of the occurrence of cavitation increases. If σ decreases below 1, cavitation will appear. With the decrease of the aforementioned number, cavitation will steadily become stronger.

Reynold's number (R_e) describes the type of flow (laminar or turbulent). It is a dimensionless number which describes the comparison of inertial force with viscous force (Squires and Quake, 2005):

$$\mathrm{Re} = \frac{\varphi v L}{\mu} \qquad [-] \qquad (8)$$

Where φ is the density of a fluid, v is the velocity of a fluid, μ is the viscosity of a fluid, and L is the length or the diameter of a fluid.

The Weber Number (*We*) is dimensionless and represents the relation between an inertial force and a surface tension force, and can be presented as (Kuiper 2012):

$$W_e = \frac{\varphi v^2 r_0}{s} \qquad [-] \qquad (9)$$

Where φ is the density of a fluid, v is the velocity of a fluid, s is the surface tension, and r_0 is the radius of the nuclei in an undisturbed flow.

The basic condition for HC generation, whether in laboratory or in targeted technology, is the construction of HC unit, i.e. the cavitation reactor. The properties of the cavitation reactor, especially its individual components, have the key role in HC generation. The equipment design is directly responsible for the creation of a diverse cavitation bubble field, as well as for achieving the collapse of cavitation bubbles in a certain time period (Ozonek, 2012).

Ozonek (2012) highlighted the key parameters that influence the HC process. They are as follows: the pressure that powers the cavitation reactor, the pressure that occurs on the expansion side, the saturated vapor pressure of the fluid and its density, velocity of the fluid that passes through the cavitation holes.

The intensity of the HC is significantly connected to the geometry of the component which generates the cavitation. This geometry can be described with the help of the following parameters (Sivakumur et al., 2002; Jyoti et al., 2004):

$$\alpha = \frac{total\ sum\ of\ all\ the\ hole\ circumferences}{the\ cross\ sectional\ area\ of\ the\ pipe} \quad (10)$$

$$\beta = \frac{sum\ of\ the\ total\ hole\ areas}{the\ cross\ sectional\ area\ of\ the\ pipe} \quad (11)$$

The *β* often indicates the flow number and its intensity is very close related to the cavitation number and intensity of the cavitation. In the case of nozzle with circular holes, the α and *β* numbers can be counted as follows (Ozonek, 2012):

$$\alpha = \frac{4}{d_0} \quad [1/m] \quad (12)$$

$$\beta = n\left(\frac{d_0}{D}\right)^2 \quad [-] \quad (13)$$

Where d_0 is diameter of the holes of the nozzle and *D* is diameter of the cylindrical part of the cavitation reactor and *n* is the number of holes in the nozzle.

The surface of the nozzle can be counted by the help of the following equations:

$$S = \frac{\pi d^2}{4} \quad [m^2] \quad (14)$$

$$S_1 = \frac{\pi d_1^2}{4} \quad [m^2] \quad (15)$$

$$S = \sum S_1 \ldots S_n \quad [m^2] \quad (16)$$

Where *S* is surface of the nozzle, *d* is diameter of the nozzle, S_1 is surface of the hole of the nozzle, d_1 is diameter of the hole of the nozzle and *n* is a number of holes.

Table 8: Basic forms of cavitation inside the cavitation reactor together with its basic characteristics (Mustapić, 2012, modified).

Preglednica 8: Osnovne oblike kavitacije v kavitacijskem reaktorju in njihove osnovne značilnosti (prirejeno po Mustapić, 2012).

Form of cavitation inside the cavitation reactor	**Flow characteristics**
Beginning of cavitation	Vapour bubbles (caverns) occurs occasionally at the edges of the liquid stream, downstream of Vena contracta
Clogged cavitation or developed cavitation	The white cloud of steam with the dispersed droplets of the fluid that extends in fluid jet, downstream form the Vena contracta
Supercavitation	The area downstream form the reactor is separated in three areas: Area A - the big cavern, full with vapour/stream, with liquid jet in the middle of the stream pocket Area B - white clouds of steam where large bubbles break down into smaller bubbles that collapse (the area in length of 3 to 5 cm) Area C - an area of the clear liquid where some small bubbles collapse. Steam clouds fulfil pipe in length more than one hundred pipe diameters downstream from the reactor.

Table 8 shows basic forms of cavitation inside the cavitation reactor together with its basic characteristics.

2.5.4 Theoretical background of biological analysis

The effectiveness of the pilot system was determined by assessing the viability of different key marine organisms after the treatment. Samples with the representatives of natural zooplankton (copepods) were chosen as test organisms - representatives for multicellular, the cultured *A. salina* cysts as representatives for the resting stages of organisms, and the natural marine bacteria as the representatives of unicellular organisms.

2.5.4.1 Theoretical background for experiments with the representatives of zooplankton (copepods)

Zooplankton represent heterotrophic plankton (Gajbhiye, 2002) and they are mostly categorized by size or developmental stage. By size they can be divided into (Chauhan, 2014): pico- (<2 μm), nano- (2-20 μm), micro- (20-200 μm), meso- (0.2-20 mm), macro- (20-200 mm) and megazooplankton (> 200 mm).

When it comes to the development stage of the zooplankton, there are three categories (IMAS, 2015): meroplankton, holoplankton and tychoplankton. Meroplankton are mostly larvae that can change into mollusks, worms, coral, crustaceans, fishes, echinoderms, or insects. Holoplankton is plankton for its entire life cycle and it mostly includes: pteropods, chaetognaths, larvaceans, siphonophores link and copepods link. Tychoplankton represents organisms, mostly free-living or attached benthic organisms, as well as other non-planktonic organism that are usually carried into the plankton by winds and currents or through disturbance of their benthic habitat. Tychoplankton are also known as pseudo-plankton or accidental plankton.

All three groups were determined in ballast water tanks. Meanwhile, among holoplankton copepods are the most common (Gollasch et al., 2000; Choi et al., 2005; David et al., 2007; Gruszka et al., 2013). Copepods are one of the most abundant, heterogeneous and biologically most prominent zooplankton groups in the sea. They are divided into ten orders. More than 9000 different copepods are known in the world’s oceans and estuaries. They are archetypal zooplankter with the following development stages: an egg, six larval (nauplius) stages and six juvenile (copepodite) stages and reproducing adult.

Gollasch et al. (2000a) emphasized that harpacticoid copepods are capable for thriving and reproducing in ballast waters. Therefore, ballast water tanks can act as incubators for some copepod species during the voyage and might have a serious impact on releasing the IAS in the coastal waters, bays or ports (Gollasch et al. 2000a).

2.5.4.2 Theoretical background for experiments with cysts

The cysts in natural marine habitats vary in their sizes and structures, depending on different environmental, physical, chemical, and biological conditions (Paul, 2001; Chen et al., 2011). Transport of long-lived, resistant cysts, especially cysts of some toxic species (e.g. dinoflagellate cysts) (Hamer et al., 2000) by ships became one of the reasons of raising concern related to global spreading of IAS to new geographical regions. Such species are able to produce a number of compounds which can be accumulated in the food chain and consequently cause different human diseases (Hallegraf, 1995; Hamer et al., 2000).

Despite the diversity in sizes and structures of the cyst shells in natural marine habitats the *A. salina* cysts have been chosen as the test organisms for the laboratory experiments that should determine the effectiveness of the new ballast water treatment system on the destruction of the cysts. Namely, the different life stages of *A. salina*, adults, cysts, or nauplii, are often used as an appropriate surrogate of many organisms that can be found in ballast water tanks (Voigt and Gollasch, 2002; Hillman et al., 2004). Therefore, *A. salina* is usually used as a standard test organism for testing different systems for ballast water treatment (Gavand et al., 2007; Tsolaki et al., 2010; Lacasa et al., 2013).

2.5.4.3 Theoretical background for experiments with natural bacteria

The changes in microbial populations, pathogenic and natural ones, represent an issue which is necessary to investigate for better understanding of the potential risks associated with the transport of microorganisms in ballast water tanks and complexity of ballast water management.

Bacteria represent microscopic, prokaryotic, unicellular organisms that constitute the biggest part of the world's biomass and mainly act as decomposers of organisms and organic waste in the way of recycling them back into the environment (Teach Ocean Science, 2015). Marine bacteria are less than 2 μm in diameter. They can be roughly divided into two forms: autotrophic and heterotrophic. Although autotrophic bacteria derive energy from photosynthesis, oxidation or inorganic compounds, heterotrophic bacteria obtain energy from organic compounds. Marine bacteria are the most abundant in the estuarine waters (10^6-10^8 cells/mL), although their number decreases in coastal oceans (1-3x10^6 cells/mL) to neritic zones (10^4-10^6 cells/mL). Bacteria have very high importance in the marine ecosystems, they are critical in decomposition of organic matter, flow of energy in food webs and cycling of nutrients and other substances (Kenish, 2000).

Drake et al. (2002); Seiden et al. (2010); Tomaru et al. (2010); Seiden et al. (2010); and Seiden and coworkers (2011) have monitored bacterial dynamics during the transit and have shown correlation of bacterial abundance with important physical factors such as temperature, dissolved oxygen concentrations and salinity. The composition of the bacteria population in the ballast tank might depend on the global bacterial biogeography (Martiny et al., 2006; Ramette and Tiedje, 2007) as well as the yearly dynamic and weather conditions (Neyland, 2009).

2.5.5 Instruments and tools used in experiments and analysis

With the aim of performing the experiments in hydraulic laboratory of UL FGG, the following instruments and tools have been used:

- **Centrifugal pump Etanorm 50-125 -- 50-315**

The pump had the following properties:

- Frequency *f*= 50 Hz;
- Flow rate *Q* [m^3/h] ≤ 660;
- Head *H* [m] ≤ 160;
- Operating temperature *T* [°C] -30 to +140;
- Operating pressure *p* [bar] ≤ 16

- **Pressure Transmitters for measuring the absolute and differential pressures**

We used three pressure transmitters HART series 2600 T for measuring the absolute pressure and one pressure transmitters HART series 2600 T for measuring the relative pressure. The pressure transmitters were electronic with multiple sensor and they could be mounted in the field range.

- **Compressor NU AIR B2800 / 100 CM3 V230**
- **Electromagnetic flowmeter ProcessMaster FEP300 –** measuring deviation ± 0.5% Q_{max}
- **Thermometer for measuring air temperature**
- **Probe for measuring the temperature of the water**
- **Camera Canon PowerShot ELPH 320HS**

While conducting the biological part of the experiments at the Marine Biology Station Piran (NIB), we used the following instruments and tools:

- **Stereo microscope Olympus SZX 16**

Stereo microscope Olympus SZX 16 has been used for counting live and destroyed copepods as well as whole and broken cysts.

- **The Olympus camera and DP70 Soft Imaging System**

Microphotographs were taken using the Olympus camera at different magnifications and analyzed with the DP70 Soft Imaging System.

- **An epifluorescence microscope Olympus BX51**

An epifluorescence microscope Olympus BX51 was used for analyzing the marine bacteria after the treatment with the pilot system. The 1000x magnification was used.

- **A Liquid Scintillation Analyzer (Canberra Packard TriCarb, model 2500 TR)**

A Liquid Scintillation Analyzer was used in the process of determining the bacterial carbon production, for measuring bacterial growth rate by radiolabeled method.

2.5.6 Program equipment (Software) used in experiments and analysis

The data and results of all experiments performed at the cavitation station in the Hydraulic laboratory of UL FGG have been compiled and statistically processed with the help of the Microsoft Excel program. All tables and figures have also been drawn in the Microsoft Office Excel program.

The statistical evaluation was carried out with the 1-way ANOVA with an independent factor ’time‘ for zooplankton, and a 2-way ANOVA with two independent factors ’treatment‘ and ’time‘ for cysts. The factor ’time’ has four levels (0, 15, 30 and 60 minutes of experiment) for both zooplankton and cysts, while the factor ’treatment’ has two levels for cysts (C and Cs). A post hoc Tukey HSD was used to analyze the pair wise differences. All statistical tests were performed using the R statistical software (R Development Core Team, 2011). The graphs were drawn in R or in Microsoft Office Excel.

2.6. The methodological approach for testing the hypotheses

The following subchapter describes the procedure that has been taken in order to prove the verity of the hypotheses 1-4. It also describes the reasons for the decision to do additional research and develop new pilot systems after the verity of all hypotheses was checked.

2.6.1 Procedure for testing “Hypothesis 1”

With the aim of testing the Hypothesis 1, the following steps have been taken:

a. The state of the art using available literature with the existing research of ballast water treatment systems has been created. The state of the art consisted of a short overview and a comparison between the main groups of existing ballast water treatment technologies, as well their advantages and disadvantages. The focus of the review is on the use of a relatively new technology in ballast water treatment, HC and its properties. All available lab scale systems, as well as all existing type approved systems that use HC in their working process have been researched comparing its main characteristics. Also, the existing type approved systems that use HC in ballast water treatment have been categorized according the use of active substances (chemicals). All findings have been published in the review article (Cvetković et al., 2015).

b. The tool (the pilot system I, II and III) the work of which is based exclusively on the combination of mechanical and physical processes, without the use of any chemicals has been constructed. In the first step of development, hydraulic characteristics of the systems (the pilot system I, II and III) have been tested. After reaching acceptable hydraulic results, the effectiveness of the pilot system III ofwere tested with different marine organisms.
c. The results of hydraulic and biologic experiments have been compared with the results of the similar lab- and large-scale systems for ballast water treatment that use HC at least as one step of their working process.

2.6.2 Procedure for testing "Hypothesis 2"

State of the art described above and published in the article Cvetković et al. 2015 was used for testing Hypothesis 2. During the detailed review of the literature, the author found that the part of the existing systems for ballast water treatment already uses different tools that help to remove and return part of the organisms to the natural habitat without the need to destroy them. The removal process of the larger organisms happens mainly during the loading of ballast water. Since other authors have already confirmed this hypothesis in their previous work, the author believes that additional experimental methods are not necessary to further confirm the validity of this hypothesis.

2.6.3 Procedure for testing "Hypothesis 3"

With the aim of testing Hypothesis 3, the tool (the pilot system), which represents one unit of ballast water treatment system in scale 1:1 has been constructed. The unit was constructed so that the serial connection of units should be possible, and therefore parameters such as flow rate and volume of treated ballast water in time could adapt to temporal and spatial preferences of the ship where the system needs to be installed. During the construction of the new technology, the design requirements and dimensions of the system have been taken into the account.

The hydraulic characteristics, as well as the effectiveness of the system (one unit) on the destruction of different marine organisms have been tested. For the purposes of the proving the validity of Hypothesis 3 and for easier comparison, the results of hydraulic experiments (flow rates, volumes, energy losses) have been calculated to approximate larger measures that have been used in similar systems for ballast water treatment on board of ships and described in the existing literature so far.

2.6.4 Procedure for testing "Hypothesis 4"

For testing Hypothesis 4, a tool (the pilot system I) whose body consisted of a hydrocyclone has been constructed. A transparent Plexiglas tube was placed inside the hydrocyclone. The end of the tube has different kind of nozzles at the end, which have been specially constructed with the aim of generating and improving the HC effect. During the hydraulic experiments with the pilot system II, the integral parameters have been used and calculated. Also, HC occurrence has been monitored and calculated at the entrance of the inner transparent tube and working process of the pilot system II have been adapted so as to achieve the best HC occurrence at the entrance of the tube inside the hydrocyclone.

2.6.5 New findings

After completing the construction of the basic tool for testing the validity of the hypotheses 1, 3 and 4, and when the working concept of the newly developed technology for ballast water treatment was proven with the first set (set A) of experiments, new possibilities to advance the technical characteristics and performances of the system I were noticed. Based on the key technical characteristics of the pilot system I, pilot system II was developed. Since the performance of similar experiments with the pilot system II yielded considerably better results than that with the pilot system I and taking into the account the knowledge about the constructional characteristics of the previous pilot systems, the authors decided to upgrade their ideas with new ones and to build a brand new pilot system (pilot system III). As the design of the new pilot system has significantly changed in comparison with the previous ones, consequently all key parameters such as flow rate, volume, velocity and HC intensity within the system have been improved.

After measuring, calculating and analyzing integral hydraulic parameters, the optimal results achieved with the pilot system III were selected for biological testing of the effectiveness of the pilot system. Biological analyses included testing the pilot system on the destruction of monitored marine organisms (representatives of zooplankton and heterotrophic marine bacteria).

3 PERFORMING EXPERIMENTS AND PARAMETERS USED

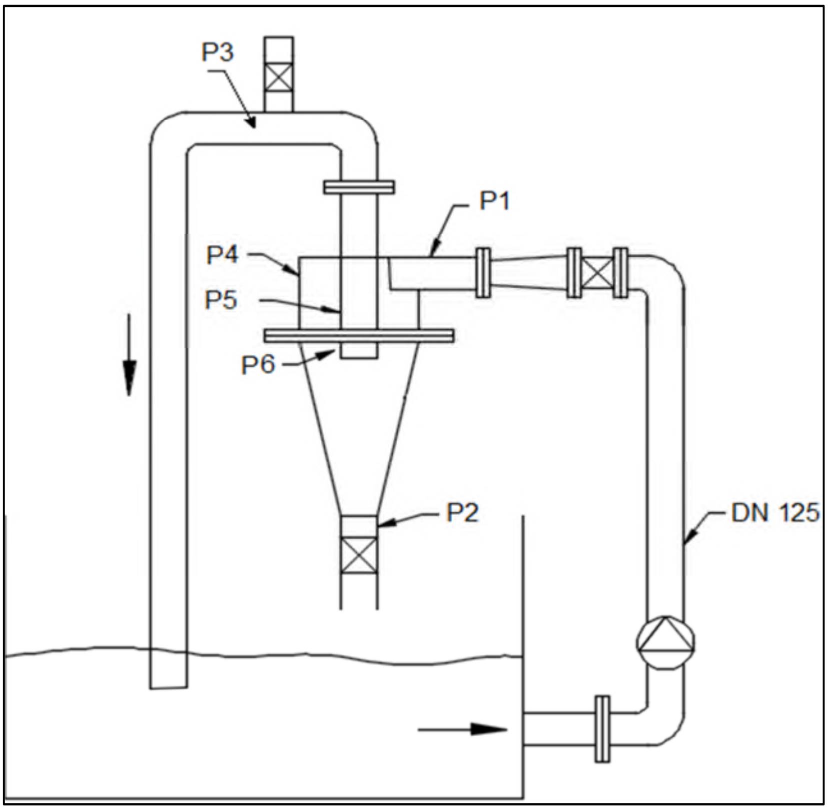
Experiments with newly developed ballast water treatment pilot systems were divided into two phases: experiments related to the verification of the working concept and performances of the pilot systems carried out at the cavitation station at the Hydraulic laboratory of UL FGG and the assessment of the biological efficiency of the pilot system performed at the Marine Biology Station Piran (NIB). The following chapter consists of materials and methods used for both phases of experiments.

3.1 Materials and methods for experiments performed on cavitation station in Hydraulic laboratory of UL FGG

Since so far three different laboratory pilot systems (pilot system I, pilot system II and pilot system III) have been developed, experiments on cavitation station at the Hydraulic laboratory of UL FGG have been performed in three sets where each set of experiments was carried out with the aim of determining the key performances important for effective operation of every single pilot system (in the following text, experiment A refers to the set of experiments with pilot system I, experiment B refers to the set of experiments with pilot system II and experiment C refers to the set of experiments with pilot system III). The following paragraphs describe the appearance of pilot systems I, II, III and their additions, as well as basic elements, settings and parameters measured for each pilot system.

3.1.1 Pilot system I

Figure 9 presents the laboratory’s installation for pilot system I. The pilot system was situated inside the laboratory’s pool, which was half filled with fresh water. The water was powered by the centrifugal pump and fed to the system through the tube on the right side (entrance) (1) of the system and it went out from the system with the help of the outlet pipe at the top of the system (exit from the system) (5). The end of the outlet pipe was immersed into the water, so once the treatment was done, fresh water returned to the pool from where it was re-circulated to the system.



Legend

P1 - Pressure at the entrance to the system

P2 - Pressure in the bilge of the system

P3 - Pressure at the exit of the system

P4 - Pressure at the outer edge of the system

P5 - Pressure at the inner edge of the system after the occurrence of the hydrodynamic cavitation

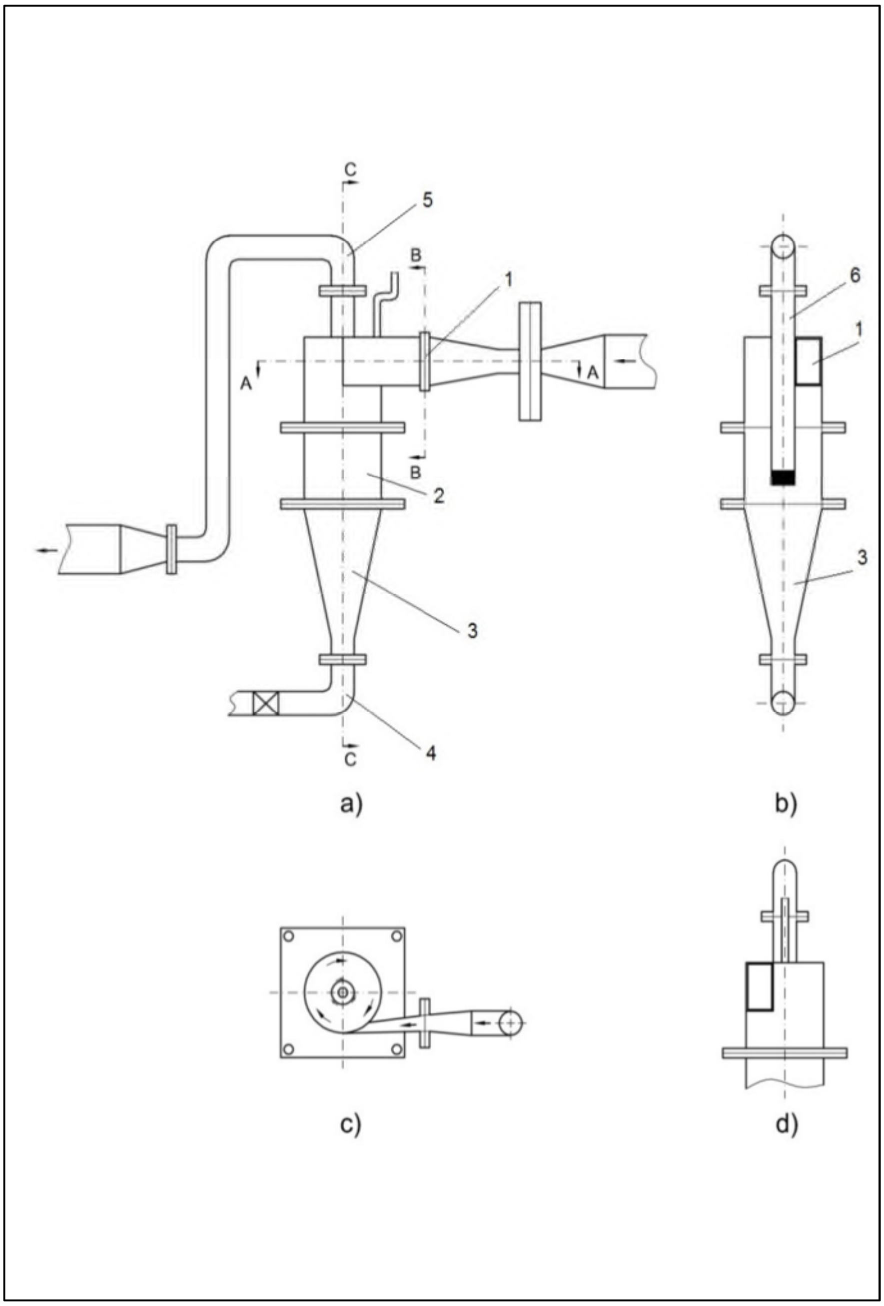
P6 - Pressure at the place of the hydrodynamic cavitation occurrence

 - Centrifugal pump

Figure 9: Laboratory's installation for pilot system I with its elements and points of measuring pressures (p_1-p_6).

Slika 9: Laboratorijska inštalacija pilotnega sistema I s svojimi sestavnimi deli in točke merjenja tlakov (p_1-p_6).

Figures 10 and 10a show the appearance of pilot system I. The body of the pilot system is constructed in the form of hydrocyclone, since its primary aim was to separate and eject particles with the density greater than water from the system. The cylindrical part of pilot system I was made of Plexiglas material for transparency which was necessary to visually monitor the experiments. Other parts of the system were made of steel. The body of the pilot system was connected to the centrifugal pump.



Legend

1 - Entrance of the system

2 - Cylindrical part

3 - Conical part

4 - Lower exit from the system

5 - Upper exit from the system

6 - Vortex finder tube

Figure 10: Scheme of pilot system I where a) illustrates the concept of the system b) illustrates the C-C section of the system, c) illustrates the A-A section of the system and d) illustrates the B-B section of the system.

Slika 10: Shema pilotnega sistema I, kjer a) ponazarja zasnovo sistema, b) prikazuje prerez C-C sistema, c) prikazuje prerez A- A sistema in d) prikazuje prerez B-B sistema.

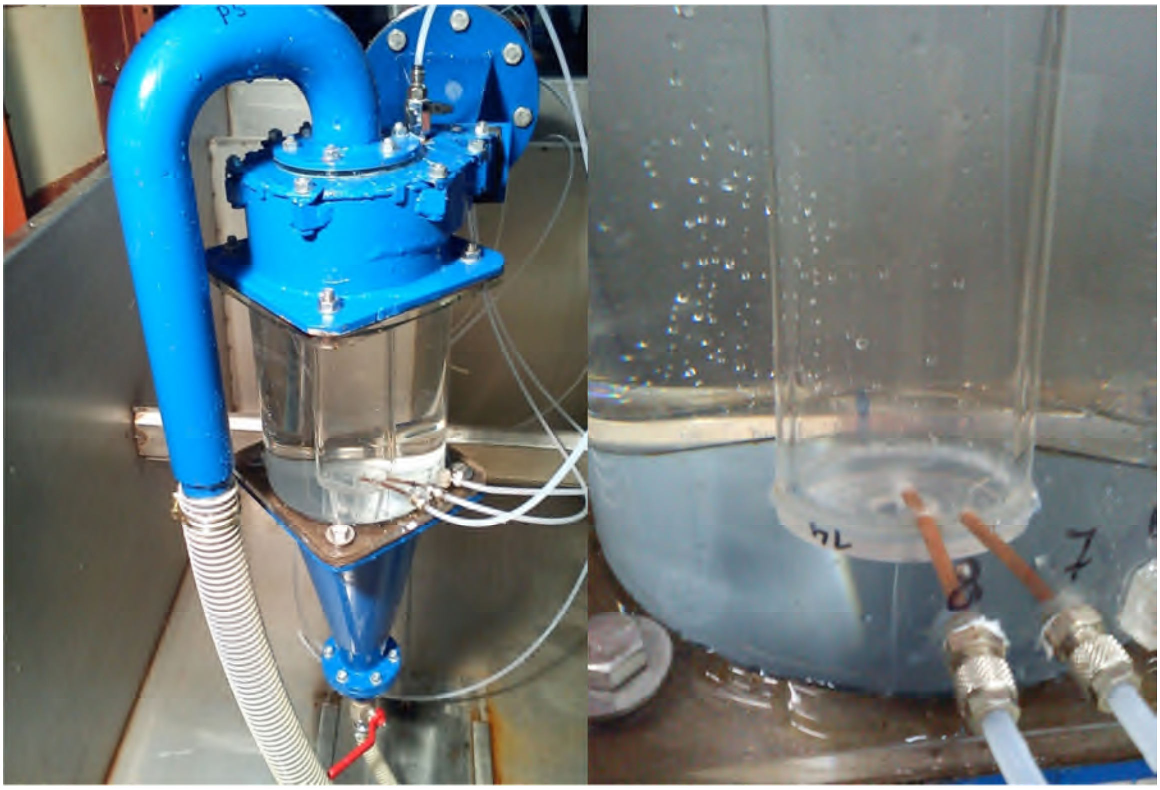


Figure 10a: Image of the pilot system I where a) represents the body of pilot system I and b) represents the cylindrical part of pilot system I during the work.

Slika 10a: Fotografija pilotnega sistema I, kjer a) predstavlja ohišje pilotnega sistema I in b) predstavlja cilindrični del pilotnega sistema I med obratovanjem.

Inside the body of the pilot system I, in the direction from the top to the bottom of the body of the pilot system, the transparent tube (vortex finder) (6) is situated. When the water enters tangentially into the system through the entrance of the system on the right side of the body of the system (rectangular cross section) (1), it rotates around the vortex finder (6). Because of the centrifugal force, majority of the particles with density greater than water are suppressed by the swirling flow towards the wall of the system. They continue to glide down the wall and are ejected through the bottom outlet of the system (4). The rest of the particles with density greater than water which had not been previously ejected through the outlet together with the particles with lower than water density are affected with the internal vortex and pass through the vortex finder (6) to the outlet pipe (upper exit) (5) on the top of the pilot system.

At the end of the vortex finder there is a nozzle with single or multiple holes with different diameters and geometrical shapes. When the water flow passes through the nozzle, HC occurs (Figure 10). The reason for the occurrence of HC is a sudden increase in the velocity of the water flow caused by the narrowing at the entrance of the vortex finder tube that will consequently cause a sudden pressure drop (see the equation 2).

The nozzles used in the experiment had different geometry and additions (Figure 11 and Table 9). The additions to the vortex finder were used as mechanisms for calming down the turbulence of the vortex and increasing the longitudinal speed of the fluid.

The aim of the experiments with the pilot system I was only to determine the key parameters of the operation and to verify the efficiency of a brand new concept that is based on the combination of the separation phase and HC. Since the need for new constructional changes of the system in order to improve its effectiveness was noticed, only rough measurements and analyses were performed with the pilot system I. Pilot system II was constructed on the basis on the constructional characteristics and working performances relevant for the operation of the pilot system I. More detailed research and analysis were performed with the pilot system II.

Set A of the experiments consisted of 14 experiments with different combinations of geometry and additions. Each experiment of the set A was performed with one nozzle with specific geometry (Figure 11). While the diameters d_1 (Figure 11, a), Table 9) changed with the experiments (A1-A14), other diameters of the nozzles d_2=49.5 mm, d_3=51.5 mm and d_4=10 mm stayed unchanged for all experiments in set A. Vortex calming crosses were situated in two different places during experiments: a) inside the vortex finder, and b) at the exit of the vortex finder as an inner extension of the vortex finder.

Furthermore, the pressure at the entrance to the system (p_1) was manually set to the value of approximately 1.5 bar for all experiments in the set A. This pressure has been constant and has not changed during the performance of the experiments.

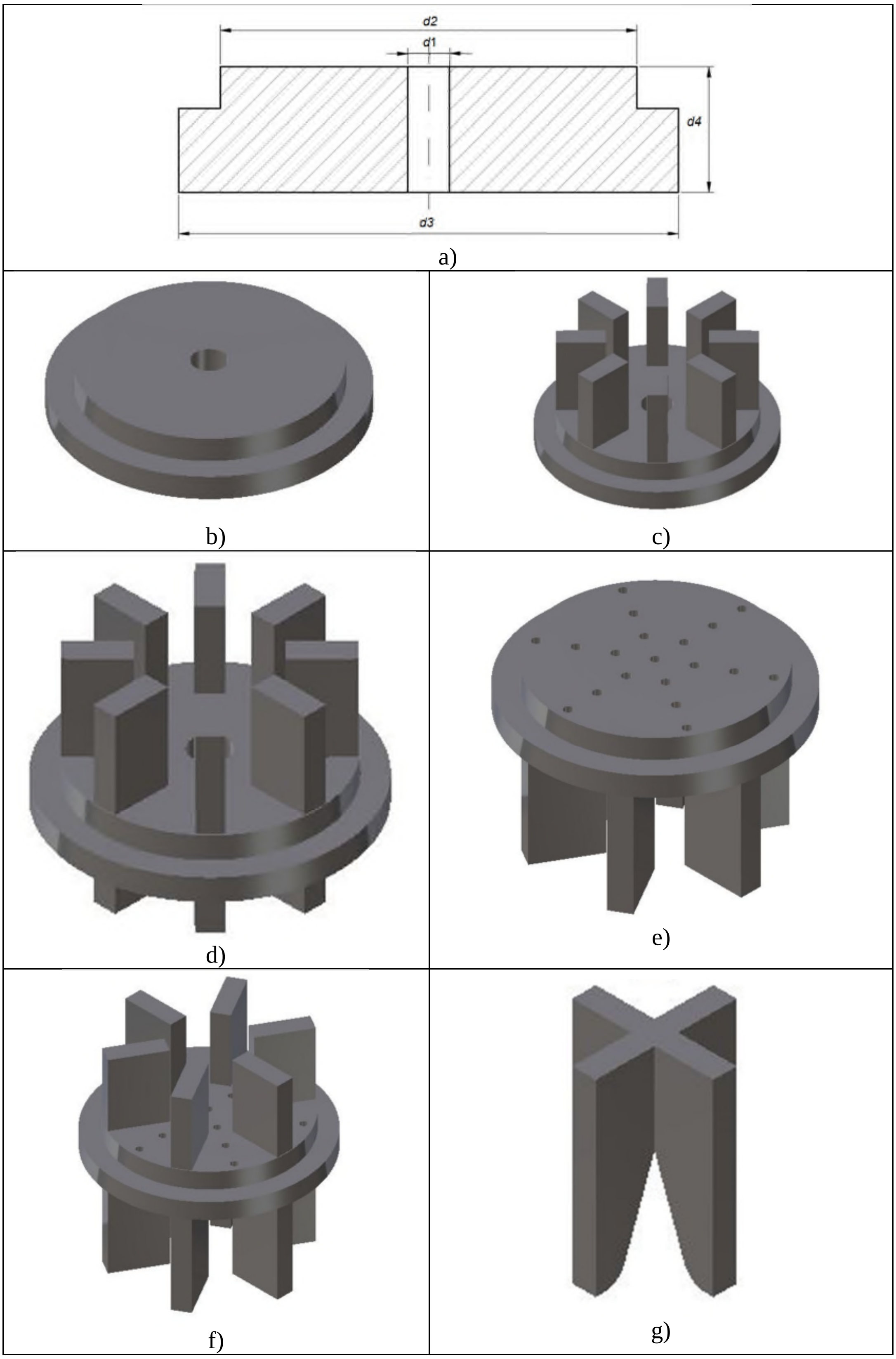


Figure 11: Appearance of the nozzles and other additions used in the experiments with the pilot system I (set A), where a) is a plain nozzle with centrally positioned circular orifice, b) is a plain nozzle with centrally positioned circular orifice and 8 wings on the lower part of the nozzle, c) is a plain nozzle with centrally positioned circular orifice, 8 wings on the upper and 8 wings on the lower part of the nozzle, d) is a plain nozzle with 19 circular orifices and 6 wings on the lower part of the nozzle, e) is a plain nozzle with 19 circular orifices with 6 wings on

the upper and 6 wings on the lower part and f) is a calming cross (in experiments positioned inside the outlet tube, or at the lower part of the nozzle).

Slika 11: Izgled šobe in dodatkov, uporabljenih v poskusih s pilotnim sistemom I (skupina A), kjer je a) Navadna šoba s centralno nameščeno krožno odprtino, b) Navadna šoba s centralno nameščeno krožno odprtino in z 8 krili na spodnjem delu šobe, c) Navadna šoba s centralno nameščeno krožno odprtino, ter z 8 krili na zgornjem in 8 krili na spodnjem delu šobe, d) Navadna šoba z 19 okroglimi odprtinami in s 6 krili na spodnjem delu šobe, e) Navadna šoba z 19 krožnimi odprtinami in s 6 krili na zgornjem in s 6 krili na spodnjem delu šobe in f) Križ za umirjanje (pri eksperimentih je bil postavljen znotraj odtočne cevi ali na spodnjemu delu šobe).

Table 9: Combination of geometry and additions used in the set A of experiments for pilot system I.

Preglednica 9: Kombinacija geometrije in dodatkov, uporabljenih v A skupini eksperimentov na pilotnem sistemu I.

Experiment	ø nozzle (d_1) [m]	No of wings	Remark	Shape of nozzle
A1	0.012	0	W	0
A2	0.012	8	B	1
A3	0.012	0	W	2
A4	0.012	8	A&B	2
A5	0.014	0	W	0
A6	0.014	0	W	2
A7	0.014	8	A&B	2
A8	0.016	0	W	0
A9	0.016	8	B	1
A10	0.016	0	W	2
A11	0.016	8	A&B	2
A12	0.020	8	B	1
A13	19*0.004	6	B	1
A14	19*0.004	6	A&B	2

Where is:

* B = Wings Below

* A&B= Wings Below and Above

* W=without addition

Shape of the nozzle:

0 - PLAIN NOZZLE WITH CENTRALLY POSITIONED CIRCULAR ORIFICE

1 - NOZZLE WITH THE CALMING CROSS AT THE LOWER PART OF THE NOZZLE

2 - NOZZLE WITH THE CALMING CROSS INSIDE THE OUTLET TUBE

With each experiment in the set A of the experiments, which included a change of the nozzles, and if necessary, the use of calming cross, the following parameters have been measured (Figure 9, Table 10,

Appendix A): temperature of the air (T_{air}), temperature of the water (T_{water}), flow rate (Q_0), air pressure (p_0), pressure at the entrance to the system (p_1), pressure in the bilge of the system (p_2), pressure at the exit of the system (p_3), pressure at the outer edge of the system (p_4), pressure at the inner edge of the system after the occurrence of the hydrodynamic cavitation (p_5), pressure at the place of the hydrodynamic cavitation occurrence (p_6). All the pressures measured in the experiments are given in absolute values.

In that first phase of the experimental work, duration of each experiment was not taken into consideration, because the primary aim of the set A of experiments was only to adjust the key parameters of the operation of the system, as well as to explore and confirm the generation of the hydrodynamic cavitation effect inside the vortex finder of the pilot system I.

Table 10: The values of main parameters measured in set A of experiments with pilot system I.

Preglednica 10: Vrednosti glavnih parametrov, izmerjenih v A skupini poskusov na pilotnem sistemu I.

Experiment	Q_0 [m^3/h]	p_0 [bar]	p_1 [bar]	p_2 [bar]	p_3 [bar]	p_4 [bar]	p_5 [bar]	p_6 [bar]
A1	2.77	0.98	1.44	1.44	0.98	1.44	0.98	0.97
A2	2.74	0.98	1.44	1.50	1.02	1.44	0.98	1.05
A3	2.72	0.98	1.44	1.43	0.99	1.44	1.00	0.75
A4	2.62	0.98	1.44	1.44	0.99	1.44	0.98	0.93
A5	4.57	0.98	1.43	1.41	1.90	1.43	0.84	0.69
A6	4.00	0.98	1.43	1.42	0.99	1.44	0.99	0.56
A7	5.96	0.98	1.42	1.41	0.99	1.42	0.91	0.64
A8	4.55	0.98	1.43	1.41	0.99	1.43	1.00	0.98
A9	5.55	0.98	1.42	1.40	0.78	1.42	0.74	0.62
A10	5.40	0.98	1.42	1.40	0.90	1.43	0.85	0.74
A11	8.88	0.98	1.38	1.34	0.82	1.39	0.75	0.72
A12	8.92	0.98	1.38	1.33	0.83	1.39	0.74	0.59
A13	8.50	0.98	1.39	1.36	0.76	1.40	0.74	0.78
A14	8.34	0.98	1.40	1.36	0.82	1.37	0.74	0.77

(Other values are given in Appendix A)

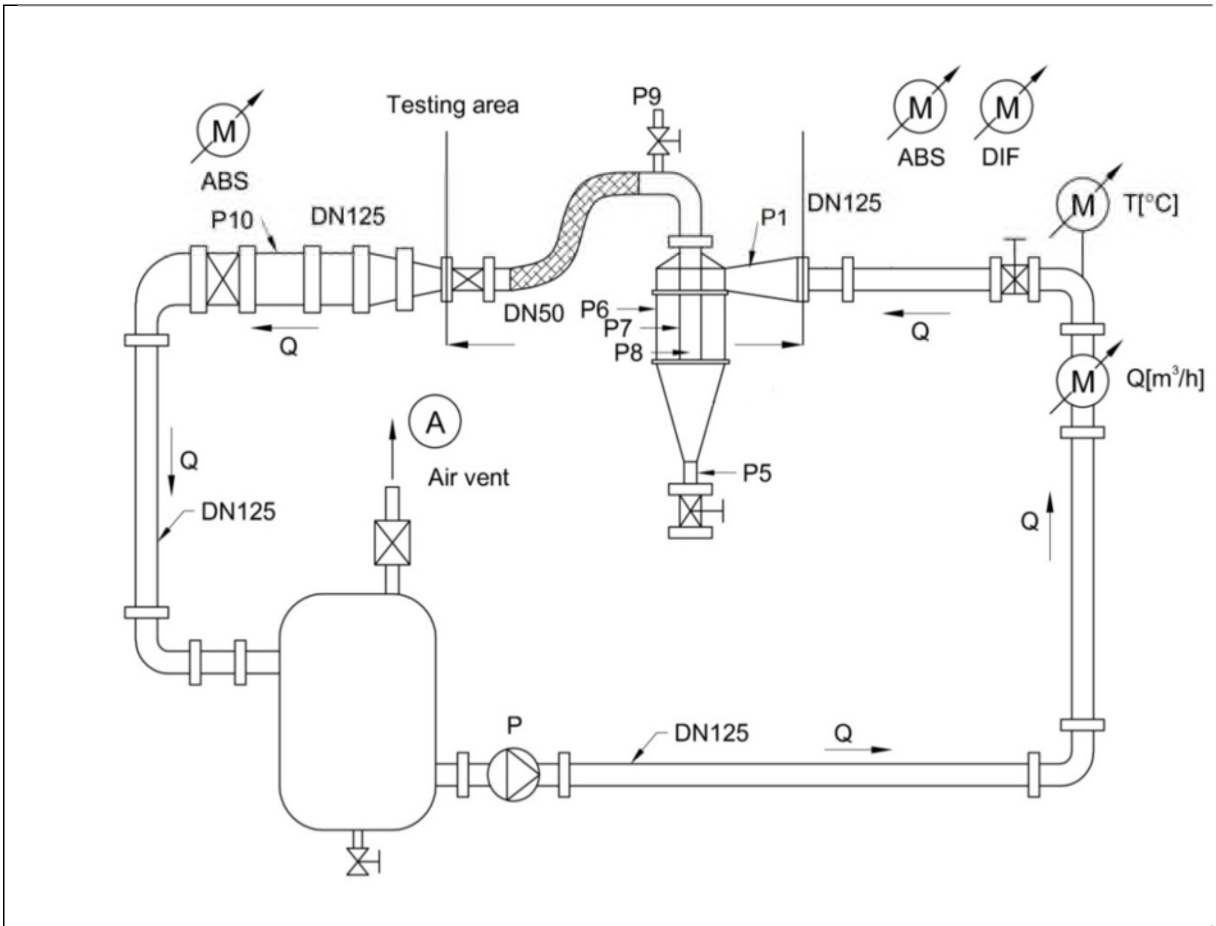
On the basis of the described parameters and the use of the equations (1,3,7,14,15,16), the following theoretical values will be calculated: area of the nozzle (S_{nozzle}), area of the vortex finder tube (S_{tube}), velocity of the water inside the nozzle (v_{nozzle}), velocity of the water at the outlet pipe ($v_{outlet\ pipe}$), cavitation number (σ), the relative thickness (α), flow number (β), pressure loss (Δp), and energy consumption (P).

After the calculation of the aforementioned theoretical values for set A of experiments, the results will be compared and experiments with the optimal theoretical values will be chosen for continuation with the performance of further experiments with the pilot system II.

3.1.2 Pilot system II

Laboratory's installation for the pilot system II is presented in Figure 12. Pilot system II was situated in the testing area of the laboratory's installation and it was circularly connected by tubes (DN125) with the reservoir for water and the centrifugal pump (Etanorm 50-125 - 50-315) that were located in the basement area of the laboratory.

Before starting the experiments, reservoir and system were filled with fresh water and the system was deaerated so the air bubbles went out from the system and it could work unhindered with the air present in the system as low as possible. Fresh water was fed to the system through the tube on the right side (entrance) (1) of the system and it went out of the system with the help of the outlet pipe (upper exit) (5) at the top of the system. After the treatment was done, fresh water returned back to the reservoir from where it re-circulated to the system again. All points of measuring the values of the pressure (p_1, $p_{5\text{-}10}$), temperature (T) and flow rate (Q_0) for all experiments of the set B are indicated in Figure 12.



Legend	
- Absolute pressure	P1 - Pressure on the entrance of the system
M DIF - Differential pressure	P5 - Pressure on the bilge exit of the system
- Air vent	P6 - Pressure on the inner edge of the system
- Centrifugal pump	P7 - Pressure on the edge of the vortex finder
DN125 - ø tube	P8 - Pressure on the place of HC occurrence
DN 50 - ø tube	P9 - Pressure on the outlet pipe
Q - Flow rate	P10 - Pressure on the exit tube
T - Temperature of air	

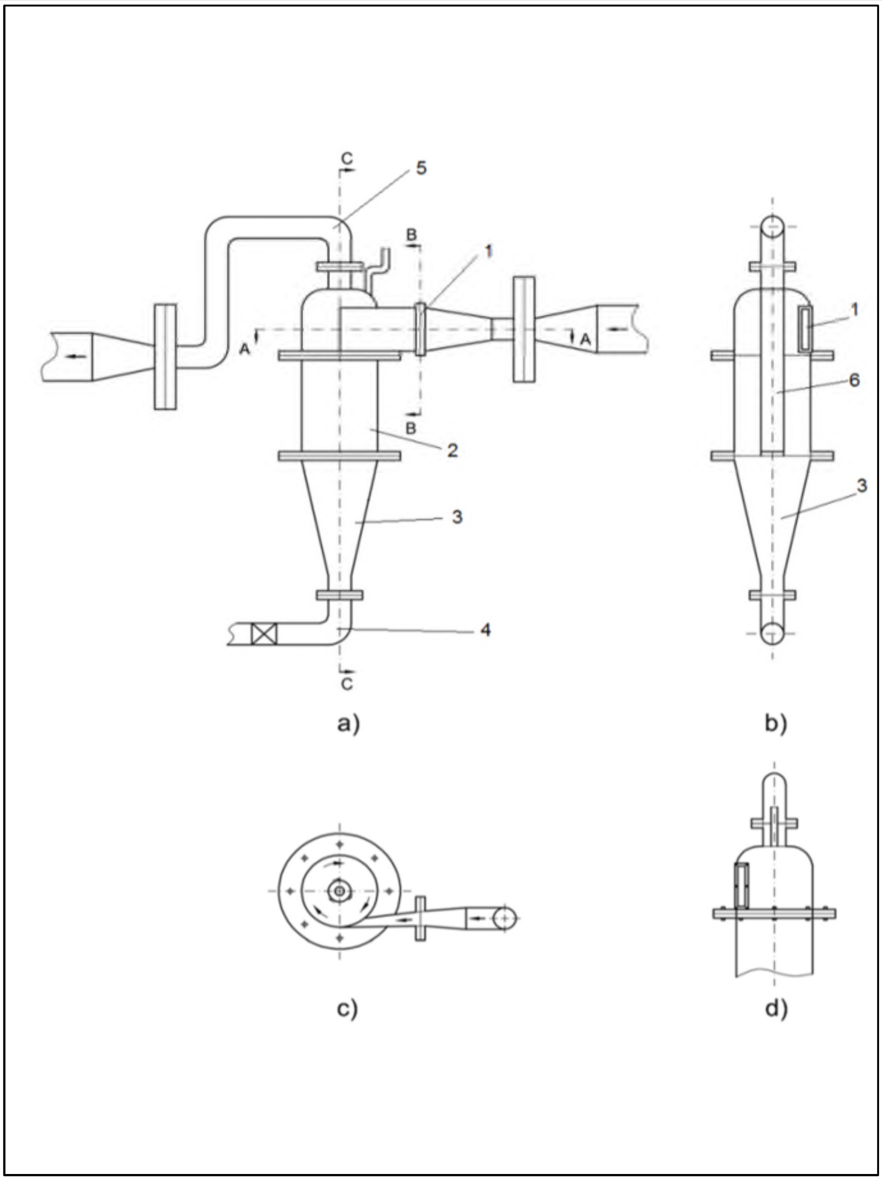
Figure 12: Appearance of laboratory's installation for pilot system II with its elements and points of measuring pressures (p_1, $p_{5\text{-}10}$), temperatures (T) and flow rate (Q_0).

Slika 12: Izgled laboratorijske inštalacije pilotnega sistema II s svojimi elementi in točke merjenja tlakov (p_1, $p_{5\text{-}10}$), temperature (T) in pretoka (Q_0).

The appearance of pilot system II is presented in Figures 13 and 13a. Similarly to the pilot system I, the body of the pilot system II is constructed in the shape of a hydrocyclone. Just like in pilot system I, the cylindrical part of the pilot system II was made of Plexiglas material and the other parts of the system were made of the steel.

With the aim of achieving better working results, the following construction changes have been made:

a. Narrowing of the entrance section to achieve higher acceleration of water at the entrance of the system
b. With the aim of easier rising and exit of the air bubbles and particles with lower density than water, rectangular geometry of the upper part of the system (the place where the outlet pipe from the system is situated) has been changed into the shape of a dome



Legend

1 - Entrance of the system

2 - Cylindrical part

3 - Conical part

4 - Lower exit from the system

5 - Upper exit from the system

Figure 13: Scheme of pilot system II where a) illustrates the concept of the system b) illustrates the C-C section of the system, c) illustrates the A-A section of the system and d) illustrates the B-B section of the system.

Slika 13: Shema pilotnega sistema II, kjer a) ponazarja zasnovo sistema, b) prikazuje prerez C-C sistema, c) prikazuje prerez A-A sistema in d) prikazuje prerez B-B sistema.

Figure 13a: Image of the pilot system II where a) is the body of the pilot system II situated on the testing area and b) cylindrical part of the pilot system II during the operation.

Slika 13a: Slika pilotnega sistema II, kjer je a) ohišje pilotnega sistema II, ki se nahaja na testnemu območju in b) cilindrični del pilotnega sistema II med obratovanjem.

The working principle of the pilot system II is the same as that of the pilot system I. After processing the results of the pilot system I, the nozzles that have shown the best results during performance of the Set A experiments for pilot system I have been be chosen for experiments in set B with pilot system II. When choosing the most effective nozzles, the following parameters have been taken into consideration: flow rate inside the system (Q_0), velocity of the water inside the tube (v_{tube}), velocity of the water inside the nozzles (v_{nozzle}), cavitation number (σ), the relative thickness (α), flow number (β), pressure loss (Δp), and energy consumption (P). The combination of the nozzles' geometry used in set

B experiments is shown in Table 11.Table 11: Combination of geometry and additions in the set B experiments for pilot system II.

Preglednica 11: Kombinacija geometrije in dodatkov, uporabljenih v B skupini poskusov na pilotnem sistemu II.

Group of experiments	ø nozzle [m]	Wings	Remark
B1	0.012	0	B
B2	0.012	8	W
B3	0.014	0	B
B4	0.016	0	W
B5	0.016	8	W
B6	5*0.008	0	W

Set B of the experiments consisted of 6 experiments with different combinations of geometry and additions. Each experiment of set B had a series of sub-experiments (6-11 experiments) and it was performed in the way that the value of the input pressure to the system (p_1) was manually adjusted and progressively increased, starting with the pressure of about 1 bar (example of experiment B5.1, Table 12) and finishing with pressure of about 4 bar (example of experiment B 5.9, Table 12). Experiments in set B differed in geometries and dimensions of the nozzles (in each experiment a different nozzle has been used). In set B of the experiments, the type of nozzle b) from the Figure 11 with different diameters (Table 11) was used. Also, one additional nozzle was constructed and its properties were examined in the set B of the experiments (experiment B6, Figure 14). The new nozzle is a plain one with 5 orifices (central orifice is positioned under 90° angle, other four orifices positioned under 45° angle) (Figure 14). Diameters d_1 (Figure 11, a) and 14 a)) are shown in Table 11, and they changed with the experiments (B1-B6). Diameters of the nozzles d_2=49.5 mm, d_3=51.5 mm and d_4=10 mm were unchanged for all experiments in the set B.

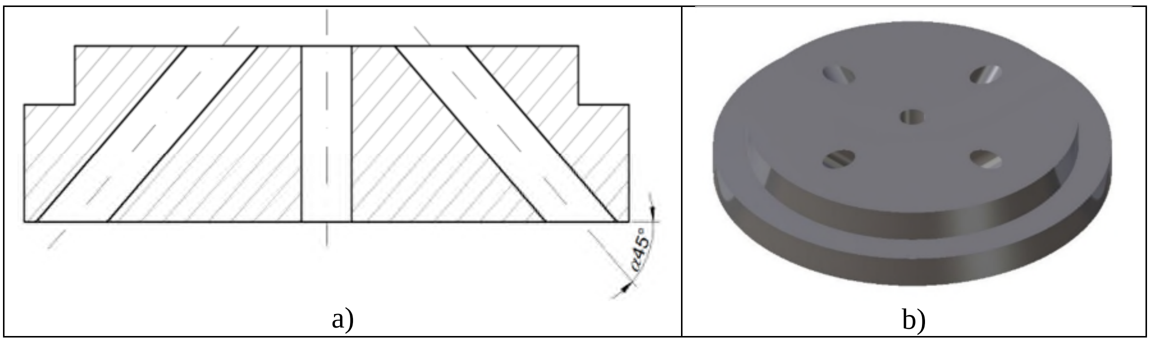


Figure 14: Appearance of the new nozzle for pilot system II, a) Technical draft of the plain nozzle with 5 orifices, b) 3D draft of the plain nozzle with 5 orifices.

Slika 14: Izgled nove šobe pilotnega sistema II, a) tehnični osnutek navadne šobe s 5 odprtinami, b) 3D osnutek navadne šobe s 5 odprtinami.

In every single experiment of the set B, which included a change of the nozzles with different geometries, the following parameters have been measured (Figure 12, Table 12): temperature of the air (T_{air}), temperature of the water (T_{water}), flow rate (Q_0), air pressure (p_0) pressure on the entrance to the system (p_1), pressure on the bilge exit of the system (p_5), pressure on the inner edge of the system (p_6), pressure on the edge of the vortex finder (p_7), pressure on the place of HC occurrence (p_8), pressure on the outlet pipe (p_9), pressure on the exit tube (p_{10}). All the pressures measured in the experiments are given in absolute values. The list of all groups of performed experiments in set B with their measurements is provided in the annexes of this paper (appendix B), while Table 12 shows an example of an experiment performed (B5) in set B with all values of the measured parameters.

Table 12: The example of the values of main parameters measured in set B of experiments with pilot system II.

Preglednica 12: Primer vrednosti glavnih parametrov, izmerjenih v B skupini eksperimentov na pilotnem sistemu II.

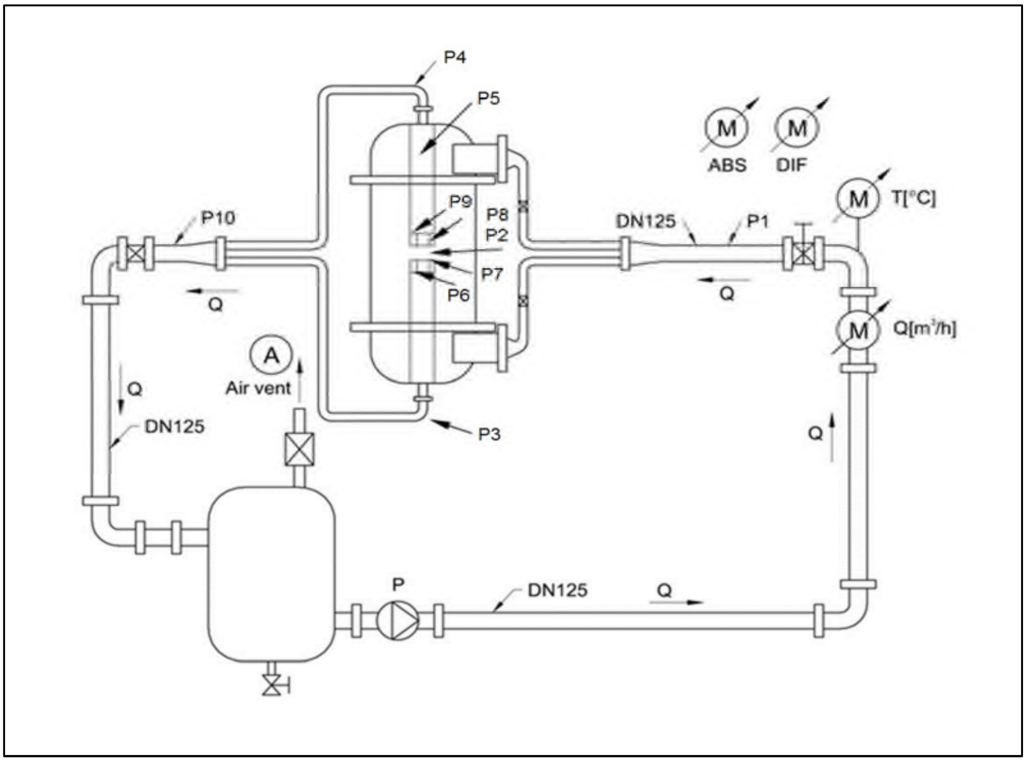
Experiment	Q_0 [m^3/h]	p_0 [bar]	p_1 [bar]	p_5 [bar]	p_6 [bar]	p_8 [bar]	p_9 [bar]	p_{10} [bar]	Δ p_7-p_8 [bar]
B5.1	0.00	0.98	1.09	1.09	1.09	1.09	1.09	1.09	-0.02
B5.2	4.92	0.98	1.41	1.37	1.39	0.79	0.97	0.96	-0.11
B5.3	5.85	0.98	1.59	1.71	1.71	0.86	1.09	1.09	-0.22
B5.4	6.99	0.98	2.00	1.95	1.97	0.75	1.07	1.09	-0.25
B5.5	7.86	0.98	2.24	2.19	2.20	0.63	1.08	1.04	-0.27
B5.6	8.85	0.98	2.59	2.53	2.55	0.45	1.09	1.09	-0.39
B5.7	9.81	0.98	2.92	2.82	2.87	0.23	1.01	1.01	-0.62
B5.8	11.08	0.98	3.54	3.40	3.44	0.20	1.07	1.06	-0.64
B5.9	11.40	0.98	3.73	3.61	3.66	0.17	1.07	1.06	-0.60

(Other values are given in Appendix B)

Similarly to the set of experiments A, the duration of each experiment for set B was not taken into consideration, because the aim of this set of experiments was the improvement of working parameters of the system in comparison with the parameters used in set A (pilot system I), as well as testing and improving the intensity of achieved HC generated in the pilot system. After the calculation of the key theoretical values for operation of the pilot system II is finished, the nozzles that show the best working performances will be chosen for use in the set C of experiments with the newly constructed pilot system III.

3.1.3 Pilot system III

Laboratory's installation for the pilot system III is presented in Figure 15. Plot system III was situated in the testing area of the laboratory's installation and it was connected the same way as pilot system II. The only difference in installation is that pilot system III has two entrances (upper and lower) and two exits from the system (upper and lower), so the installation was adjusted to these changes of construction of the pilot system. All points of measuring the values of the pressure (p_1-p_{10}), temperature (T) and flow rate (Q_0) for all experiments of the set C are shown in Figure 15.



Legend

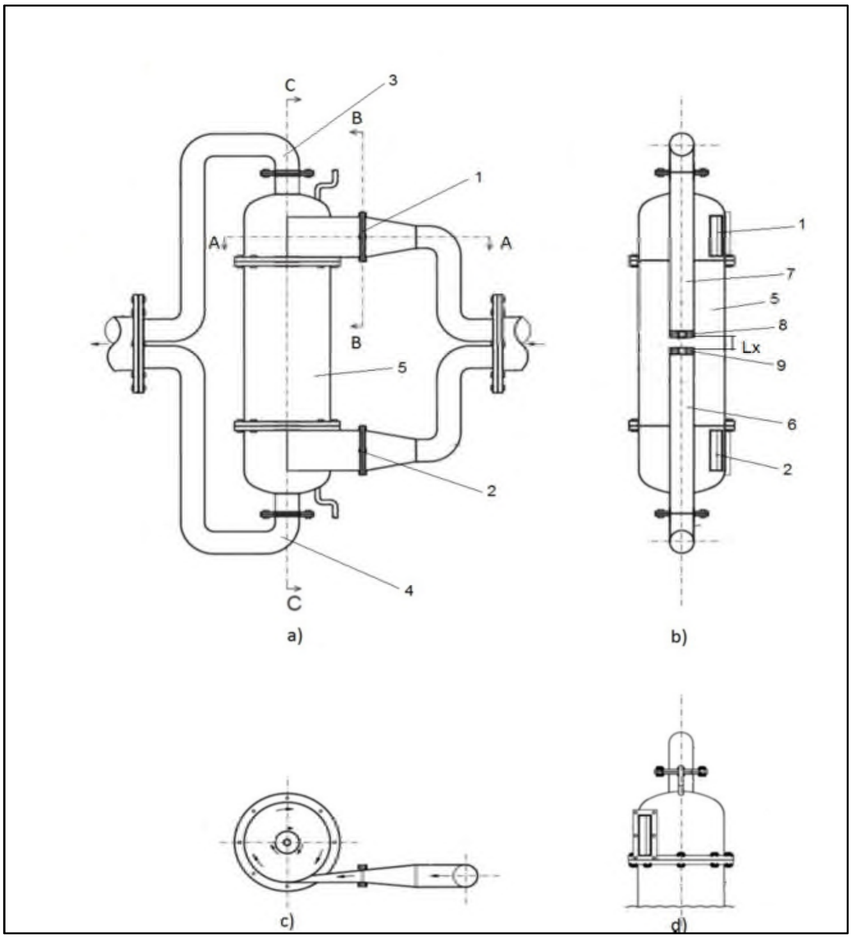
- Absolute pressure	DIF - Differential pressure
- Air vent	- Centrifugal pump
DN125 - ø tube	DN 50 - ø tube
Q - Flow rate	*T* - Temperature of air
P1 - Pressure on the inlet pipe of the system	P2 - Pressure between the nozzles
P3 - Pressure on the lower exit of the system	P4 - Pressure on the upper exit of the system
P5 - Pressure on the vortex finder	P6 - Pressure on the inner edge of the lower nozzle
P7 - Pressure on the outer edge of the lower nozzle	P8 - Pressure on the inner edge of the upper nozzle
P9 - Pressure on the outer edge of the upper nozzle	P10-Pressure on the outlet pipe

Figure 15: Appearance of laboratory's installation for pilot system III with its elements and points of measuring pressure (p_1-p_{10}), temperature (T) and flow rate (Q_0).

Slika 15: Izgled laboratorijske inštalacije pilotnega sistema III z elementi in točke merjenja tlakov (p_1-p_{10}), temperature (T) in pretoka (Q_0).

Appearance of pilot system III is shown in Figures 16 and 16a. Just like in previous pilot systems, the cylindrical part of the pilot system III was made of Plexiglas material and the other parts of the system were made of steel. However, construction characteristics of pilot system III differ from those of pilot system I and II. The main differences are:

a. The body of the pilot system that was previously in the shape of hydrocyclone is now replaced with the new one in the shape of the separator. However, the primary function of the body of the pilot system still remained the same, i.e. separate the particles with densities greater than water
b. With the aim of increasing the speed of the vortex of the water flow, the pilot system has now two symmetric tangential entrances (upper and lower) and two exits (upper and lower)
c. With the aim of improving the intensity of HC effect inside the system and increasing the number of HC events, one vortex tube is now replaced with two symmetrical vortex tubes which are situated opposite each other at the certain distance.



Legend

1 - Upper entrance of the system	6 - Upper vortex finder
2 - Lower entrance of the system	7 - Lower vortex finder
3 - Upper exit of the system	8 - The nozzle
4 - Lower exit of the system	9 - The nozzle
5 - The cylindrical body (separator)	Lx - Distance between the nozzles

Figure 16: Scheme of the pilot system III where a) illustrates the concept of the system b) illustrates the C-C section of the system, c) illustrates the A-A section of the system and d) illustrates the B-B section of the system.

Slika 16: Shema pilotnega sistema III, kjer a) prikazuje zasnovo sistema, b) prikazuje prerez C-C sistema, c) prikazuje prerez A-A sistema in d) prikazuje prerez B-B sistema.

Figure 16a: Image of the pilot system III where a) is body of the pilot system III situated on the laboratory's installation, b) the inner part of the pilot system III without the nozzles at the end of the vortex finders, c) the inner part of the pilot system III during the operation.

Slika 16a: Slika pilotnega sistema III, kjer je a) ohišje pilotnega sistema III, ki se nahaja na laboratorijski inštalaciji, b) notranji del pilotnega sistema III brez šobe na koncu vrtinčnih nastavkov, c) notranji del pilotnega sistema III med obratovanjem.

Water tangentially enters into the system at the same time and at the same direction through the upper (1) and lower (2) entrance of the system (rectangular cross section) and, affected by centrifugal force it rotates around the upper (7) and lower (6) vortex finder. Consequently, two water vortexes (upper and lower) are formed. The vortexes merge in the area between the vortex finder tubes (6 and 7). The merging of the vortexes causes an increase in the speed of the water flow rotation and consequently the dispersion of the particles with density greater than water toward the walls of the cylindrical body (5) (separator). All particles with density greater than water are pushed down toward the walls of the system's body and continue to glide down to the exit at the bottom of the system (4). At the end of the both vortex finders there are the nozzles (8 and 9) (one nozzle for each vortex finder) with single holes in different diameters and geometries. When the water flow passes through the nozzle (8 and 9), HC occurs. Furthermore, affected by vortex and after the passing through the nozzles where the HC occurs, the particles with density lower that water are pushed through the inner part of the both vortex finder tubes (6 and 7) (upper and lower) and exit from the system through the upper and lower exit (3 and 4). Also, together with the particles with density lower than water, the air bubbles exit from the system through the upper exit of the system (3). After the treatment, the treated water returns to the reservoir from which, if necessary, re-circulates to the pilot system.

The system may operate with or without the separation phase (separator) which is adjusted by valves (open valve means an open process of separation). In the case of all the experiments in the set C with the pilot system III, the nozzle with a single hole ((d_1) = 16 mm) has been used (the type of nozzle b), Figure 11). Diameters of the nozzles d_2=49.5 mm, d_3=51.5 m and d_4=10 mm remained unchanged during all experiments of the set C. The variation in different experiments has been made with the regulation of distance between the nozzles (L_x) (Figure 17), i.e. vortex tubes and openness of the upper and lower valve of the system (Table 13).

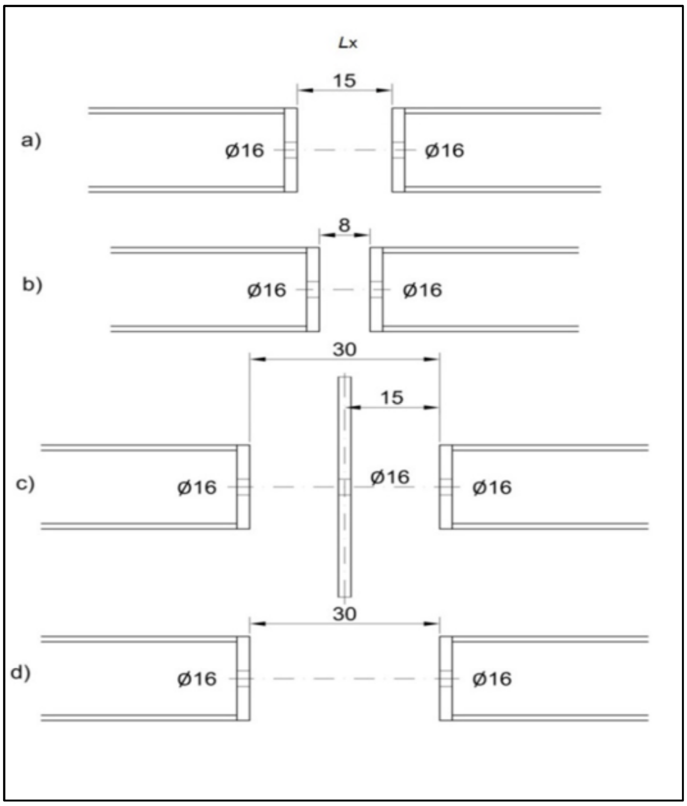


Figure 17: Appearance of the nozzles and other additions to the vortex finder and distances between the vortex finders of the pilot system III.

Slika 17: Izgled šob in ostalih dodatkov k vrtinčnim nastavkom in razdalje med vrtinčnima nastavkoma pilotnega sistema III.

In the group of experiments C3, the plate made of steel has been inserted in the area between the two nozzles (Figure 17, c)). The list of all combinations and the nozzles' geometry used in set C of experiments is shown by Table 13.

Table 13: Combination of geometry and additions in the set of experiments C for the pilot system III (*U - upper valve, *V - lower valve).

Preglednica 13: Kombinacija geometrije in dodatkov, uporabljenih v C skupini eksperimentov na pilotnem sistemu III (U - zgornji ventil, * V - spodnji ventil).*

Group of experiments	ø nozzle [m]	Distance between the nozzles [m]	Openness of the valves
C1	0.016 (*2)	0.02	100% U&L
C2	0.016 (*2)	0.008	100% U&L
C3	0.016 (*3)	0.03	100% U&L
C4	0.016 (*2)	0.03	100% U&L
C5	0.016 (*2)	0.03	100% U; 0% L

In all the experiments of the set C with the pilot system III, the following parameters have been measured (Figure 15, Table 14): temperature of the air (T_{air}), temperature of water (T_{water}), flow rate (Q_0), air pressure (p_0), pressure on the inlet pipe of the system (p_1), pressure between the nozzles (p_2), pressure on the lower exit of the system (p_3), pressure on the upper exit of the system (p_4), pressure on the vortex finder (p_5), pressure on the inner edge of the lower nozzle (p_6), pressure on the outer edge of the lower nozzle (p_7), pressure on the inner edge of the upper nozzle (p_8), pressure on the outer edge of the upper nozzle (p_9), pressure on the outlet pipe (p_{10}). The list of all groups of performed experiments in set C with their measurements is presented in the annexes of this paper (Appendix C), while Table 14 shows an example of an experiment performed (C4) in set C with all values of the measured parameters.

Table 14: The example of the values of main parameters measured in set C of experiments with pilot system III.

Preglednica 14: Primer vrednosti glavnih parametrov, izmerjenih v C skupini eksperimentov na pilotnem sistemu III.

Experiment	Q_0 [m^3/h]	p_0 [bar]	p_1 [bar]	p_2 [bar]	p_3 [bar]	p_4 [bar]	p_5 [bar]	p_6 [bar]	p_7 [bar]	p_8 [bar]	p_9 [bar]	p_{10} [bar]
C4.1	0.00	0.94	1.09	0.95	0.96	0.91	0.95	0.96	0.96	0.96	0.96	1.02
C4.2	7.45	0.94	1.53	1.03	0.94	0.96	1.47	1.01	0.83	0.98	0.98	0.91
C4.3	11.10	0.94	2.03	1.05	0.92	0.92	0.93	1.96	0.60	0.66	0.79	0.90
C4.4	13.30	0.94	2.56	1.18	0.96	0.97	2.57	1.64	0.50	0.45	0.79	0.93
C4.5	14.70	0.94	3.12	1.37	1.10	1.11	3.10	1.24	0.51	0.91	0.92	1.08
C4.6	16.30	0.94	3.75	1.58	1.14	1.14	3.71	1.33	0.42	0.81	0.90	1.12

(Other values are given in Appendix C)

Similarly to the previous sets of experiments (A and B), the duration of each experiment for set C was not taken into consideration, because the aim of this set of experiments was the improvement of the working effectiveness of the system.

Like in previous two systems, when using the equations (1,3,7,14,15,16) the following theoretical values will be calculated: area of the nozzle (S_{nozzle}), area of the vortex finder tube (S_{tube}), velocity of the water on the outlet pipe ($v_{outlet\ pipe}$), velocity of the water inside the nozzles (v_{nozzle}), cavitation number (σ), the relative thickness (α), flow number (β), pressure loss (Δp), and energy consumption (P).

After the calculation of the theoretical values for pilot system III is finished, the nozzle that shows the best working properties will be chosen for further experiments whose aim will be to test the efficiency of the pilot system in destroying the targeted marine organisms.

3.2 Materials and methods for biological analysis and parameters

According to the previous analysis and comparison of the key performances of all three newly developed pilot systems, pilot system III was selected for further experiments whose goal was to assess the efficiency of the newly developed concept on the destruction the aimed marine organisms.

The pilot system was moved from the Hydraulic laboratory of UL FGG to the yard of the Marine Biology Station (NIB) and its installation consisted of the following parts: container for the storage of sea water (mesocosm), centrifugal pump, pipes for water circulation and the chamber for HC (Figure 18). The total volume of seawater treated with the pilot system was 150 L (100 L in the mesocosm and 50 L in the chamber and pipes). The seawater from the mesocosm was pumped through the pipes to the chamber for the treatment (pilot system III) (Figure 18) and was discharged back to the container after each treatment cycle.

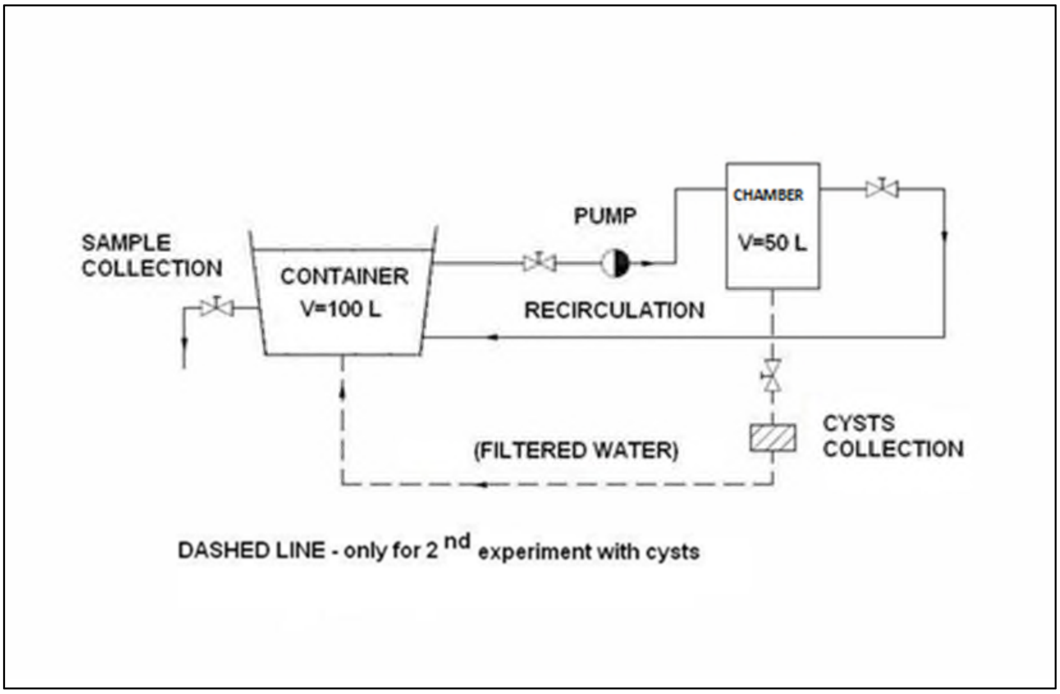


Figure 18: Scheme of the installation of the system for ballast water treatment together with sampling points.

Slika 18: Shema inštalacije sistema za obdelavo balastnih voda in točke vzorčenja.

The values of the key parameters during the operation of the pilot system were as follows: the pressure on the entrance of the chamber varied between 1.8 and 2.8 bar, the flow rate of the seawater through the system was 15 m^3/h, and the duration of each cycle was 0.6 minutes (see equation 5). The whole amount of the seawater (150 L) re-circulated through the system during one experiment. For each experiment 100 cycles were performed per hour (see equation 4).

3.2.1 Experimental set up

The efficiency of the pilot system for ballast water treatment was tested on natural population of planktonic marine organisms (representatives of zooplankton and heterotrophic marine bacteria) in seawater collected in the Gulf of Trieste (Northern Adriatic Sea). Before each experiment the pilot system and tubes (150 L) (Figure 18) were filled with fresh seawater using the pumping system for running seawater at the laboratories. Zooplankton samples were collected with plankton net (pore size of 50 μm) at the station 00BF (45° 32.93' N, 13° 33.03' E) and concentrated zooplankton samples were added into the mesocosm with seawater.

In addition to copepods, the experiments with *A. salina* (Crustacea, Anostraca) cysts were carried out, including the combination of the HC and separation phase (referred to as Cs) or with the use of only the HC phase (with a closed process of separation) (referred to as C). Before inoculation into 150 L mesocosm with seawater, *A. salina* cysts (40 g) (Dajana Aqua, Czech Republic) were hydrated for 2 hours in seawater (until all changed shape to spheric).

The samples for zooplankton and cyst analysis were taken from the container (mesocosm) before the treatment (t0), after 15 minutes (t15), 30 minutes (t30) and 60 minutes (t60) of treatment for each experiment. For bacteriological analyses samples were taken at same time intervals, except the t15. For all analyses and each step of the treatment samples were taken in triplicates. Experiments were conducted between October 2013 and May 2014.

Altogether, five experiments with zooplankton (copepods) samples, six experiments with *A. salina* (Crustacea, Anostraca) cysts and six experiments to follow changes in bacterial abundance and growth rate (bacterial carbon production) were conducted. In all experiments with the pilot system, the initial technical parameters were identical (see section 3.2.).

Separation (pre-treatment) phase (Figure 18, dashed line) was used only in experiments with cysts, which have density greater than seawater (Van Stanpen, 1996; Vos and de la Rosa, 1980). Most zooplankton organisms are denser than seawater (Visser and Jónasdóttir, 1999; Knutsen et al., 2001; Abatzopoulos et al., 2003) but have several mechanisms, like large appendages and lipid storage, which increase their buoyancy (Campbell and Dower, 2003; Jiang and Osborn 2003; Sartois et al, 2010; Pond, 2012) therefore, separation phase was not useful. Most marine bacteria have lower density than seawater, but gas vacuoles present in their cells provide their buoyancy (Cohen-Bazire et al., 1969; Walsby, 1972; Wheelis, 2008).

3.2.2 Determination of zooplankton (copepods) and *A. salina* cysts abundance and morphology

The samples with the zooplankton (copepods) were first filtered through a sieve with 38 μm pores size and then fixed with formaldehyde in final concentration of 4%. Afterwards, they were put into the tubes with 10 mL filtered seawater (Whatman GF/F). Copepods, the predominant taxa in the samples, were observed and counted under stereo microscope Olympus SZX 16. If the carapax and appendages of the copepods were intact, the copepods were considered as alive. In the case when the copepod exoskeleton was destroyed, empty or broken, the copepods were not considered as a count. Pictures of the copepod samples were taken using Olympus DP70 camera and Soft Imaging System.

Subsamples with *A. salina* cysts were also fixed with formaldehyde (4% final concentration). From each 100 mL sample, three subsamples of 10 mL were analyzed; the whole - intact cysts were counted under research stereo microscope Olympus SZX 16. Microphotographs were taken using Olympus camera at different magnifications and analyzed with DP70 Soft Imaging System.

Three experiments were conducted using only the hydrodynamic cavitation phase (referred to as C) and three experiments were performed with a combined use of the pre-treatment (separation) phase and hydrodynamic cavitation (referred to as Cs).

Additionally, the viability of cysts at the end of treatments was preliminary tested. The aim of this stage of analysis was to determine the percentage of hatched nauplii. Subsamples of 5 L (for the C and Cs experiments) were taken from 100 L container before (time interval t0) and at the end (t60) of the experiments and were placed in the thermostatic chamber. Seawater with cysts was incubated at 25 ° C for 48 hours with 12/12h day/night cycle. From each 5L container, three subsamples (10 mL) were taken and fixed with formaldehyde with the final concentration of 4%. The number of hatched nauplii was subsequently counted under the research stereo microscope Olympus SZX 16. Pictures were taken using Olympus DP70 camera and Soft Imaging System.

3.2.3 Determination of bacterial abundance

The subsamples of seawater (50 mL) collected during all treatments were fixed with formaldehyde solution (0.22 μm pre-filtered, 2% final concentration) and kept at 4°C. Bacterial cells were filtered onto a 0.2 μm black polycarbonate membrane filter (25 mm diameter, Millipore) and stained with 4',6-diamino-2-phenylindole (DAPI, 1 μg/mL final concentration), according to the protocol of Porter and Feig (1980). Bacterial cells were counted using the epifluorescence microscope Olympus BX51 at 1000x magnification, each field of view was photographed and counted using Olympus DP70 camera and Soft Imaging System.

3.2.4 Bacterial carbon production (BCP)

Bacterial carbon production (BCP) was measured by the incorporation of ^{3}H-leucine into newly synthesized proteins in the bacterial cells (Kirchman et al., 1985) using the centrifugation protocol by Smith and Azam (1992). Triplicates of each sample were incubated with ^{3}H-leucine (20 nM final concentration, Amersham) for 1 hour at *in situ* temperature in the thermostatic chamber in the dark. Trichloroacetic acid (TCA, 5 % final concentration, Sigma) was added prior to addition of ^{3}H-leucine to the controls. Incubation was stopped by adding TCA (5% final concentration) to all samples. The scintillation liquid (Ultima gold, PerkinElmer) was added to each sample and the radioactivity was measured using a liquid scintillation counter (Canberra Packard TriCarb Liquid Scintillation Analyzer, model 2500 TR). BCP was calculated from the measured dpm (disintegration per minute) as described by Simon and Azam (1989).

3.2.5 Statistical analyses

The initial number of zooplankton (copepods) at the beginning of each experiment (t0) varied, because field sampling for zooplankton has been conducted in different periods of the year and consequently densities in planktonic nets were different. Moreover, there were differences in the number of zooplankton between 3 replicates of 1L taken from 150 L mesocosm at the start of the experiment. Therefore for each experiment separately, the starting density of zooplankton (t0) was averaged per 3 replicates. The zooplankton density from each sample was than divided by this average and multiplied by 100. In this way the densities of zooplankton were synchronised in all the experiments, as if the starting densities of zooplankton in all experiments were the same.

Although all the experiments with cysts were conducted with the same quantities of *A. salina* cysts (in each experiment a box with 40 g of cysts was added to 100L seawater), the starting (t0) densities of *A. salina* cysts varied and were also synchronized to same starting conditions as described for zooplankton.

4 PROCESSING THE EXPERIMENTAL RESULTS, SYNTHESIS AND VERIFICATION OF THE HYPOTHESES

After all experiments at the cavitation station in the Hydraulic laboratory of UL FGG and biological analysis at the Marine Biology Station Piran were finished and all data needed for further discussion of the hypotheses were collected, they were processed. The most important results and findings are summarized in the following chapter.

4.1 Findings of the experiments performed at the cavitation station in Hydraulic laboratory of Faculty of Civil and Geodetic Engineering Ljubljana

With the aim of selecting the indicative parameters for the effective work of the pilot system I, II and III, basic parameters of the behavior of the fluid within the pilot systems were calculated, analyzed and presented in tables and graphs.

Since the hydraulic experiments have been performed in three sets (A, B and C) for three different pilot systems, with the aim of easier understanding of the topic, the analysis of the results will be also divided into three separated subchapters (each subchapter for each pilot system).

4.1.1. Pilot system I

Calculations of the key theoretical values for the operation of the pilot system I (surface of the nozzle, velocity of the water flow in the nozzle, velocity of the water flow in the vortex finder tube, cavitation number) on the basis of data shown in Tables 9 and 10 are presented in Table 15.

Table 15: Calculation of the key values for the operation of the pilot system I (S_{nozzle}, v_{nozzle}, v_{tube}, cavitation numbers σ_1, σ_2) based on values of the pressures measured at the entrance to the system (p_1) and the geometry of the nozzles for different flow rates (Q_0).

Preglednica 15: Izračun ključnih vrednosti za delovanje pilotnega sistema I ($S_{šobe}$, $v_{šobe}$, v_{cevi}, kavitacijski števili σ_1, σ_2), ki temelje na vrednostih tlakov merjenih na vhodu v sistem (p_1) in geometriji šob za različne pretoke (Q_0).

Experiment	Q_0 [m^3/h]	S nozzle [m^2]	S tube [m^2]	v nozzle [m/s]	v outlet pipe [m/s]	Cavitation numbers σ_1	σ_2
A1	2.77	1.13E-04	2.09E-03	6.80	0.37	1.54	1.03
A2	2.74	1.13E-04	2.09E-03	6.73	0.36	1.55	1.05
A3	2.72	1.13E-04	2.09E-03	6.68	0.36	1.59	1.09
A4	2.62	1.13E-04	2.09E-03	6.43	0.35	1.71	1.16
A5	4.57	1.54E-04	2.09E-03	8.25	0.61	1.04	0.60
A6	4.00	1.54E-04	2.09E-03	7.22	0.53	1.36	0.93
A7	5.96	1.54E-04	2.09E-03	10.75	0.79	0.61	0.38
A8	4.55	2.01E-04	2.09E-03	6.29	0.60	1.80	1.23
A9	5.55	2.01E-04	2.09E-03	7.67	0.74	1.21	0.61
A10	5.40	2.01E-04	2.09E-03	7.46	0.72	1.27	0.75
A11	8.88	2.01E-04	2.09E-03	12.27	1.18	**0.47**	**0.24**
A12	8.92	3.14E-04	2.09E-03	7.89	1.18	1.14	0.58
A13	8.50	2.39E-04	2.09E-03	9.89	1.13	0.72	0.37
A14	8.34	2.39E-04	2.09E-03	9.70	1.11	0.75	0.38

The blue color in Table 15 indicates the experiment with the lowest cavitation number. Furthermore, all the values with the cavitation number lower than 1, where hydrodynamic cavitation theoretically should occur, are marked in bold. Since the equation for the calculation of the cavitation number does not precisely define the point of measuring the characteristic pressure (p_0), the calculation of the cavitation number in this study was performed with two different characteristic pressures; p_1, pressure at the entrance to the system and p_5, pressure at the inner edge of the system after the occurrence of the hydrodynamic cavitation (place of the pressure recovery after the occurrence of hydrodynamic cavitation). Similarly, according to our experiences, no matter which cavitation number (σ_1 or σ_2) we took into consideration, the calculations of the cavitation number did not always prove to be entirely reliable, since there were certain deviations when we compared the value of the cavitation number and visual observation for the same experiment. It means that in some cases there was visually no cavitation occurrence noticed or the cavitation was very insignificant and vice versa, even though the cavitation number dropped under 1. Therefore, in majority of further experiments within this study, the cavitation number will be calculated for two different characteristic pressures (with the exception of set C experiments, where σ_1 and σ_2 have approximately the same values): pressure at the entrance to the system and pressure at the inner edge of the system after the occurrence of the hydrodynamic cavitation (place of the pressure recovery after the occurrence of hydrodynamic cavitation). However, since it did not prove to be entirely reliable, the cavitation number will not be taken into the consideration as the key factor during the evaluation of the effectiveness of the experiments.

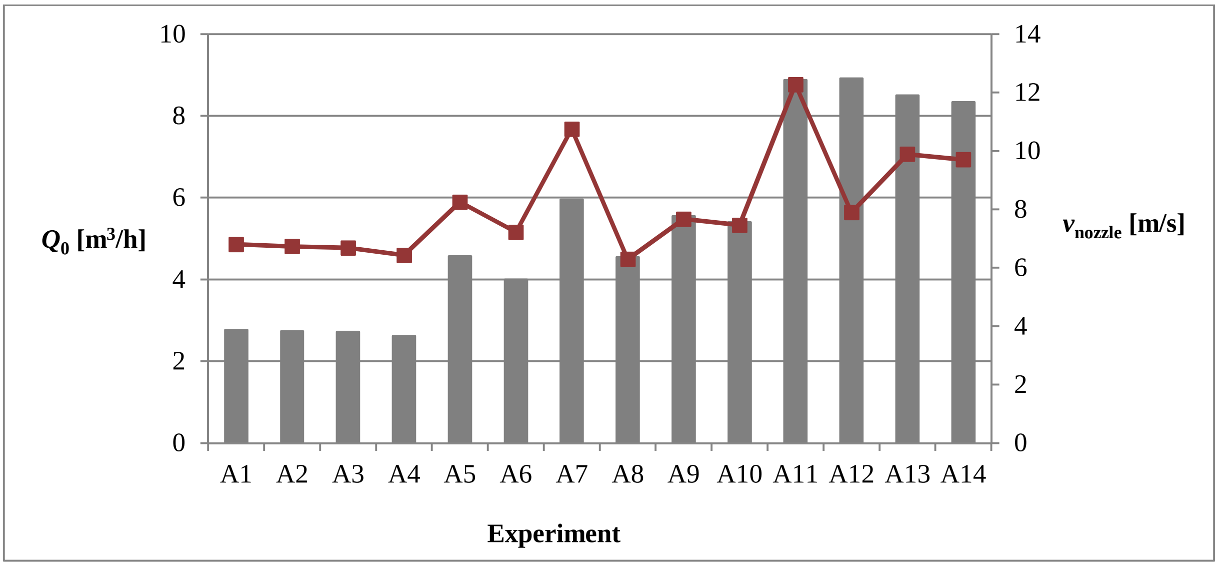


Figure 19: Correlation between the flow rate (Q_0) and the velocity of the liquid in the nozzle (v_{nozzle}) in the set A experiments.

Slika 19: Korelacija med pretokom (Q_0) in hitrostjo tekočine v šobi ($v_{šobe}$) v skupini eksperimentov A.

Relation between the flow rate (Q_0) and the velocity of the liquid in the nozzle (v_{nozzle}) for the experiments A1-A14 of the set A is presented in Figure 19. The figure reveals the proportional behavior between the factors Q_0 and v_{nozzle} within the experiments of the set A. Namely, the experiments with higher values of the flow rates have higher velocities of the liquid in the nozzle than the experiments with lower value of the flow rate. Since it is known that higher velocities and lower pressures will create more suitable conditions for the generation of the hydrodynamic cavitation, it is possible to draw a conclusion that in the experiments with the higher flow rates and velocities in the nozzle, the possibility of the occurrence of hydrodynamic cavitation will increase too. The said fact is also confirmed by the values of the cavitation number (σ_1 and σ_2) in Table 15, since the experiments with highest values of the flow rates and velocities of the liquid in the nozzle have also the lowest values of the cavitation number.

Table 16: Calculation of the pressure loss (Δp), loss coefficient (ξ) and power requirements (P) of the pilot system I.

Preglednica 16: Izračun razlik tlaka (Δp), koeficienta izgub (ξ) in poraba energije (P) za pilotni sistem I.

Experiment	Q_0 [m^3/s]	p_1	p_3	Δp [bar]	Δp [Pa]	ξ	P [W]
A1	7.69E-04	1.44	0.98	0.46	46000	599.09	35.39
A2	7.61E-04	1.44	1.02	0.42	42000	559.04	31.97
A3	7.56E-04	1.44	0.99	0.45	45000	607.81	34.00
A4	7.28E-04	1.44	0.99	0.45	45000	655.10	32.75
A5	1.27E-03	1.43	0.90	0.53	53000	253.59	67.28
A6	1.11E-03	1.43	0.99	0.44	44000	274.81	48.89
A7	1.66E-03	1.42	0.99	0.43	43000	120.97	71.19
A8	1.26E-03	1.43	0.99	0.44	44000	212.39	55.61
A9	1.54E-03	1.42	0.78	0.64	64000	207.63	98.67
A10	1.50E-03	1.42	0.90	0.52	52000	178.20	78.00
A11	2.47E-03	1.38	0.82	0.56	56000	70.97	138.13
A12	2.48E-03	1.38	0.83	0.55	55000	69.08	136.28
A13	2.36E-03	1.39	0.76	0.63	63000	87.14	148.75
A14	2.32E-03	1.40	0.82	0.54	58000	83.33	134.37

Pressure loss and loss coefficient for each experiment of the set A was calculated based on the value of the flow rate (Q_0), the pressure at the entrance of the system (p_1) and the pressure at the outlet pipe of the system (p_2). While the pressure loss for the pilot system I varied between 0.42 bar for A2 experiment and 0.64 bar for A9 experiment, the average value of the pressure loss was 0.5±0.07 bar with the loss coefficient (ξ) of 284±221.

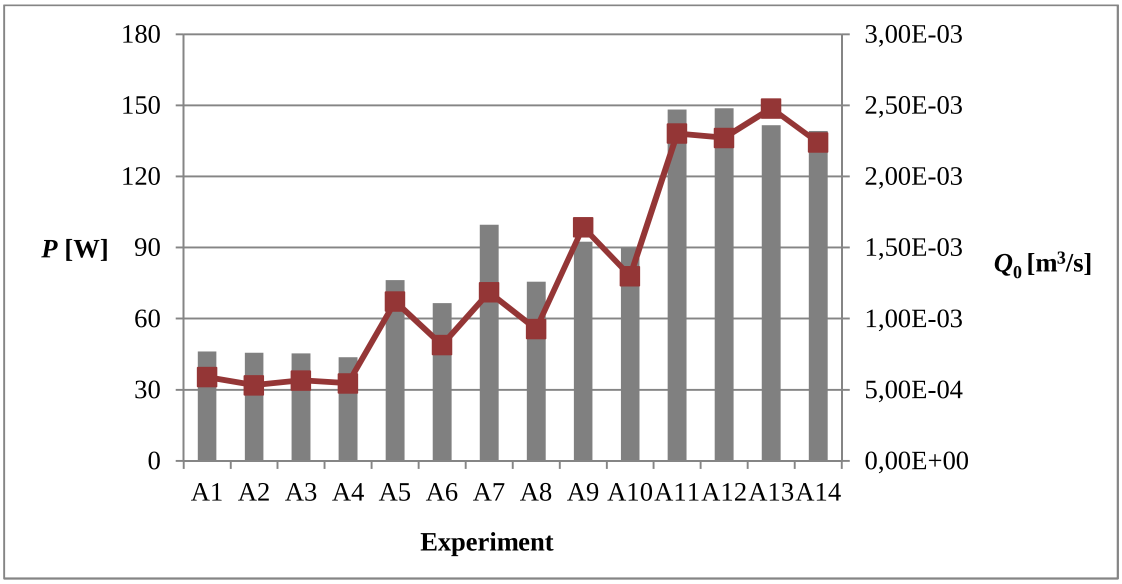


Figure 20: Dependence of the power consumption (P) of the pilot system I on the flow rate (Q_0).

Slika 20: Odvisnost porabe električne energije (P) pilotnega sistema I od pretoka (Q_0).

Additionally, power requirements for each experiment of the set A were calculated. Although power requirements considerably varied from experiment to experiment depending on the flow rate (Q_0) which is presented in Figure 20, the average power consumption of the pilot system I was 79 W.

Since all experiments in the set A were performed with different geometry of the nozzles and there has not been any scaling of the values within each experiment, it has not been possible to make a larger comparison between the factors measured in the various experiments of the set A. Also, there were certain technical obstacles during the performance of the experiments with the pilot system I (e.g. it was almost impossible to eject the large amount of the air from the system which often caused problems with operation of the system like variations of the pressures inside the system for some experiments, etc.). With the aim of choosing the most appropriate geometry of the nozzles for the next set of experiments (set B), the geometric numbers which are characteristic of the hydrodynamic flow conditions (α and β) and which strongly affect the intensity of the generated cavitation were calculated. The values of α and β parameters are given in Table 17.

Table 17: The values of the characteristic numbers for the hydrodynamic flow conditions, α and β in the set A of experiments.

Preglednica 17: Vrednosti značilnih števil za hidrodinamične tokovne razmere, α in β v skupini eksperimentov A.

Experiment	Number of holes	d_{nozzle} [mm]	The relative thickness α [1/mm]	The flow number β
A1	1	12	0.333	0.009
A2	1	12	0.333	0.009
A3	1	12	0.333	0.009
A4	1	12	0.333	0.009
A5	1	14	0.286	0.006
A6	1	14	0.286	0.006
A7	1	14	0.286	0.006
A8	1	16	0.250	0.005
A9	1	16	0.250	0.005
A10	1	16	0.250	0.005
A11	1	16	0.250	0.005
A12	1	20	0.200	0.003
A13	19	4	1.000	1.513
A14	19	4	1.000	1.513

The data presented in the Table 17 reveal that it is possible to make the correlation between the diameter of the nozzle and the values of α and β. If the experiments A13 and A14 are excluded from the observation, in all other experiments when the diameter of the nozzle increases, both parameters α and β will decrease in their value.

According to the parameters Q_0, σ, v, α and β, the nozzle from the experiment A11 with the diameter of the hole of 0.016 m, 8 wings above and below and calming cross inside the vortex finder tube proved to be the optimal choice for the continuation of the experiments with the pilot system II (set B of experiments). Likewise, in the case of the selection of the other nozzles used in the set A of experiments or the construction the new nozzles, it is particularly important to take into account the values of the parameters Q_0, v, α, β as well as to take into account the experiments with a relatively low value of the cavitation number σ.

4.1.2 Pilot system II

As an example of the calculations of the key theoretical values for the set B experiments, the experiment B5 with its sub-experiments was selected and presented in Table 18. The whole list of the calculations of the key theoretical values for the operation of the pilot system II on the basis of the data presented in Tables 11, 12 and the Appendix B, is given in Appendix D.

Table 18: The example of the calculation of the key values for the operation of the pilot system II (S nozzle, v nozzle, v tube, cavitation numbers σ_1 and σ_2) on the basis of pressures measured inside the system and diameter of the nozzles (d_1) for different flow rates (Q_0).

Preglednica 18: Primer izračuna ključnih vrednosti za delovanje pilotnega sistema II ($S_{šobe}$, $v_{šobe}$, v_{cevi}, kavitacijski števili σ_1 in σ_2) na podlagi merjenih tlakov v sistemu in premera šob (d_1) za različne pretoke (Q_0).

Experiment	S_{nozzle} [m^2]	S_{tube} [m^2]	v_{nozzle} [m/s]	$v_{outlet\ pipe}$ [m/s]	Cavitation numbers σ_1	Cavitation numbers σ_2
B5.1	2.01E-04	2.09E-03	0.00	0.00	-	-
B5.2	2.01E-04	2.09E-03	6.80	0.65	1.50	**0.94**
B5.3	2.01E-04	2.09E-03	8.08	0.78	1.20	0.81
B5.4	2.01E-04	2.09E-03	9.66	0.93	1.06	0.52
B5.5	2.01E-04	2.09E-03	10.86	1.04	**0.94**	0.37
B5.6	2.01E-04	2.09E-03	12.23	1.18	0.86	0.27
B5.7	2.01E-04	2.09E-03	13.55	1.30	0.79	0.22
B5.8	2.01E-04	2.09E-03	15.31	1.47	0.75	0.17
B5.9	2.01E-04	2.09E-03	15.75	1.51	0.75	0.15

(Other values are given in Appendix D)

Similarly to the experiments of the set A, the calculation of the cavitation numbers (σ_1 and σ_2) has been made on the basis of two characteristic pressures, the pressure on the entrance of the system (p_1) and the pressure on the edge of vortex finder (p_7). The blue color in the table indicates the sub-experiments of the set B with the cavitation number lower than 1. According to the calculations of the cavitation numbers from Table 18, the conditions for the occurrence of hydrodynamic cavitation in the sub-experiments of the B5 experiment differ. Namely, the σ_1 indicates to the cavitation occurrence from the experiment B5.5 onwards, where the pressure at the entrance of the system was 2.24 bar, while the values of the σ_2 indicated that the cavitation should already occur from the sub-experiment B5.2 onwards, where the pressure at the entrance of the system was 1.41 bar. The visual observations of the occurrence of hydrodynamic cavitation coincided with the calculations of the σ_2, since the cavitation with insignificant intensity was already noticed in the sub-experiment B5.2.

Figure 21 summarizes the correlations between the flow rates (Q_0) and cavitation numbers (σ_1 and σ_2) for all experiments of the set B.

Figure 21 reveals that the increase of the flow rates (Q_0) affected the decrease of the value of the cavitation number in all experiments of the set B, regardless of which cavitation number (σ_1 and σ_2) was taken into the consideration. As the value of the flow rate becomes higher, the value of the cavitation number will be consequently lower. According to Figure 21, the experiments B4, B5 and B6 seemed to operate with the highest flow rates, as well as the lowest cavitation numbers (the difference between the values of the flow rate and cavitation numbers for experiments B4 and B5 was negligible because those two experiments used the nozzle with the same diameter of the hole). The calculations given in the Appendix D also confirmed aforementioned correlations.

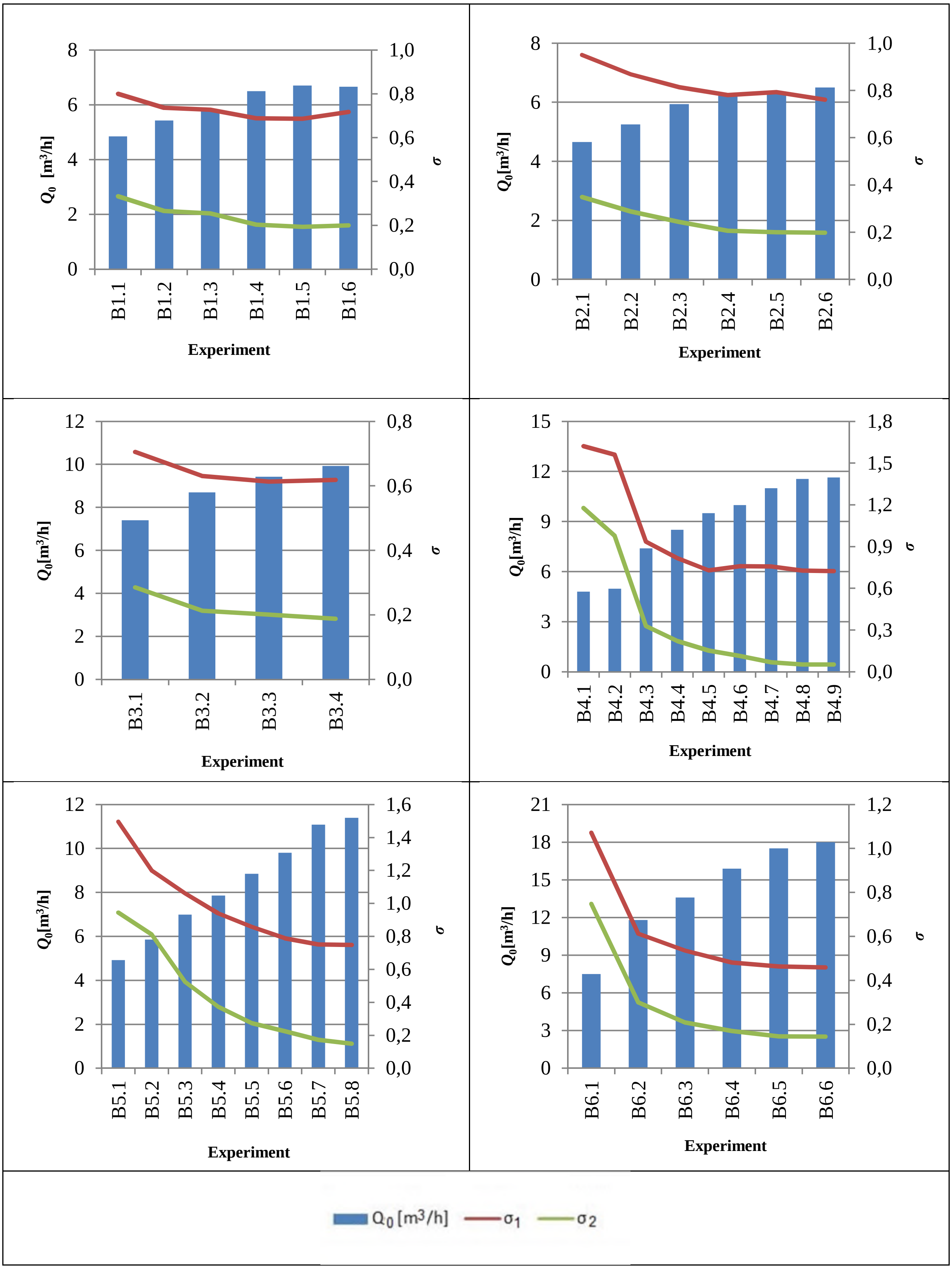


Figure 21: Dependence of the flow rate (Q_0) on the cavitation numbers (σ_1 and σ_2) for experiments of the set B (see appendix D).

Slika 21: Odvisnost količine pretoka (Q_0) od kavitacijskega števila (σ_1 in σ_2) za eksperimente iz skupine B (glej prilogo D).

Relation between the values of the flow rate (Q_0) and the velocity of the liquid in the nozzle (v_{nozzle}) of the experiments in set B is illustrated in Figure 22. These parameters behaved similarly like in the set A, whereas the increase of velocity of the liquid in the nozzle affected the increase of the flow rate. Since the possibility of the occurrence of hydrodynamic cavitation will also increase in the experiments with higher flow rates and velocities in the nozzle, which is simultaneously confirmed with the data from the Appendix D, experiment B6 was the experiment that showed the most suitable values of the observed parameters among the experiments in the set B. However, experiments B4 and B5 were the experiments which showed slight difference in the values of the flow rate and velocity of the liquid in the nozzle in comparison with the experiment B6. There was no significant difference between the values of the observed parameters in experiments B4 and B5 because the same nozzle was used for those two experiments.

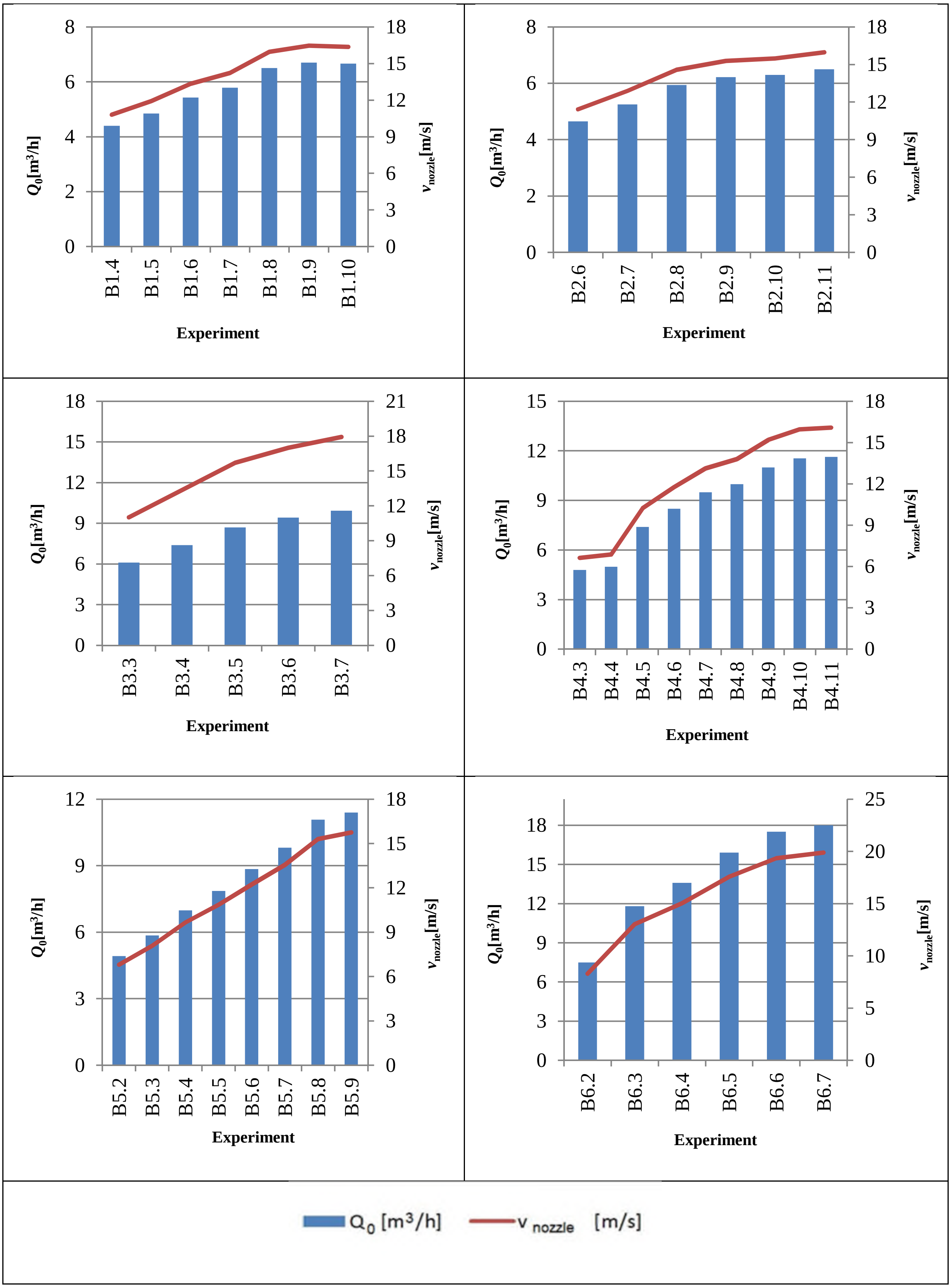


Figure 22: Correlation between the flow rate (Q_0) and the velocity of the liquid in the nozzle (v_{nozzle}) in the set B of experiments (see appendix D).

Slika 22: Korelacija med pretokom (Q_0) in hitrostjo tekočine v šobi ($v_{šobe}$) v skupini eksperimentov B (glej prilogo D).

Since it was concluded in experiments of the set A that the factors α and β will decrease with the increase of the diameter of the nozzle, according to parameters α and β the nozzles with as smallest value of α and β should be the optimal ones for the continuation of the experiments. The values of α and β for experiments of the set B are presented in Table 19.

Table 19: The values of the characteristic numbers for the hydrodynamic flow conditions, α and β in the set B of experiments.

Preglednica 19: Vrednosti značilnih števil za hidrodinamične tokovne razmere, α in β v skupini eksperimentov B.

Group of experiments	Number of holes	d_{nozzle} [mm]	α [1/mm]	β
B1	1	12	0.333	0.009
B2	1	12	0.333	0.009
B3	1	14	0.286	0.006
B4	1	16	0.250	0.005
B5	1	16	0.250	0.005
B6	5	8	0.500	0.100

It is evident from the data shown in Table 18 that B4 and B5 are the experiments with the lowest α and β in the set B, the experiments in which the same nozzle, the one with a single hole with the diameter of 16 mm, was used. The only constructional difference between the nozzles used in the experiments B4 and B5 is the addition of the wings that will not have any influence on the values of α and β.

Since the pressures inside the system have an important role in the generation and regulation of the intensity of hydrodynamic cavitation, it is important to explore the influence of pressures at the specific points inside the system, as well as to reveal the relation between values of those pressures and cavitation number. Firstly, the influence of the value of input pressures in the system (p_1) to both calculated cavitation numbers (σ_1 and σ_2) for example of B4 experiment has been observed. The results are shown in Figure 23.

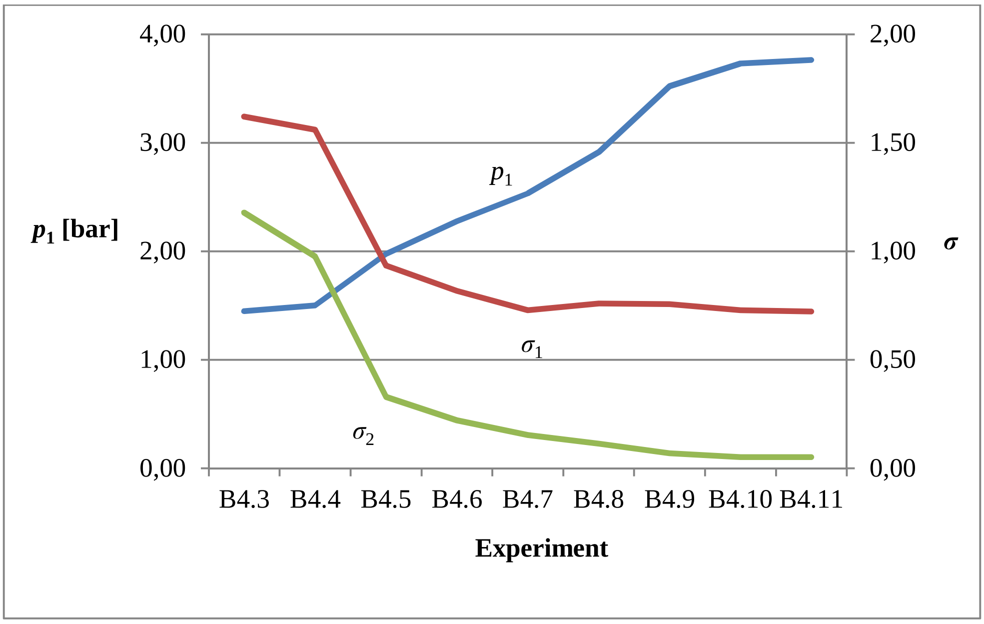


Figure 23: The correlation of the pressures on the entrance to the system (p_1) and cavitation numbers (σ_1 and σ_2) for experiment B4 (see appendix D).

Slika 23: Korelacija med tlakom na vhodu v sistem (p_1) in kavitacijskim številom (σ_1 in σ_2) za eksperiment B4 (glej prilogo D).

It is evident from the Figure 23 that no matter which value of the cavitation number (σ_1 and σ_2) is taken into observation to determine the correlation with the parameter $p_{1,}$ the dependence of those two factors will not change. Specifically, in the case when the value of the p_1 increases, the value of σ will always decrease. It means that as the value of the pressures on the entrance to the system (p_1) is higher, there is higher probability for the occurrence of hydrodynamic cavitation.

Next correlation of the pressures that should have an important role in the generation, as well as the influence on the intensity of hydrodynamic cavitation, is the correlation between the pressures at the entrance to the system (p_1) and pressures at the place of the occurrence of hydrodynamic cavitation (p_8). This correlation for the example of B6 experiment is presented in Figure 24.

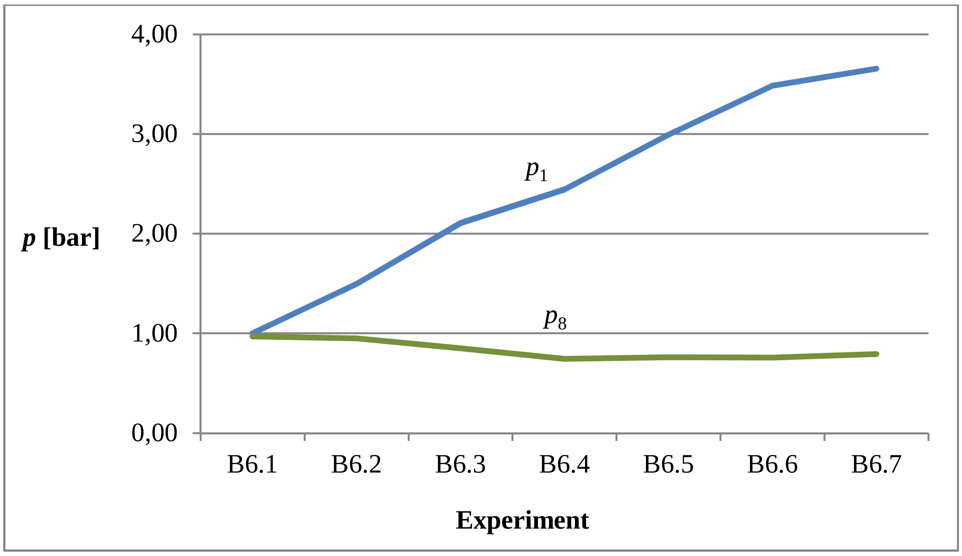


Figure 24: Dependence of the values of the pressure on the entrance to the system p_1 (pressure on the entrance to the system) on the pressure on the place of HC occurrence p_8 (pressure on the place of HC occurrence) for experiment B6 (see appendix B).

Slika 24: Odvisnost vrednosti tlaka na vstopu v sistem (p_1) od vrednosti tlaka na mestu pojava hidrodinamične kavitacije (p_8) za eksperiment B6 (glej prilogo B).

It is evident from the Figure 24 that the value of the pressure at the entrance to the system (p_1) will have an impact on the value of the pressure at the place of the hydrodynamic cavitation occurrence (p_8) in the way that when p_1 increases, the value of the p_8 will consequently decrease. Decrease of the pressure on the narrowing (i.e. orifice of the nozzle) will create the conditions for sudden increase of velocity at the same place and the generation of hydrodynamic cavitation. This means that as the value of the p_1 gets higher and as value of the p_8 simultaneously gets lower, the probability of the occurrence of hydrodynamic cavitation will increase.

The principle of the hydrodynamic cavitation generation used in our pilot systems is the same as it shown in Figure 5. More precisely, the nozzle with a hole in our pilot system presents the construction with the throat which is used for hydrodynamic cavitation generation. Consequently, pressure changes occur caused by sudden change in the cross-section of the flow of fluid through the nozzle. The “vena contracta” presents the point of lowest pressure and downstream from that point there is a complete recovery of pressure in the system. Dependence of the pressure changes (differential pressure, Δp_7-p_8) before and after the passage of water flow through the nozzle of the flow (Q_0) in the system for the example of B4 experiment is illustrated in Figure 25.

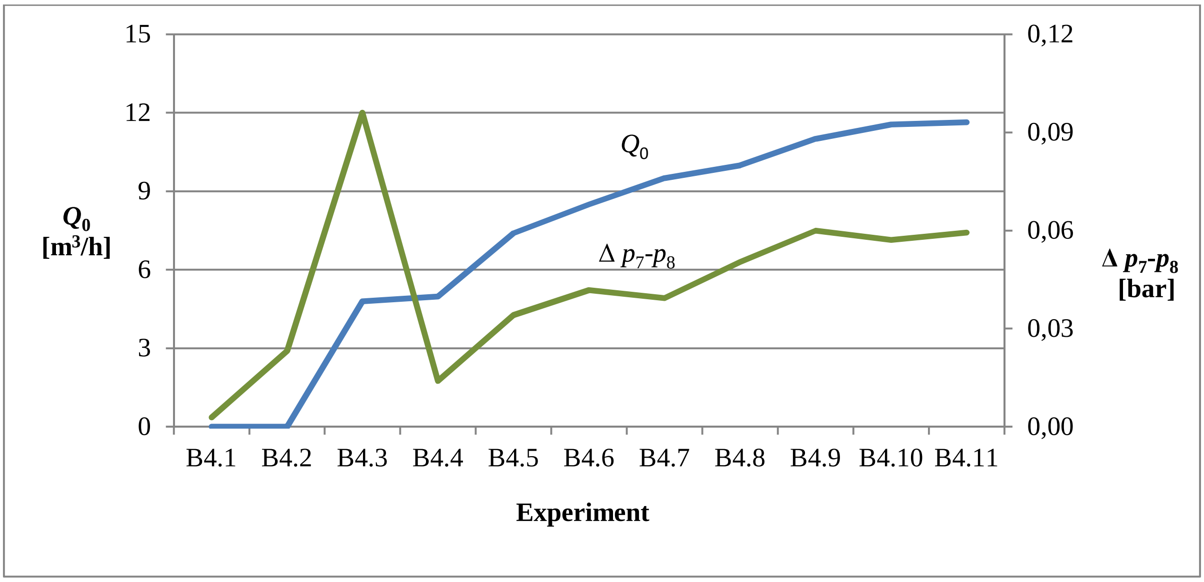


Figure 25: Dependence of the differential pressure (Δp_7-p_8) before and after the passage through the nozzle on the flow rate (Q_0) in the example of the experiment B4 (see appendix D).

Slika 25: Odvisnost diferenčnega tlaka (Δp_7-p_8) pred in po prehodu skozi šobo glede na vrednost pretokov (Q_0) v primeru poskusa B4 (glej prilogo D).

Figure 25 illustrates mostly linear behavior of the values of the flow rates (Q_0) as well as the pressure changes, i.e. the differential pressure (Δp_7-p_8) for the selected example of the experiment B4. Namely, variation of the values for both observed factors is visible only in the case of the sub-experiments B4.1-B4.3, where according to the visual observations and calculations given by the Appendix D, hydrodynamic cavitation has not occurred yet. If the sub experiments B4.1-B4.3 are neglected due to hydrodynamic cavitation absence, it is possible to notice correlation between the factors Δp_7-p_8 and Q_0. Namely, the increase of the flow inside the system affected to the value of the differential pressure (Δp_7-p_8) in the way that if the value of the flow rate increased, the value of the differential pressure in the place of the throttling (the nozzle) is supposed to increase, too.

Table 20: Calculation of the pressure loss (Δ*p*), loss coefficient (ξ) and power requirements (*P*) for the example of B4 experiment of the set B for the pilot system II.

Preglednica 20: Izračun razlike tlaka (Δp), koeficienta izgube (ξ) in porabe energije (P) za primer B4 eksperimenta z skupine B za pilotni sistem II.

Experiment	Q_0 [m^3/s]	p_1 [bar]	p_{10} [bar]	Δ*p* [bar]	Δ*p* [Pa]	ξ	*P* [W]
B4.1	0.00E+00	1.09	1.09	0.00	-350.00	0.00	0.00
B4.2	0.00E+00	1.18	1.09	0.09	8660.00	0.00	0.00
B4.3	1.33E-03	1.45	1.09	0.36	35690.00	175.58	47.59
B4.4	1.38E-03	1.50	1.09	0.41	40890.00	186.88	56.56
B4.5	2.06E-03	1.98	1.09	0.88	88430.00	183.04	181.77
B4.6	2.36E-03	2.28	1.09	1.19	118540.00	185.97	279.89
B4.7	2.64E-03	2.53	1.09	1.44	144180.00	181.08	380.48
B4.8	2.78E-03	2.91	1.09	1.82	182310.00	207.06	505.91
B4.9	3.06E-03	3.52	1.09	2.43	242510.00	227.17	741.00
B4.10	3.21E-03	3.73	1.10	2.63	263380.00	223.79	845.01
B4.11	3.23E-03	3.76	1.10	2.66	266290.00	222.77	861.00

(Other values are given in Appendix E)

Pressure loss, loss coefficient and power consumption were calculated based on the values of the flow rate (Q_0), pressure at the entrance of the system (p_1) and pressure at the outlet pipe of the system (p_{10}) for each experiment of the set B (Appendix E, Table 20). In the case of the experiment B4, the pressure loss has varied into the wide range, between 0 bar and 2.66 bar, depending on the pressure at the entrance of the system (p_1) (Figure 26), which means that the sub-experiment (B4.11) with the highest value of the p_1 will simultaneously have the highest pressure loss in the system, 2.66 bar. However, the average pressure loss for the experiments of the set B was 1.38±0.94 with the average loss coefficient (ξ) of 176±18. The average value of the power consumption for the pilot system II was 330 W.

According to Figure 26 and the data presented in Table 20, the line of the power consumption for the experiment B4 of the pilot system II has progressively ascended with the increase of the pressure at the entrance of the system (p_1). The data for all experiments presented in the Appendix E showed a similar trend of dependence on those three factors.

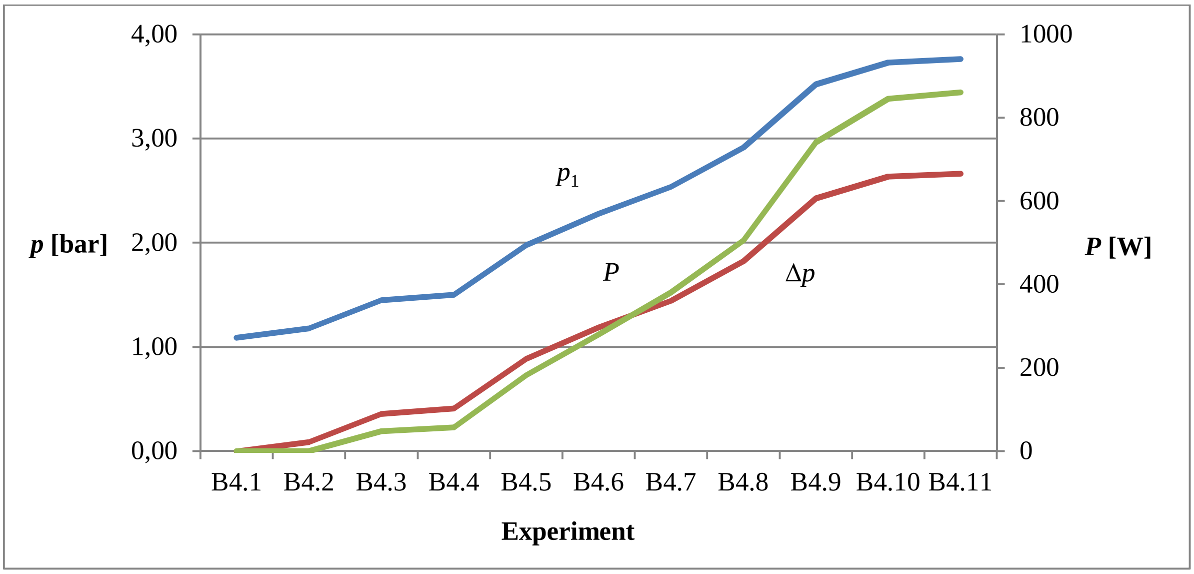


Figure 26: Dependence of the power consumption (P) and pressure losses in the system (Δp) on the pressure at the entrance of the system (p_1) for the experiment B4 (see appendix E).

Slika 26: Odvisnost porabe energije (P) in razlike tlakov v sistemu (Δp) glede na tlak na vhodu v sistem (p_1) za eksperiment B4 (glej prilogo E).

According to the previously presented data, the selection of the nozzle for further research should depend on the values of the following parameters: the flow rate (Q_0), the cavitation number (σ), factors α and β, the pressures on the entrance to the system (p_1), the pressures on the place of the occurrence of hydrodynamic cavitation (p_8), the pressure drops (Δp) and the power consumption (P) of the system. Experiments from the set B that have shown optimal values according to the aforementioned parameters are experiments B4, B5 and B6. Experiments B4 and B5 had very similar values of these parameters, due to the use of the nozzle with the same diameter. The only difference between them was the addition of the wings to the nozzle that did not show any considerable influence to the operation of the pilot system.

Therefore, in further research the nozzle used in the experiment B4 with a hole of diameter of 16 mm without additional wings will be selected for use in the set C experiments (experiments with the pilot system III).

4.1.3 Pilot system III

An example of the calculations of the key theoretical values for one experiment of the set C, experiment C1 with its sub-experiments is presented in Table 21. The whole list of the calculations of the key theoretical values for the operation of the pilot system III based on the data presented in Tables 13, 14 and the Appendix C, is given in Appendix F.

Table 21: Theoretical values for the operation of the pilot system III (S_{nozzle}, v_{nozzle}, v_{tube} and σ) on the basis of pressures measured inside the system and dimensions of the nozzles for different flows (Q_0) (example of the experiment C1).

Preglednica 21: Teoretične vrednosti za delovanje pilotnega sistema III ($S_{šobe}$, $v_{šobe}$, v_{cevi} in cavitation number, σ) izračunane iz tlakov izmerjenih znotraj sistema in dimenzij šob za različne pretoke (Q_0) (primer za poskus C1).

Experiment	S_{nozzle} [m^2]	S_{tube} [m^2]	v_{nozzle} [m/s]	$v_{outlet\ pipe}$ [m/s]	σ
C1.1	2.01E-04	2.09E-03	0.00	0.00	/
C1.2	2.01E-04	2.09E-03	11.33	1.09	0.56
C1.3	2.01E-04	2.09E-03	18.37	1.77	0.31
C1.4	2.01E-04	2.09E-03	21.80	2.10	0.26
C1.5	2.01E-04	2.09E-03	24.87	2.39	0.24
C1.6	2.01E-04	2.09E-03	26.87	2.58	0.24

(Other values are given in Appendix F)

Like in the majority of experiments from the Appendix F, the data presented in the Table 21 (example of the C1 experiment of set C) indicates that the conditions for the occurrence hydrodynamic cavitation are supposed to be fulfilled at the initial absolute pressure at the entrance to the system (p_1) of already about 1.5 bar. In the experiments of the set C, only one cavitation number was calculated (in the calculations, the initial absolute pressure at the entrance to the system (p_1) was considered). The reason for the selection of only one cavitation number is that no matter which value of the pressure was included into the calculations (p_1 or p_7, the pressure after the recovery), the values of the cavitation numbers will be approximately same.

Since the most important parameters for the optimal operation of pilot systems from this study were already discussed in the previous subchapters, the Figures 27 and 28 should reveal the experiments that have shown the optimal relation of the values of the flow rate, cavitation number and velocity of the fluid inside the nozzle for the experiments of the set C.

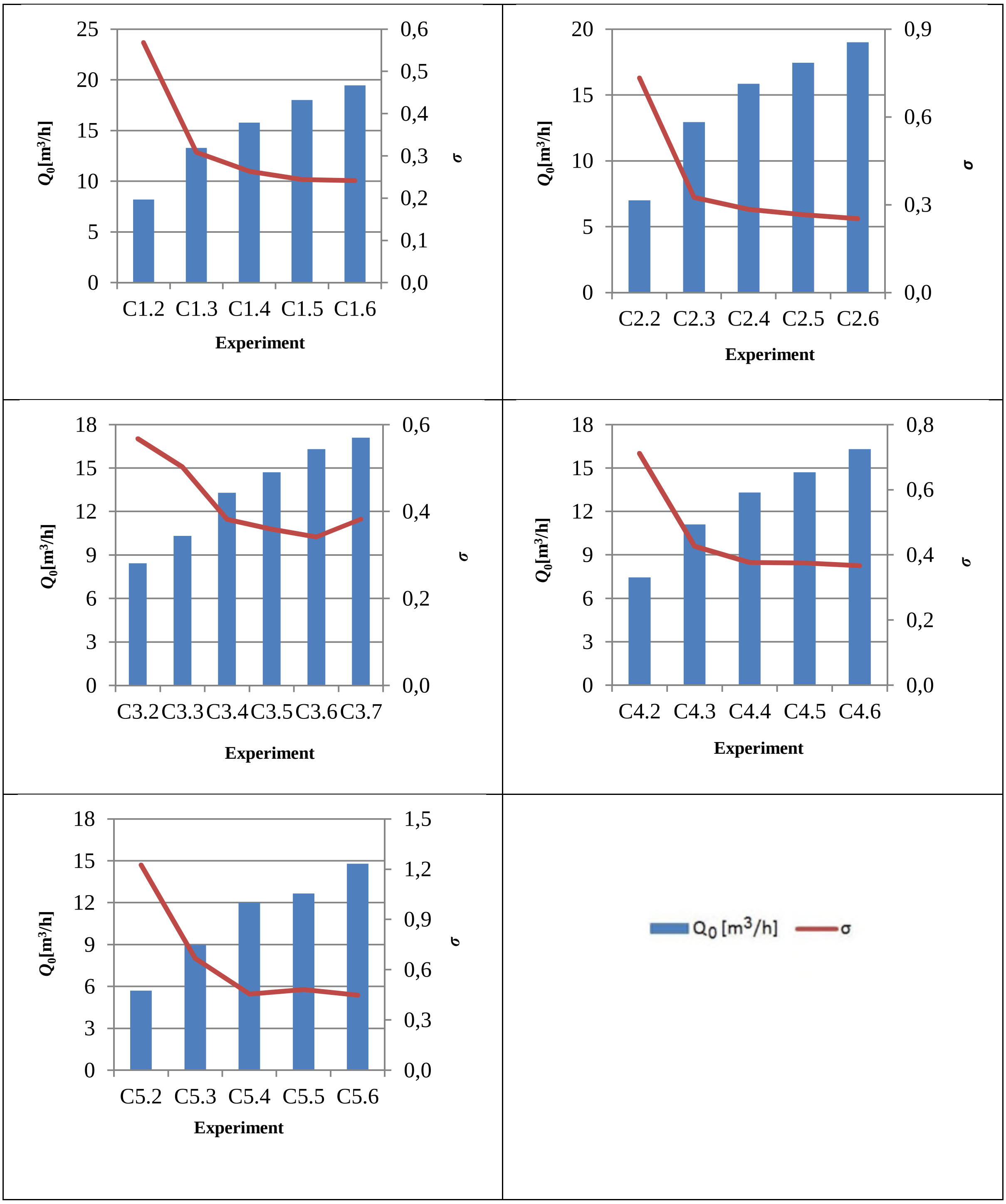


Figure 27: Dependence of the flow rate (Q_0) on the cavitation number (σ) for the experiments of the set C (see appendix F).

Slika 27: Odvisnost vrednosti pretoka (Q_0) od kavitacijskega števila (σ) za eksperimente skupine C (glej prilogo F).

According to the values of the flow rate (Q_0) and the cavitation number (σ) (Figure 27), the experiments C1 and C2 seemed to operate with the optimal ratio of the aforementioned parameters, i.e.

the lowest value of the cavitation number (lower than 1) with a relatively high value of the flow rate (up to 19.5 m^3/h). Those results were also confirmed by the calculations presented in the Appendix F. The experiment with the lowest value of the flow rate and the highest value of the cavitation number among the experiments of the set C was experiment C5. Namely, according to the calculations, in the sub-experiment C5.3., the cavitation should begin only when the value of the pressure at the entrance to the system was 2.1 bar, which is almost 0.6 bar higher than the pressure of the beginning of cavitation in other experiments of the set C. Furthermore, experiment C5 was performed with lower values of the flow rate, with the maximum achieved flow rate of 14.8 m^3/h for sub-experiment C5.6. This value of the flow rate was almost 5 m^3/h lower than in the case of maximum flow rate for the sub-experiment C 1.6 (19.5 m^3/h), where approximately the same pressure at the entrance to the system was used (about 3.5 bar). According to the analyzed results, the closing of the valve in the experiment (like in the example of the experiment C5) will reflect negatively on the flow rate, as well as on the beginning of the cavitation occurrence.

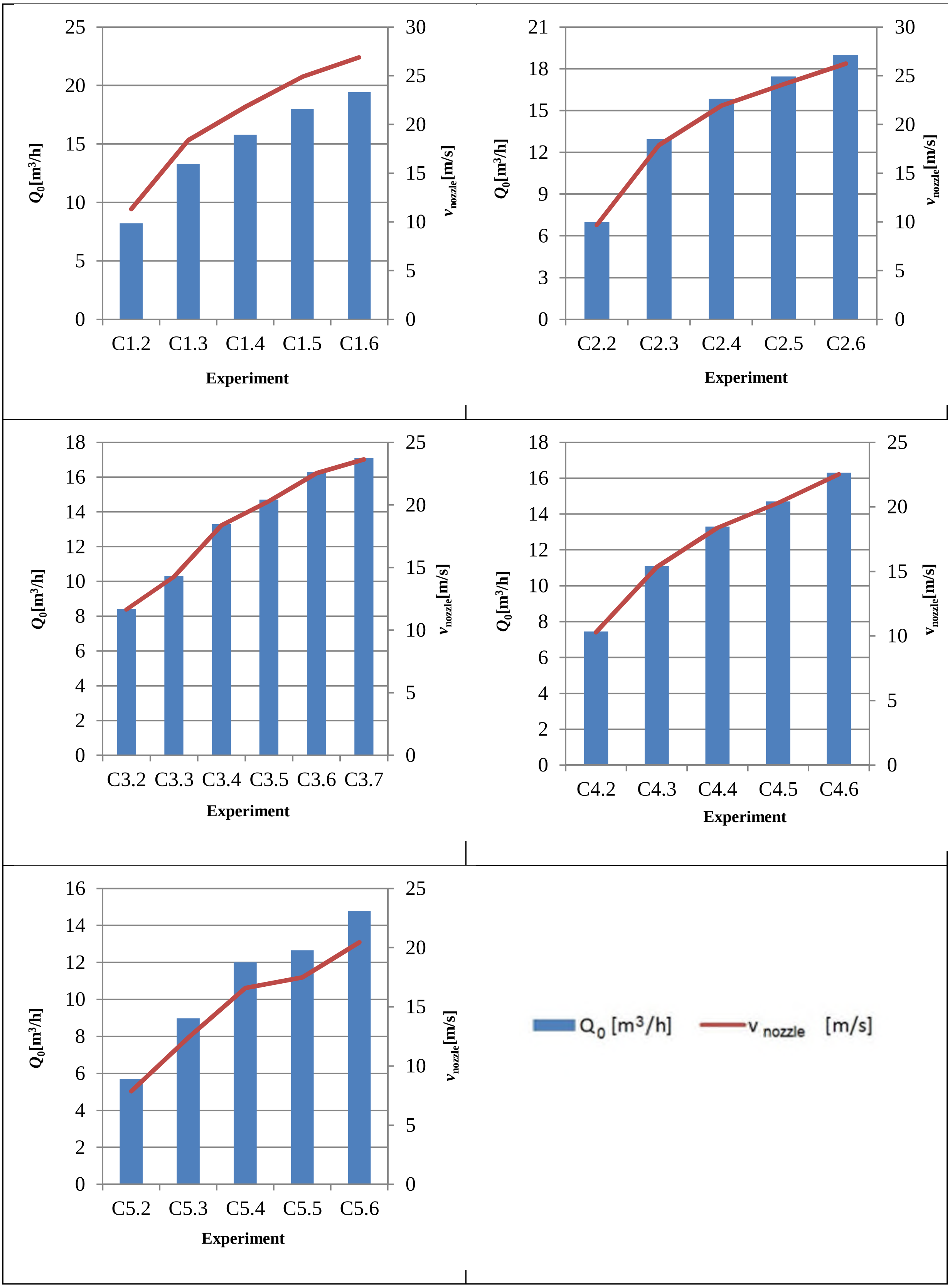


Figure 28: Correlation between the flow rate (Q_0) and the velocity of the liquid in the nozzle (v_{nozzle}) in the set C of experiments (see appendix F).

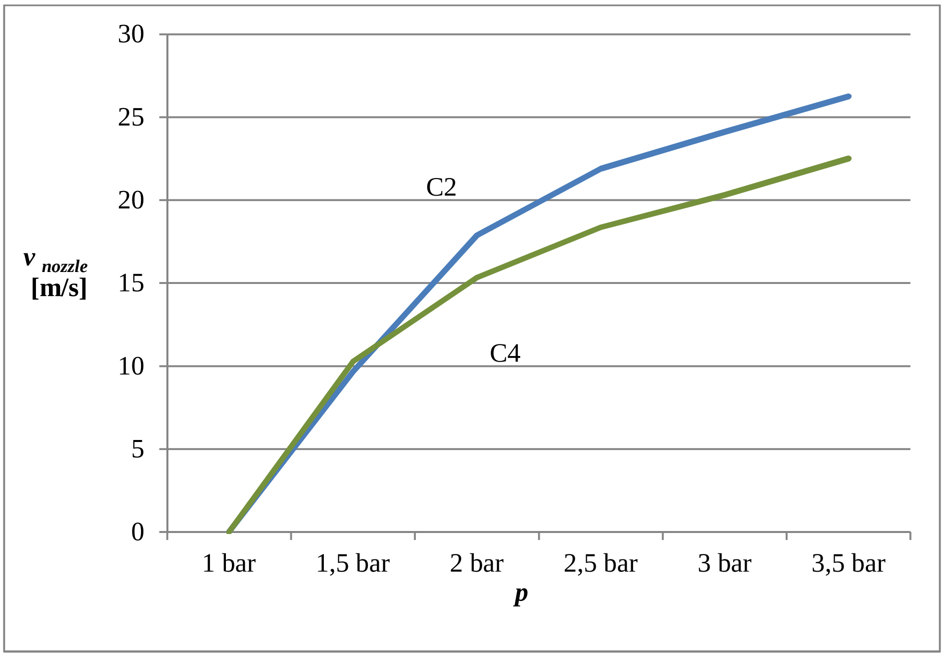
Slika 28: Korelacija med vrednostmi pretokov (Q_0) in hitrostmi tekočine v šobi ($v_{šobe}$) za eksperimente skupine C (glej prilogo F).

Experiments C1 and C2 had the highest flow rate and consequently the highest velocity of the liquid in the nozzle in the set C, which coincides with the values from the previous figure (Figure 28) where the experiments C1 and C2 had the lowest values of the cavitation number.

Since the same nozzle with the single hole of 16 mm diameter was used in all experiments of the set C, the values of α and β remained unchanged for the whole set of experiments (α = 0.250 and β = 0.005).

The nozzle with the same characteristics (one hole with the diameter of 16 mm) has been used in all experiments of the set C. The difference between the sub-experiments has been done by the variation of the distances between the nozzles, addition of the circular plate made of steel, or by the regulation of the upper and lower valve of the pilot system.

In order to research the most effective performance of the system, we compared selected sub-experiments. The aim of the first comparison was to determine the impact of the distance between the nozzles on the occurrence of the cavitation and value of the velocities of the fluid in the nozzles. Experiments C2 and C4 were selected for the comparison. All the conditions of the operation of the pilot system in the experiments C2 and C4 were identical, except the distance between the nozzles that was adjusted to 8 mm in the case of experiment C2 and to 30 mm in the experiment C4. Figure 29 a and b illustrates the results of comparison for those two experiments according to the parameters v_{nozzle} and σ versus pressure (p).



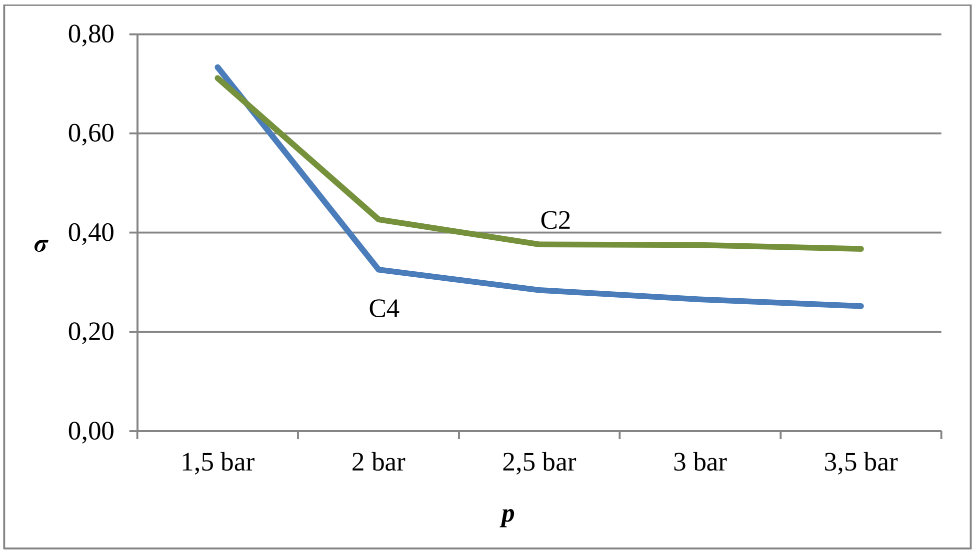


Figure 29: Comparison of the experiments C2 and C4 according to the parameters a) v_{nozzle} and b) σ *(see appendix F).*

Slika 29: Primerjava poskusov C2 in C4 po parametrih a) $v_{\check{s}obe}$ *in b) kavitacijsko število, σ (glej prilogo F).*

The lines that illustrate the velocity in the nozzles showed the same trend, i.e. trend of ascending with the increase of the value of the pressure at the entrance to the system in case of both compared experiments (C2 and C4). Although both experiments operated with the same initial parameters, it is evident that higher velocities of the liquid inside the nozzle for the experiment C2 were reached. In the case of the experiment C2, the maximum measured velocity for operation of the system with the pressure at the entrance of the system (p_1) of 3.5 bar was 26.24 m/s. It was about 4 m/s higher than in experiment C4, where in the similar pressure at the entrance of the system (p_1) of 3.75 bar the velocity in the nozzle was 22.51 m/s. When comparing the values of the cavitation numbers for the experiments C2 and C4 (Figure 29b), it is evident that the experiment C4 had slightly lower cavitation number for the same pressure to the entrance to the system. However, according to the previous analyses, due to the fact that the flow rate was supposed to increase with the increase of the velocity of the liquid inside the nozzle and that the difference between the cavitation numbers of analyzed two experiments was too low to notice the real difference in the intensity of the cavitation, the experiment C2 is assessed as the one with more convenient parameters for the efficient operation of the system. It follows from the results that the pilot system III should have as higher values of the flow rates and velocities of the liquid inside the nozzle as lower is the distance between the nozzles.

The second parameter whose influence on the operation of the system was assessed is the parameter "openness of the valves". Since it was already concluded on the basis of Figure 27 that the closed valves will negatively reflect on the operation of the pilot system III, it follows that the experiments with both open valves should have higher values of the flow rates, as well as higher velocities of the liquid inside the nozzle and consequently better conditions for the generation of hydrodynamic cavitation.

The third parameter whose influence on the operation of the system was evaluated was addition of the plate made of steel in the area between the nozzles. Experiment C3 with the diameter of the hole of 16 mm, distance between the nozzles of 30 mm, both valves 100% open (upper and lower) and added plate made of steel with the circular hole was compared with the experiment C4, whose values of the initial parameters were all the same, but it was performed without addition of the plate made of steel. The results of the comparison are presented in Figure 30.

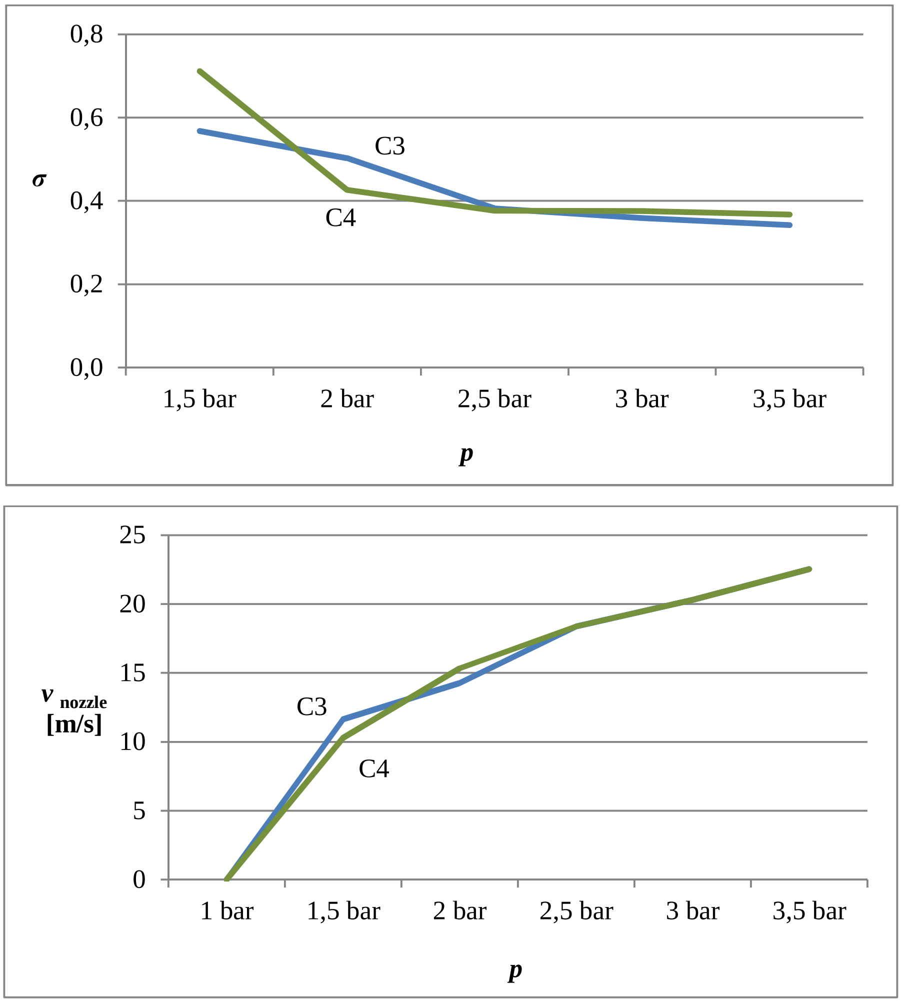


Figure 30: Comparison of the experiments C3 and C4 according to the parameters a) v_{nozzle} and b) σ *(see appendix F).*

Slika 30: Primerjava eksperimentov C3 in C4 po parametrih a) v $_{šobe}$ *in b) kavitacijsko število, σ (glej prilogo F).*

According to the parameters v_{nozzle} and σ, experiments C3 and C4 showed almost the same trend, regardless of which two parameters were observed. Since the results for those two experiments were almost identical, it is possible to conclude that adding of the circular plate made of steel will not have any considerable influence on the performance of the pilot system III.

Table 22: Calculation of the pressure losses, loss coefficient and power requirements for the example of B4 experiment of the set C of experiments for the pilot system III.

Preglednica 22: Izračun izgub tlakov, koeficienta izgub in porabe energije za primer eksperimenta B4 iz skupine eksperimentov C na pilotnem sistemu III.

Experiment	Q_0	p_1 [bar]	p_{10} [bar]	Δp [bar]	Δp [Pa]	ξ	P [W]
C1.1	0.00E+00	1.13	1.08	0.05	4540	0.00	0.00
C1.2	2.28E-03	1.48	1.09	0.40	39730	66.97	90.50
C1.3	3.69E-03	2.10	1.09	1.02	101810	65.24	376.13
C1.4	4.38E-03	2.53	1.09	1.44	144400	65.73	632.95
C1.5	5.00E-03	3.04	1.09	1.95	194630	68.09	973.15
C1.6	5.40E-03	3.51	1.10	2.41	241050	72.22	1302.34

(Other values are given in Appendix G)

Pressure loss, loss coefficient and power consumption were calculated based on the values of the flow rate (Q_0), pressure at the entrance of the system (p_1) and pressure at the outlet pipe of the system (p_{10}) for experiments of the set C and the results were presented in the Appendix G, while the example of the said calculations, experiment C1 with its sub-experiments, is presented in Table 22.

Although the pressure loss for the experiment presented in Table 22 (C1) varied between 1.13 and 3.51 bar, the average pressure loss for the pilot system III was 1.31±0.9 bar with the loss coefficient ξ of 98±8, while the required power consumption of the system was 0.53 kW. Similarly to the analysis of the results for the previous pilot systems (pilot system I and II) and according to the Appendix G, the trend of the dependence of the pressure loss and power consumption on the pressures at the entrance to the system (p_1) will be ascending, i.e. when the pressures at the entrance to the system (p_1) increases, those two factors will increase as well. Moreover, Appendix G indicates the increase of the aforementioned parameters with the increase of the flow rate $Q_{0.}$

4.1.4 Findings based on the processing of the hydraulic results

With the aim of the testing the efficiency of the innovative technology whose operation is based on the combination of the mechanical (separation) and physical process (hydrodynamic cavitation) incorporated together into a common unit for treatment, three different models of the pilot system for ballast water treatment were developed. While the experiments with the pilot system I (set A) were primarily focused on the verification of the efficiency of the new technology and determining the key factors of its effective operation, the primary goal of the experiments preformed with the pilot system II and III was to improve the working performances of the newly developed technology.

In order to make the comparison between the operation of the pilot systems I, II and III, the experiments from the sets A, B and C in which the same nozzle was used (the nozzle with a single hole of a 16 mm diameter) are summarized in Table 23. The comparison was done between the groups of sub-experiments of the set A, B and C with approximately the same value of the pressure at the entrance to the system. This means that the values of the flow rate (Q_0), cavitation number (σ_1 and σ_2), pressure loss (Δp) and power consumption (P) correspond to the value of the pressure at the entrance to the system for p_1~1.5 bar, p_1= 2 bar and p_1=3.75 bar for all three experiments.

Table 23: Summary of the key parameters of the operation of the pilot system I, II and III when the same nozzle was used (single hole with a 16 mm diameter and without additions).

Preglednica 23: Ugotovitve o ključnih parametrih delovanja pilotnih sistemov I, II in III, kadar so imeli iste šobe (ena luknja s premerom 16 mm in brez dodatkov).

Pilot system	p_1 [bar]	Q_0 [m^3/h]	σ_1	σ_2	Δp	P
I	1.43	4.55	1.80	1.23	0.44	55.61
II	1.45	4.80	1.62	1.18	0.36	47.95
III	1.53	7.45	0.71	0.71	0.62	129.15
I	no data	no data	no data	no data	no data	no data
II	1.98	7.40	0.93	0.33	0.88	181.77
III	2.03	11.10	0.43	0.43	1.13	348.82
I	no data	no data	no data	no data	no data	no data
II	3.76	11.64	0.72	0.05	2.66	861.00
III	3.75	16.30	0.37	0.37	2.63	1189.76

In the case of the same pressure at the entrance to the system of about 1.5 bar, Table 23 reveals that the pilot system I and II will operate with almost 3 m^3/h lower flow rates than pilot system III. Also, the pressure at the entrance to the system of about 1.5 bar has not proven to be high enough to induce the occurrence of the hydrodynamic cavitation inside the chamber of the systems I and II. However, the same pressure at the entrance of the pilot system III was sufficient for the generation of hydrodynamic cavitation.

Since the measurements were not performed for pressure higher than 1.5 bar at the entrance of the pilot system I, further analysis is based on the comparison between the parameters of the pilot system II and III. Since the pilot system III significantly differed in constructional performances from the pilot systems I and II, the primary aim of the set C of experiments was to explore how the constructional changes of the pilot system III reflected on the values of the key factors for operation of the pilot system. Experiments B.4 and C.4 (with the same nozzle used) were selected for the purpose of comparison and presented in Figure 31 a and b.

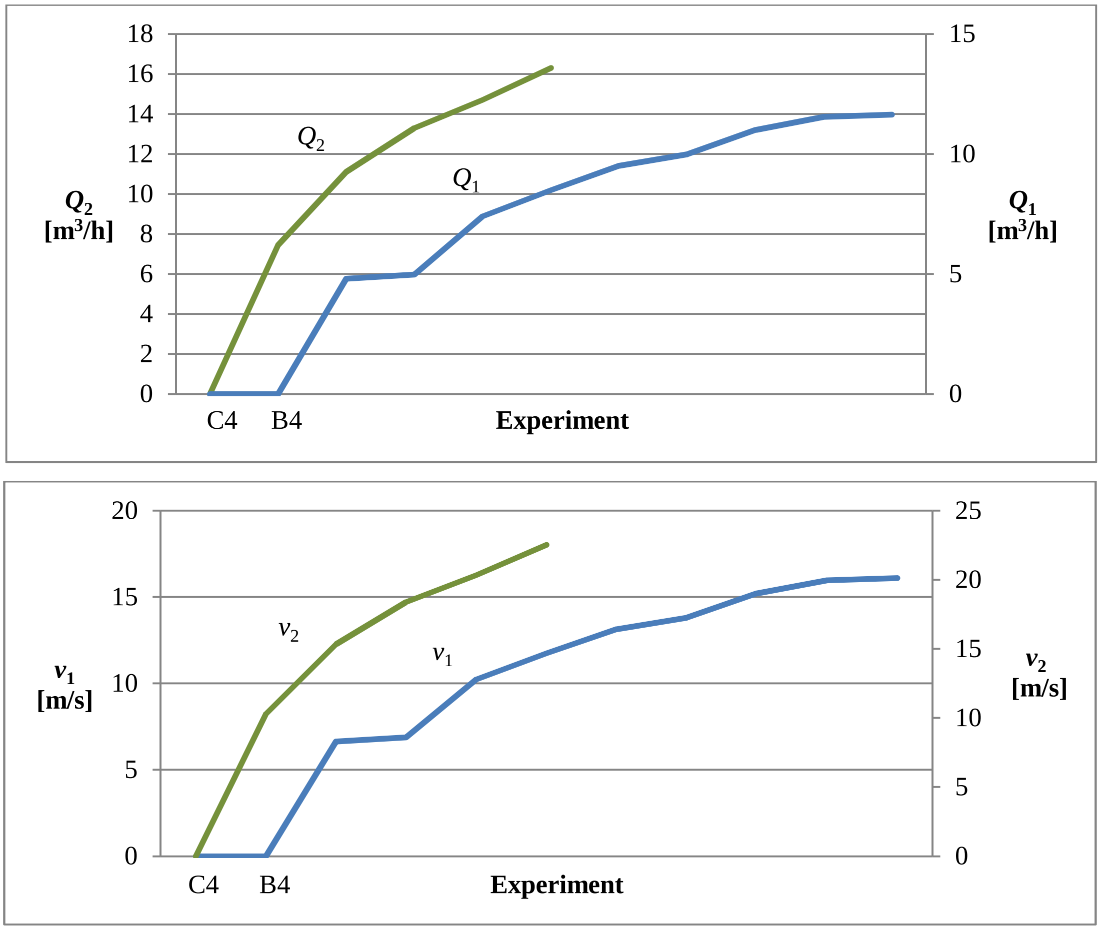


Figure 31: Comparison of the a) flow rates (Q_0) and b) velocities of the liquid in the nozzle (v_{nozzle}) for experiments B4 and C4 (identical technical parameters) (see annexes D and F).

Slika 31: *Primerjava a) količine pretoka (*Q_0*) in b) hitrosti tekočine v šobi (*$v_{šobe}$*) za eksperimente B4 in C4 (glej priloge D in F).*

Even though the same nozzle has been used in experiments B4 and C4, Figure 31 illustrates considerable differences in the values of the observed parameters (Q_0 and v_{nozzle}) in these experiments. While the flow rate in the experiment B4 did not exceed value of 11.6 m^3/h for the pressure at the entrance to the system (p_1) of 3.76 bar, the highest achieved flow rate for the experiment C4 at the almost identical value of the input pressure (p_1) of 3.75 bar was as much as 5 m^3/h higher (16.30 m^3/h) than in experiment B4 (Figure 31a, Table 23). Similar correlation can be noticed between the values of the velocities of the liquid in the nozzle (v_{nozzle}) for experiments B4 and C4 where for the same input pressures (about 3.75 bar) the velocity in the nozzle in the case of experiment C4 was significantly higher (as much as 22.5 m/s in comparison with 16.1 m/s for B4 experiment) (Figure 31b, Table 23).

When it comes to the pressure loss (Δp), according to the Table 23, pilot systems II and III will operate with the approximately same pressure loss in case of the same pressures at the entrance to the system. The system with the highest power consumption is the pilot system III which simultaneously operated with considerably higher flow rates and velocities of the flow inside the nozzles than the other two pilot systems (Table 23, Figure 31). However, it was shown that a slightly higher power consumption of the tested pilot systems is the condition for achieving the desired results and generating considerably higher overall working efficiency of the system.

4.2 Findings from the biological experiments

The effectiveness of the newly developed ballast water treatment pilot system (pilot system III) was tested in a 150 L container (mesocosm) with added seawater and natural marine organisms that had been collected in the shallow coastal area in the Gulf of Trieste. The abundance and viability of zooplankton, cysts and natural population of heterotrophic bacteria were determined before and after the exposure to the hydrodynamic cavitation treatment or combination of the hydrodynamic cavitation and separation treatment for various time intervals.

4.2.1 Effectiveness of treatment on zooplankton (copepods)

Since the experiments with zooplankton (copepods) were performed in different seasons, the starting abundance of zooplankton varied considerably from experiment to experiment (Appendix H). In all five experiments, the number of intact zooplankton rapidly dropped after only 15 minutes of treatment with the pilot system from 346.5±216.3 to 2.53±2.12 organisms/L (Appendix H). This resulted in 99.4% of destroyed organisms (copepods) (Cvetković et al., 2016) (Appendix H).

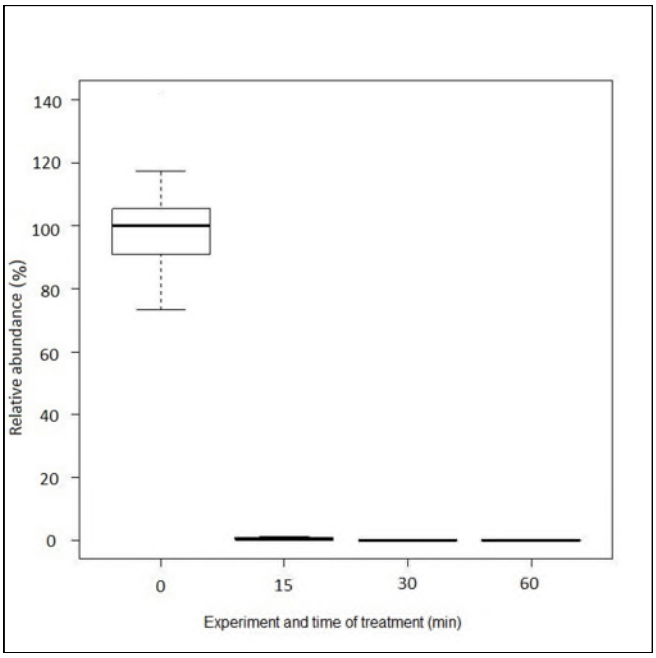


Figure 32: Box plot of the relative abundance of live zooplankton (copepods) (%) in seawater samples after treatment with the pilot system at different time intervals: before treatment (t0), after 15 minutes (t15), 30 minutes (t30) and 60 minutes (t60) of treatment.

Slika 32: Box Plot prikaz relativne številčnosti preživelega zooplanktona (kopepodov) (%) v vzorcih morske vode po obdelavi v pilotnem sistemu v različnih časovnih intervalih: pred obdelavo (t0), po 15 minutah (t15), 30 minutah (t30) in 60 minutah (t60) obdelave.

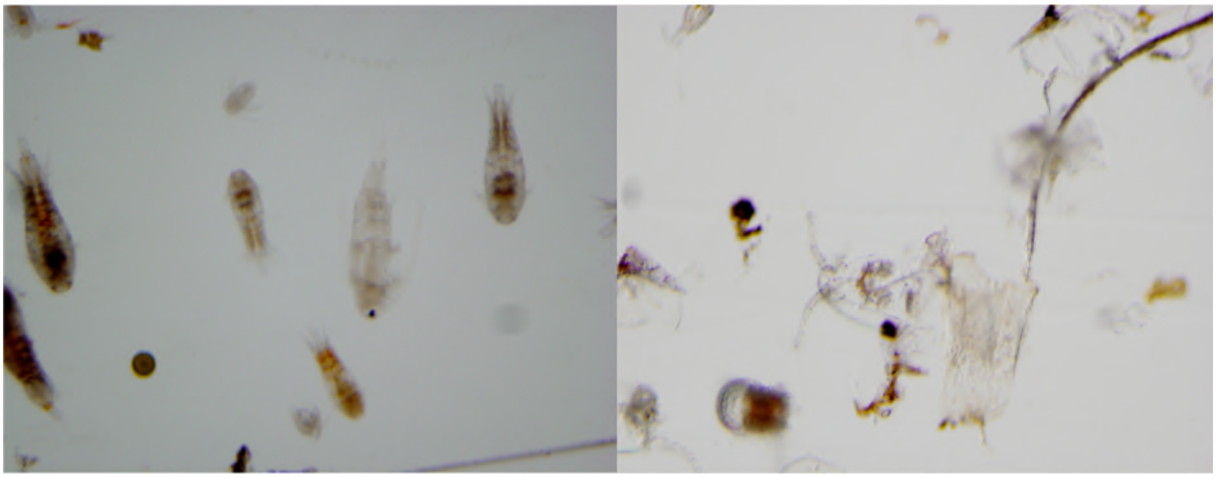


Figure 33: Images of zooplankton sample before treatment with the pilot system a) and after 60 minute treatment with the pilot system b).

Slika 33: Slike vzorca zooplanktona a) pred obdelavo in b) po 60 minutah obdelave s pilotnim sistemom.

Furthermore, there was a significant impact of the duration of cavitation (factor ’time‘) on the part of survived zooplankton (1-way ANOVA; Table 24, Figure 32).

Table 24: One-way ANOVA with an independent factor ‘time’ for zooplankton experiments.

Preglednica 24: One-way ANOVA za neodvisni dejavnik »čas obdelave« za eksperimente z zooplanktonom.

	Df	Sum Sq	Mean Sq	F value	Pr (>F)
Time	3	112051	37350	595.7	$<2e^{-16}$
Residuals	56	3511	63		
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1					

The pairwise Tukey HSD tests revealed a significant difference between the starting densities of zooplankton (t0) with either densities after 15, 30 or 60 minute duration of treatment with the pilot system. After 30 minutes of treatment, all the zooplankton was destroyed, there were pieces of exoskeleton present, and no intact copepod was observed (Figure 33, Appendix H). The treatment with the pilot system therefore resulted in broken carapace of all copepods, and dissociation of copepod appendages from the body (legs, antennae) (Figure 33).

4.2.2 Effectiveness of hydrodynamic cavitation against *A. salina* cysts

Three experiments were performed using cavitation to treat *A. salina* cysts. The number of whole cysts significantly dropped after 15 minutes of treatment from 527.3±161.2 to 190.3±130.0 (Cvetković et al., 2016) (Appendix H). This resulted in 66.7% of destroyed cysts. The number of cysts continued to drop during 60 minutes of treatment to 49.9±23.4, which resulted in 90.2% of destroyed cysts (Appendix H). Furthermore, additional three experiments that used the hydrodynamic cavitation and the separation (pre-treatment) phase were performed. The number of whole cysts dropped from 560.4±174.1 to 152.8±102.6 in 15 minutes of treatment and decreased to 8.4±5.9 after 60 minutes of treatment (Appendix H). This resulted in the 69.9% (after 15 minutes) and finally 98.2% of destroyed cysts after 60 minutes of treatment.

The system (Figure 34 a,b) proved to be more effective when using also the separation (pre-treatment) phase (Table 24; 2-way ANOVA, factor ‘treatment’ (C and Cs) and ‘time’ (t0, t15, t30, t60)), as there was a significantly lower number of whole cysts when using the pre-treatment phase. This was particularly evident after 30 minutes of treatment when the number of cysts was much lower if pre-treatment phase was used. Moreover, 30 minutes of treatment with the included pre-treatment was sufficient to leave only 44.1±35.1 whole cysts (90.5 % of cysts were destroyed), and a 30 min longer treatment (60 min) yielded almost the same result without the included pre-treatment, where 49.9±23.4 cysts was left (90.2 % of cysts were destroyed) (Appendix H and Figure 34 a, b).

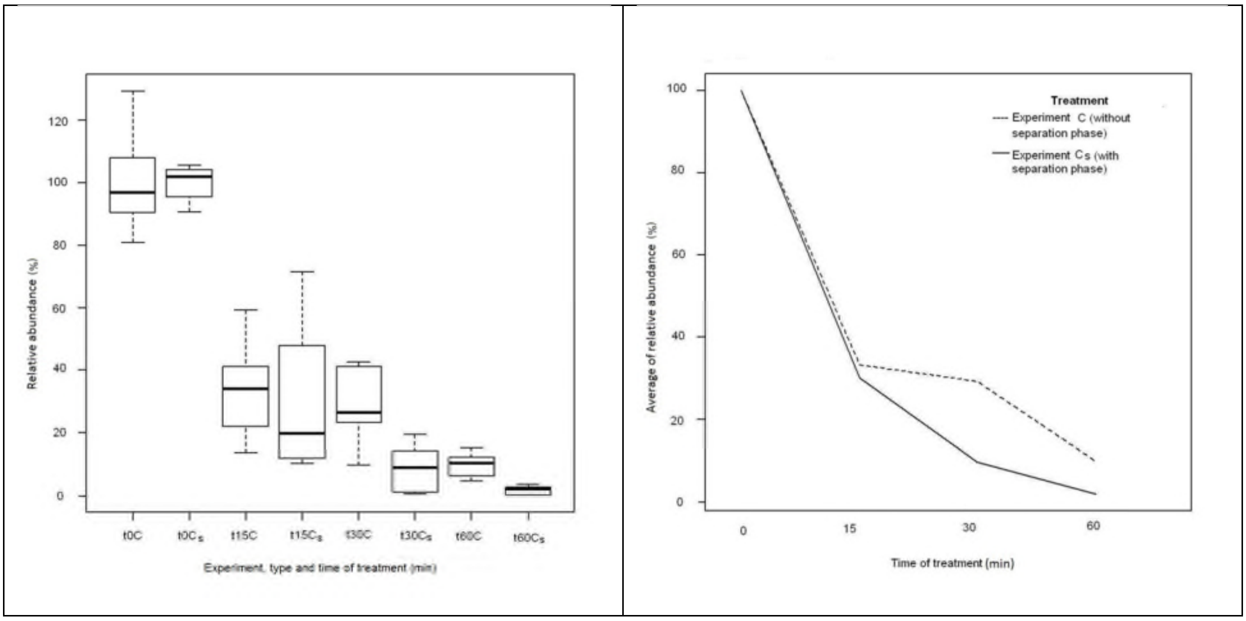


Figure 34: a) Box plot of the relative abundance of whole cysts (%) after the treatment with the pilot system at different time intervals: before treatment (t0), after 15 minutes (t15), 30 minutes (t30) and 60 minutes (t60) of treatment. The “C” refers to the treatment with hydrodynamic cavitation, while the “Cs” refers to the treatment with hydrodynamic cavitation and separation phase. b) The average percentage of whole cysts (%) after treatment with the pilot system using hydrodynamic cavitation (C - dashed line), and using combined hydrodynamic cavitation that follows the separation phase (Cs - full line).

Slika 34: a) Box Plot prikaz relativne številčnosti celih cist (%) po obdelavi s pilotnim sistemom v različnih časovnih intervalih: pred obdelavo (t0), po 15 minutah (t15), 30 minutah (t30) in 60 minutah (t60) obdelave. Oznaka "C" se nanaša na obdelavo s hidrodinamično kavitacijo, medtem ko se "Cs" nanaša na kombinacijo obdelave s hidrodinamično kavitacijo in s predfazo ločevanja, b) Povprečni delež celih cist (%) po obdelavi s pilotnim sistemom, ki uporablja hidrodinamično kavitacijo (C - črtkana črta) in z uporabo kombinacije hidrodinamične kavitacije s predfazo ločevanja (CS - polna črta).

Table 25: Two-way ANOVA with the independent factors ‘treatment’ and ‘time’ for *A. salina* cysts experiments.

Preglednica 25: Two-way ANOVA za neodvisna dejavnika »obdelava« in »čas obdelave« za eksperimente z A. salina cistami.

	Df	Sum Sq	Mean Sq	F value	Pr (>F)
Treatment	1	1076	1076	6.937	0.0105
Time	3	94718	31573	203.465	$< 2E^{-16}$
Residuals	67	10397	155		

However, comparing the pairs of the single experiments, variations were evident, i.e. comparing experiments C1 and Cs1 (Appendix H), there was a similar percentage of successfully destroyed cysts, whereas the experiment C3 and Cs3 showed that the separation phase succeeded to destroy almost 50% more cysts (58% in C3 vs 99% in CS3) (Appendix H). This difference has not been as apparent in case of the 60-minute treatment, where the average of destroyed cysts was only about 16 % higher if the combination of hydrodynamic cavitation and pre-treatment phase was used.

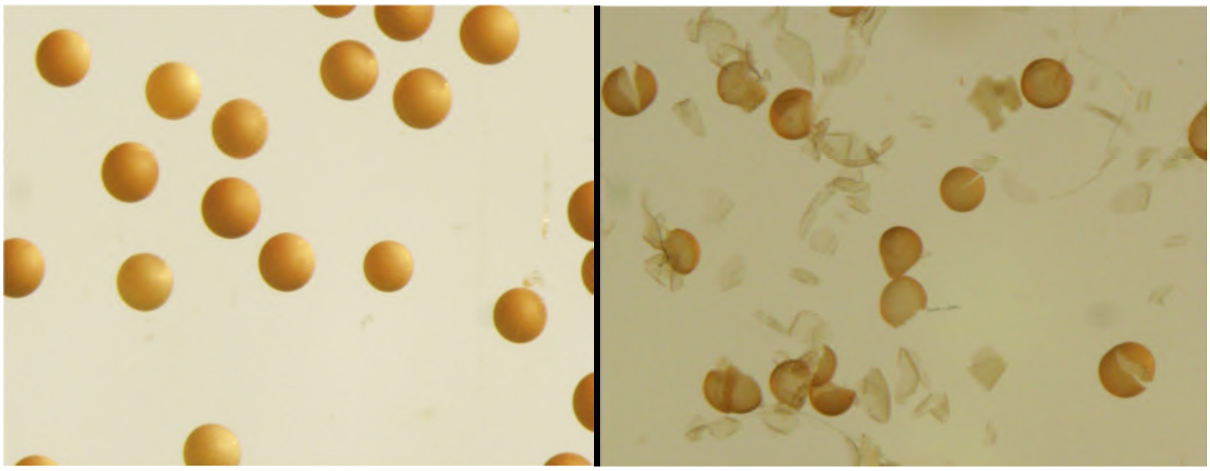


Figure 35: Images of *A. salina* cysts a) before the treatment (t0) and b) after 60 minutes treatment (t60) with the pilot system.

Slika 35: Slike A. salina cist, a) pred začetkom obdelave (t0) in b) po 60 minutah obdelave (t60) z pilotno napravo.

Treating the cysts with the pilot system resulted in the breakage of cysts (Figure 35 a, b) and 60-minute treatment was sufficient to break most of the cysts (Figure 35a, b). The 2-way ANOVA (Table 25) (factor 'time' and factor 'treatment') also confirmed that the effectiveness of the system on the breakage of cysts depends significantly on time and treatment.

Additionally, the number of the hatched *A. salina* nauplii was significantly lower if cysts were treated with the pilot system: 0.33±0.58 hatched nauplii after 60 minutes of treatment with the system where only cavitation part without separation was used, ti. 0.22±0.19 hatched nauplii after 60 minutes of treatment with the system where the cavitation together with the separation was used in comparison with the number of the hatched nauplii from the cysts taken before treatment with the system (hatched nauplii 227.39±35.29) (Figure 36).

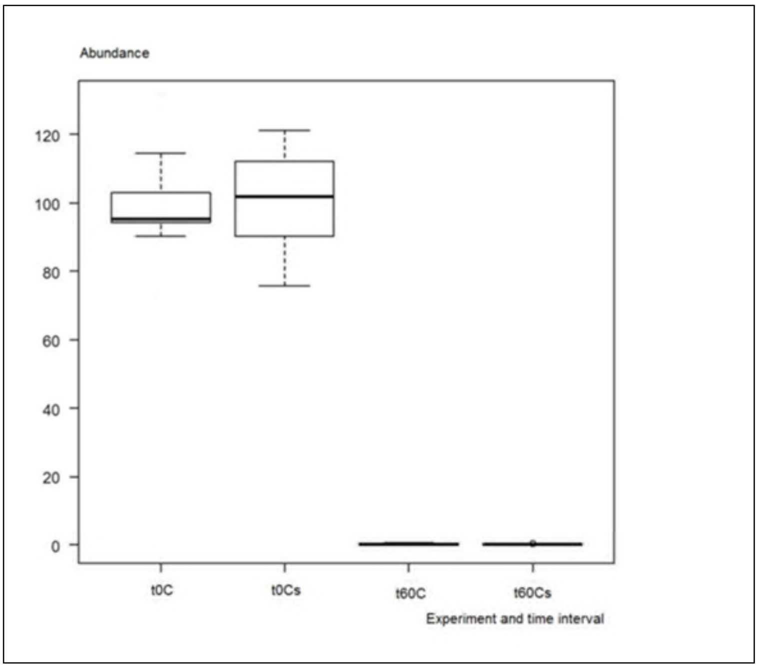


Figure 36: Box plot of the relative abundance (%) of hatched nauplii of *A. salina* cysts (a) after the treatment with the pilot system at different time intervals: before treatment (t0) and after 60 minutes (t60) of treatment The ‘C’ refers to the treatment with cavitation phase, while the “Cs” refers to the treatment with combined cavitation and separation phase.

Slika 36: Box Plot relativne številčnosti (%) izvaljenih nauplijev A. salina cist, a) po obdelavi z pilotnim sistemom v različnih časovnih intervalih: pred obdelavo (t0) in po 60 minutah (t60) obdelave. Oznaka "C" se nanaša na obdelavo s fazo kavitacije, medtem ko se "Cs" nanaša na obdelavo s kombinirano kavitacijo in predfazo ločevanja.

Table 26: Two-way ANOVA with the independent factors ‘treatment’ and ‘time’ for hatched *A. salina* nauplii.

Preglednica 26: Two-way ANOVA za neodvisna dejavnika »obdelava« in »čas obdelave« za valjenje nauplijev A. saline.

	Df	Sum Sq	Mean Sq	F	value	Pr(>F)
Treatment	1	0	0		0	0.991
Time	1	89746	89746		720.7	$<2e^{-16}$
Residuals	33	4109	125			
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1						

There was a significant influence of the cavitation on the hatching of nauplii (2-way ANOVA; Table 25), but there was no statistical difference between two treatments (with or without the separation phase) on the viability of cysts (2-way ANOVA, Table 26).

4.2.3 Efficacy of treatment on marine bacteria

The samples contain an average of 0.9 to 3.1 x 10^8 bacteria/L in the tank (mesocosm) before the treatment with the pilot system, which approximately coincides with the monthly concentrations of bacteria in the Gulf of Trieste in the autumn (Tinta et al., 2015).

After 60 minutes of the treatment bacterial number decrease and varied between 2.6 and 9.2 x 10^7 cells/L in different experiments (Figure 37). The concentration of the bacteria was higher during the second and the third experiment, with the initial value of 3.1 x 10^8 cells/L, where the maximum decrease in number occurred at the end of the treatment with the pilot system (t60). The number of marine bacterial cells declined up to 80 % (Figure 37) (Cvetković et al., 2016).

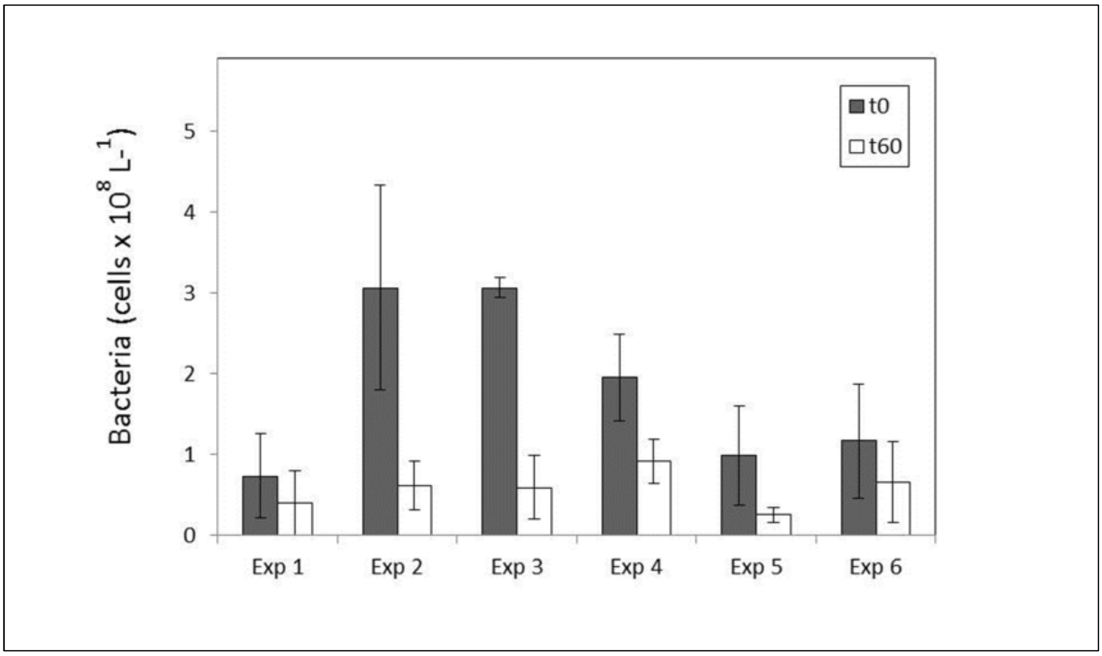


Figure 37: Changes in bacterial abundance (±SD) in the mesocosm (No. cells/L) before (t0) and after the treatment with the pilot system (t60).

Slika 37: Spremembe v številčnosti bakterij (±SD) v modelnem ekosistemu (št. Celic/L) pred (t0) in po obdelavi z pilotnim sistemom (t60).

At the same time, the growth rate of bacteria (BCP) was measured as incorporation ^{3}H-Leucine labeled compounds into newly synthesized bacterial cell proteins (Kirchman et al., 1985) in all subsamples. The bacterial growth rates varied between 0.7 to 2.1 x 10^7 cells/L/h at the beginning of the experiments and did not exceed 0.013 to 0.43 x 10^7 cells/L/h at the end (Figure 38).

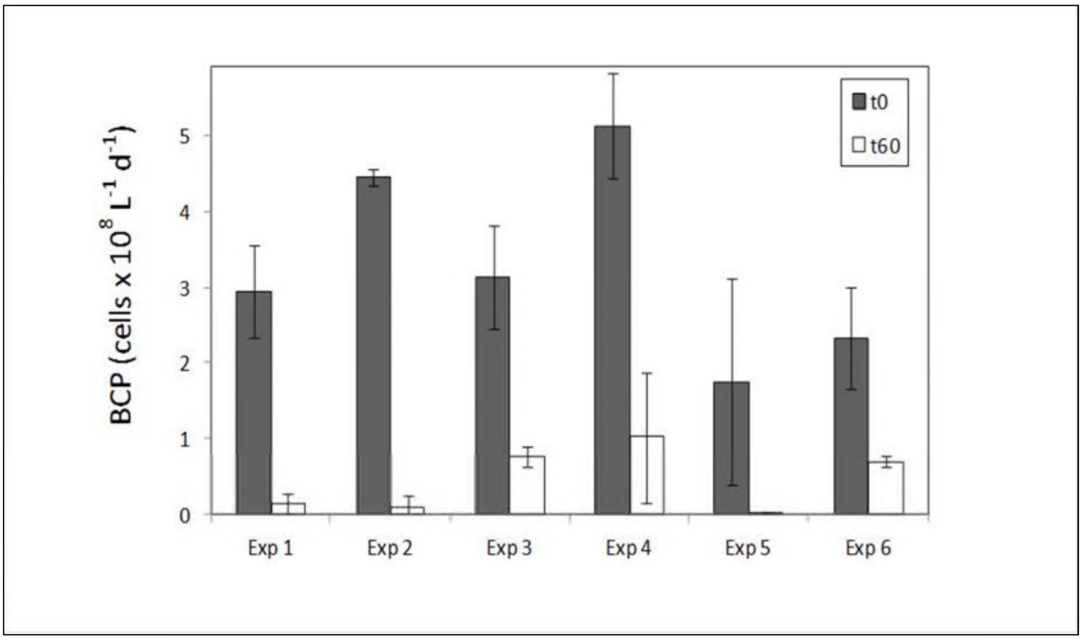


Figure 38: Changes in bacterial carbon production (BCP) (±SD) of natural bacterial population in the mesocosm (No. cells/L/d) before (t0) and after (t60) the treatment with the pilot system.

Slika 38: Spremembe v bakterijski proizvodnji ogljika (BCP) (± SD) naravne bakterijske populacije v modelnem ekosistemu (št. celic/L/d) pred (t0) in po (t60) obdelavi s pilotnim sistemom.

Compared to the initial growth rate, the decrease in BCP was on average 86% after the 60 minutes of the treatment with the pilot system. In all experiments, only 1.7 to maximally 30% of bacteria were able to grow, in comparison with the bacterial population growth potential. However, the overall effectiveness of the treatment depended mainly on the duration of the treatment.

4.2.4 Findings based on the processing of the biological results

The efficiency of the pilot system III, which uses innovative solution in combination of the physical (hydrodynamic cavitation) and the mechanical phase (the separation) in its operation, was tested on the viability of the selected marine organisms. The preliminary results of the experiments suggest that the newly developed pilot system offers an effective solution for breaking down individual representatives of zooplankton organisms (copepods), *A. salina* cysts, and inhibits the growth rate of the natural population of marine bacteria (Cvetković et al., 2016). In all experiments with a mixed population of net zooplankton samples, the number of intact copepods decreased after only 15 minutes of the treatment with the pilot system, since 99.4% copepods were destroyed (Figure 34; Appendix H). On the other hand, when treating the seawater with a high concentration of *A. salina* cysts with the pilot system, a longer time was needed to decrease the amount of whole cysts closer to zero. In former laboratory experiments *A. salina* cysts were for the tests since the cysts of *A. salina* were previously used in different treatment systems for ballast water treatment (Gavand et al., 2007; Tsolaki et al., 2010; Lacasa et al., 2013). The treatment was even more efficient after the inclusion of the separation phase because a significantly higher number of destroyed cysts (98.2%) were counted (Figure 37; Appendix H). The results of the experiments where hydrodynamic cavitation phase was used together with the separation phase showed higher efficiency in breaking the *A. salina* cysts than the experiments where separation was excluded from the treatment. The efficiency was evident after only 30 minutes of treatment, where the same results yielded as when using the 60-minute treatment with only hydrodynamic cavitation. At the same time, six samples (with three subsamples for each sample) of seawater with cysts was incubated in the thermostatic chamber at 25°C for 48 hours with 12/12h day/night cycle with the aim of determining the percentage of hatched nauplii of *A.salina* cysts before (time interval t0) and at the end (t60) of the treatments. The results showed that after 48 h the number of hatched nauplii in the samples that were treated with the pilot system for 60 minutes was low (only a few nauplii hatched), regardless if the separation phase was used or not.

The tests have also shown a considerable impact of the pilot system on the decrease of the natural population of heterotrophic bacteria, since the number of bacteria and BCP dropped after 30 and 60 minutes of the treatment (Figure 37; Figure 38). The decrease in BCP was evident in all experiments. Like in many other mechanical technologies currently used in ballast water treatment, the possible concern with our pilot system could be related to long-term destruction of organisms in ballast water tanks. Namely, in case of death and decomposition of the phytoplankton and zooplankton in ballast tanks, the concentrations of dissolved organic matter (DOM) and nutrients might increase. Consequently, the augmented DOM pool influence the growth and activity of the bacterial population that might have an important influence on biogeochemical cycles in new environments. Furthermore, the interactions with other members of the food web in competition for resources might change (Drake et al., 2007). When it comes to the newly developed pilot system, the problem of DOM present in the ballast water tank could be partially solved in the way that the ballast water is treated at the beginning of the voyage, where larger organisms would be removed using the ship’s filtration and system’s separation that will immediately return part of organisms to natural habitats at the place of ballast water loading.

4.3 Experimentally proved efficiency of developed ballast water treatment system

All three newly developed pilot systems confirmed the fact that the innovative concept which includes hydrodynamic cavitation and separation phase incorporated together in the common unit can successfully operate. However, according to the results of the hydraulic experiments performed in the Hydraulic laboratory of UL FGG, pilot system III showed the highest working efficiency among the pilot systems (see previous sections). Therefore, it was chosen for further experiments with seawater and marine organisms. The results of hydraulic experiments, together with the biological test confirmed that the innovative concept can work on its own and that it can be successfully used in the treatment process. Furthermore, it was shown that the design of the pilot system would have an impact on the effectiveness of the technology. It means that there is still room for further research and improvement of the technology in the near future.

According to our knowledge, there is only a few available data on previous lab-scale systems for ballast water treatment whose operation is based on the use of the HC alone or as a main step of treatment in combination with other technologies. A summary of the description of those three systems (Kato, 2003; IMO, 2006a; Ranade, 2009; Sawant et al., 2008) together with the main results is presented in section 2.5.1.

Although it is difficult to make a detailed comparison between our and other pilot systems for ballast water treatment and our pilot system because some data about described systems are missing (e.g. detailed technical data, determination of observed organisms e.g. plankton in general in other studies), few important advantages of our system over the existing systems can be found (Cvetković et al., 2016):

- Compared to the treatment system by Sawant et al. (2008), higher percentage of broken zooplankton (around 17%) was achieved with our pilot system. Namely, for approximately the same duration of both treatments (15 minutes), about 99.4% of zooplankton was destroyed with our system in contrast to the results achieved by Sawant et al., (2008), who succeeded in destroying 82% of the zooplankton present in the samples in the condition of 75% open orifice plate of the pilot system. Moreover, our system achieved a significantly higher flow rate (15 m^3/h) with the same or even lower working pressures (between 1.8-2.8 bar) than Sawant et al. (2008), who used a pressure of 2.9 bar to achieve the flow rate of 4.68 m^3/h in their experiments.
- Compared to the treatment system used by Ranade et al. (2009), our system achieved about a 23% higher decrease in marine bacterial abundance and the same effectiveness in destroying the zooplankton (more than 99% for both systems). Ranade and coworkers (2009) achieved the best result, a 46% in reduction of bacterial cells, along with the needed pressure of 6.9 bar and the flow rate of 2.95 m^3/h to yield this result. Our system was able to reduce the number of bacterial cells, as well as inhibit the bacterial growth, using a significantly lower working pressure (1.8 - 2.8 bar), as well as, a significantly higher flow rate (15 m^3/h).

- In comparison to the treatment system used by Kato (2003), our pilot system was able to break most of the *A. salina* cysts during the pressure exposure in variation between 1.8 - 2.8 bar and the flow rate of 15 m^3/h, while Kato's (2003) treatment system needed a significantly higher pressure (10 bar) and a significantly lower flow rate (1.13 m^3/h) to achieve only partial efficiency (the exact percentage has not been specified).

Nowadays, the market of ballast water treatment systems offers many different technologies that are in compliance with the requirements of IMO D-2 Standard. Even though these technologies do not have any direct negative chemical influence to humans and marine environment, some of them often have certain limitations. For example, when it comes to UV (ultraviolet) irradiation, one of the most commonly used technologies in ballast water treatment (30% of approved systems today use UV) (David and Gollasch, 2012; Cvetković et al., 2015), the mentioned technology was not proven to be successful enough in the inactivation of cysts (Minchin, 2006; Liebich et al., 2012). Additionally, some microorganisms can also survive the treatment with the UV due to the enzyme repair systems (Modak, 2008). Most of the above mentioned problems were successfully solved by our pilot system.

Our pilot system does not include active substances or chemicals in its working process, which is in contrast to most of existing ballast water treatment systems (Perrins et al., 2006; Gregg and Hallegraeff, 2007; Lafontaine, 2008; Banerji, 2012; IMO, 2014; Werschkun et al., 2014) that use them to improve their overall efficiency. The active substances which are mostly used in former ballast water treatment systems are oxidizing agents, systems that employ the use of chlorine which is usually generated by electrolysis of seawater or from solutions of hypochlorite stock, peracetic acid, ozone or chlorine dioxide.

Regardless of the addition of active substances or chemicals to numerous existing systems, when compared with the results achieved with our pilot system, some of them achieved similar or even lower results when it comes to the destruction of marine organisms (Gavand et al., 2007; Gregg and Hallegraeff, 2007; Lafontaine, 2008). For example, Gavand et al. (2007) used a combination of sonication and advanced chemical oxidants in treatment of *A. salina* (larvae, adults, and cysts). The abovementioned method proved to be very successful when it came to the destruction of larvae and adult zooplankton. While it destroyed 100% and 95% of larvae and adults of zooplankton, respectively, in only two minutes of exposure, our pilot system successfully destroyed almost 100% of the zooplankton (copepods) with the treatment in duration of 15 minutes (effects of shorter treatment duration were observed). At the same time, Gavand et al. (2007) succeed to destroy 92% of the cysts in approximately 20 minutes of exposure to the treatment, which is comparable to our results where 90.5% of cyst destruction was achieved with the treatment lasting 30 minutes.

Although the active substances improve the efficiency of many ballast water treatment technologies, the time period required for reaching its effectiveness is often not shortened due to the addition of active substances. Moreover, sometimes the duration of the treatment can be much longer than with our technology, i.e. when treated with our pilot system most organisms were destroyed within 1 hour, while a few hours to several weeks of exposure to the substance is needed for the destruction of the majority of organisms with tested biocides (Gregg and Hallegraeff, 2007). Unfortunately, most of the experience with the behavior of chemicals in sea water is still in fact based on the fresh water research and some of the chemicals, together with their side effects and consequences of their usage have still not been fully or sufficiently researched in sea water conditions (Zhang et al., 2013).

Despite the high efficiency of the pilot system in destroying of the tested organisms, especially the copepods where 30 minutes of the treatment was sufficient to meet the requirements of D-2 standard in the category of organisms ≥ 50μm, in this development stage it is not possible to claim that the tested pilot system can meet all of the D-2 organism's limitations. Namely, even though the rate of removal/inactivation of *A. salina* cysts was almost 99%, the concentration of tested organisms in the samples were too low (the results were expressed in the number of cysts/10 mL, i.e. 10^{-5} m^3), therefore theoretically, the number of *A. salina* cysts was too high to meet the requirements of D-2 standard. Further improvements and experiments should be performed with the different microorganisms, mainly with phytoplankton, zooplankton (copepods and cysts) and pathogenic bacteria.

If the system is designed for full-scale onboard usage, it should have the design in the form of a modular concept (Figure 39). More precisely, one module should consist of multiple smaller units such as the tested pilot system. The certain number of units incorporated into the module will depend on the volumes and flow rates of the ballast water that needs to be treated. In addition, the modular design of the pilot system should be able to adapt to different space requirements and limitations on board the ship. The footprint of the tested pilot system with the flow rate up to 20 m^3/h (one unit of the modular system for ballast water treatment) is 0.12 m^2. If these five units are connected to one circular module so that the module can achieve a flow rate of 100 m^3/h, the footprint of one module is supposed to be about 2.00 m^2.

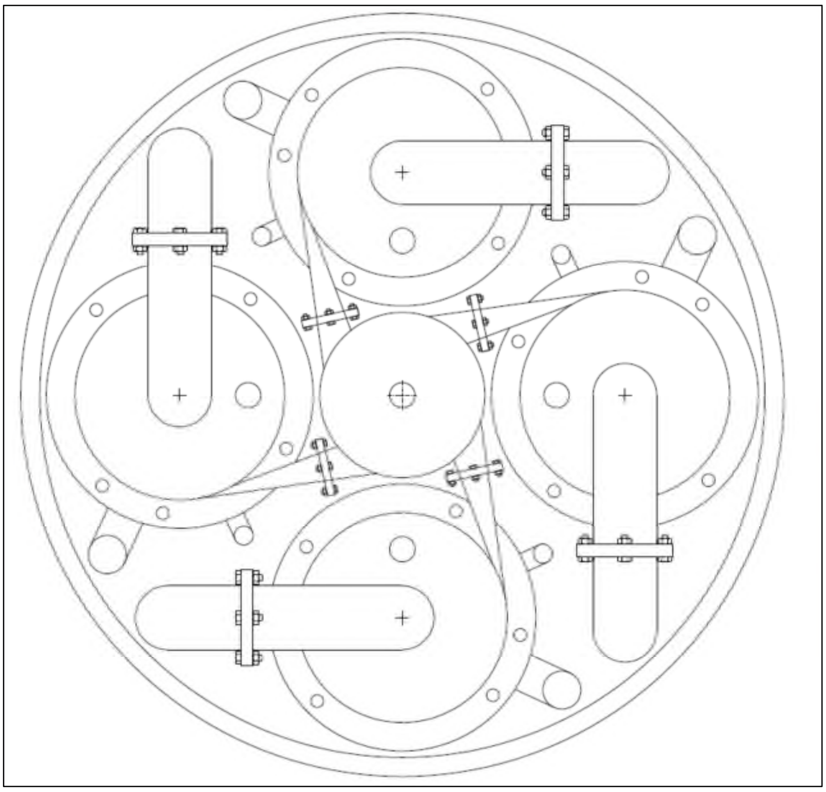


Figure 39: Example of the appearance of one module of ballast water treatment system which consists of 4 ballast water treatment units.

Slika 39: Prikaz enega modula sistema za obdelavo balastnih voda, ki je sestavljen iz 4 enot za obdelavo balastnih voda.

Furthermore, the calculated pressure loss for one unit of our system for ballast water treatment, which operates with the pressure at the entrance to the system of 2.8 bar and the flow rate of 15 m^3/h will be 1.63 bar. Since the modular concept for ballast water treatment should consist of the serially connected units whose operation will not affect each other and which will be fed by the common centrifugal pump, the pressure loss inside the modular system should remain the same for the whole system (Δp=1.63 bar). The power consumption for one unit of such modular system should be 600 W, which means that the whole module consisting of five units will require the power of 3 kW.

4.4 Verification of the validity of the hypotheses

Based on the analysis of the results of hydraulic experiments and biological tests whose aim was to verify the efficiency of the innovative technology for ballast water treatment and to review the existing literature about technologies and processes which have been used in ballast water treatment so far, it is possible to draw a conclusion about the validity of the hypotheses set at the beginning of the doctoral dissertation.

4.4.1 The findings on the validity of the "Hypothesis 1"

In the first hypothesis of the doctoral dissertation it was claimed that with the use of the new environmentally friendly and cost effective technology for ballast water treatment, whose work includes only the combination of mechanical and physical processes without adding any chemicals, it is possible to achieve the same or even higher efficiency than with the existing technologies for ballast water treatment, and simultaneously reduce the risk to ships' crew and the marine environment.

As it is described in the section 3.1, the working process of the newly developed technology does not include the addition of any chemical to improve its working effectiveness, regardless of which model of the pilot system was used (pilot system I, II or III). Moreover, the working process is based only on the combination of the mechanical (separation) pre-treatment and physical (hydrodynamic cavitation) main treatment phase. Since it does not employ the use of chemicals, it does not present any danger for the marine environment or for the members of the crew of the ship who may be in close contact with the device. However, there are no technical obstacles for combining the technology with chemicals in some of the future phases of testing and development, if necessary.

Due to the fact that pilot system III showed the highest working efficiency among the tested pilot systems during the hydraulic experiments (see the section 4), its biological effectiveness on destroying the aimed marine organisms was tested. Hence, pilot system III with its technical parameters which were set during the performance of the tests on the biological efficiency, was chosen for further comparison with the existing lab and large scale systems. When compared with the lab-scale systems for ballast water treatment whose working process includes the HC and which have been developed so far (Kato, 2003; IMO, 2006a; Ranade, 2009; Sawant et al., 2008) (see section 4.3), it was proved that our pilot system has the highest hydraulic performances (the highest achieved flow rates and the lowest values of the pressures at the entrance to the system) and also the highest overall effect on destroying the observed marine organisms. Furthermore, chapter 4.3 revealed that despite of the use of the active substances in some of the existing technologies, the overall effect of some of such systems could be the same or even lower than with our pilot system whose work does not include the use of chemicals (Gavand et al., 2007; Gregg and Hallegraeff, 2007; Lafontaine, 2008).

When it comes to the existing large scale systems which are approved for use in the ballast water treatment on ships and whose operation includes HC, which is mostly combined with some other technology (hydrodynamic cavitation has not been used by itself for ballast water treatment so far), the summary of their main performances presented in section 2.5.2 can be found in Table 27. In addition, Table 27 also contains some of the frequently used ballast water treatment technologies (see section 2.5.2) with their main performances (flow rates, footprint and power consumption), which are compared with our pilot system consisting of five modules and which are supposed to treat the approximately equal quantity (500 m^3/h) of ballast water, like the other presented technologies.

Table 27: Main performances of frequently used ballast water treatment systems (flow rates, power requirements and the footprint) and the newly developed pilot system.

Preglednica 27: Glavne značilnosti pogosto uporabljenih sistemov in novo razvitega pilotnega sistema za obdelavo balastnih voda (pretoki, poraba energije in potrebna tlorisna površina).

Name of the system	**Technology used**	**Flow rate (m^3/h)**	**Power requirements (kW)**	**Footprint (m^2)**
JFE Ballast Ace	filtration + chemical + HC	500	6.2	5
OceanSaver	filtration + HC + chemical	500	59	11
Fine Ballast OZ	HC + ozonation	500	no data	15
Venturi Oxygen Stripping	HC + inert gas	500	22	3
OceanGuard	AC + chemical	500	8.5	3.5
Ecomarine	filtration + UV	500	52	8
Cathelco	filtration + UV	500	107	9
Our system	**Separation + HC**	**500**	**15**	**10**

According to Table 27, power consumption of frequently used systems for ballast water treatment ranges between 6.2 kW for JFE Ballast Ace to 107 kW for Cathelco. Since our system needs only 15 kW to achieve the flow rate of 500 m^3/h, it is possible to conclude that it fall into the category of systems with low power consumption. Technologies which employ chemicals, UV lamps and ozone in their work spend much more energy due to expensive and complex constructional requirements than our system which does not need chemicals or combination with other technologies or special constructional requirements for its operation. This characteristic of our system is considered as another advantage over the existing systems in the category of cost-effectiveness. Furthermore, since our system is constructed from relatively cheap materials and its constructional characteristics allow the long lifespan of the device, the system is likely to be cost-effective also in large scale conditions. The footprint of frequently used technologies for ballast water treatment ranges between 3 and 15 m^2. Since the footprint of our system is 10 m^2, which belongs approximately to the middle of the size range of the selected technologies (Table 27), it is considered that the size of our technology should be acceptable for use in the large scale conditions. Moreover, due to the modular concept of the system, it is supposed to be highly adaptable to different limitations and requirements of the ship's areas.

According to the facts presented in this section, it is possible to conclude that our former research completely confirmed the first hypothesis of this study.

4.4.2 The findings on the validity of the "Hypothesis 2"

The goal of the second hypothesis was to check the fact that with the application of the new technology for ballast water treatment, which will try to remove and return part of the organisms to their natural habitat immediately during the ballast water loading, the number of organisms which have to be destroyed will considerably decrease. It is also supposed to partially protect marine ecosystems from where the ballast water is loaded.

Detailed review of the literature on existing ballast water treatment systems (section 2.6.2) present very different tools to remove and return part of the organisms to its natural habitat, mainly as a pre-treatment phase. These systems are based on the mechanical principle, such as filtration, cyclonic separation (hydrocyclones), electro-mechanical separation (Jelmert, 1999; Parsons and Harkins, 2000; Waite et al., 2003; Veldhuis et al., 2006; Cangelosi et al., 2007; Gregg et al., 2007) (see the section 2.2).

Most of the approved ballast water treatment systems employ different filtering systems as a pre-treatment phase, while only several of them use hydrocyclones instead of the filters. Some such systems are (Lloyds register, 2014): Alfa Laval Pure Ballast (combination of filtration, UV and AO), MMC Green Technology (combination of particle filtering and UV), Eco Marine (filtration + UV), Erma First (combination of hydrocyclones and chemical treatment), Wuxy Brightsky Electronic (combination of hydrocyclones and UV), etc. The common characteristic of all these systems is that the filtration/separation phase is used immediately after the ballast water loading, at the beginning of the ballast water treatment.

Similarly to the existing systems for ballast water treatment, all our pilot systems include the pre-treatment phase for the removal of larger organisms and other particles. While in the pilot systems I and II classic construction of the hydrocyclone was used for the separation phase, pilot system III used an innovative designed separator for the removal of the particles and organisms with density greater than water.

Due to the fact that the common practice with the existing approved systems for ballast water treatment already verified the author’s assumptions, it is possible to conclude that this hypothesis was confirmed. Furthermore, the development of our pilot system, which has the ability to separate all the particles with density greater than water at the beginning of the treatment, additionally confirmed the thesis.

4.4.3 The findings on the validity of the "Hypothesis 3"

The third assumption referred to the possibility of the treatment of large volumes of ballast water with a spatially flexible system with relatively small dimensions. This system should also reach high effectiveness in destroying organisms, and higher level of protection of marine ecosystem where the treated water will be returned.

Section 4.3 describes the main characteristics of the modular system which should be used for the ballast water treatment on board of ships and which consists of the modules whose number will depend on the desired flow rate and the quantity of ballast water which needs to be treated. Each module will consist of four to five serially connected smaller units (tested pilot system) (Figure 42). Full scaling of the concept should not have any influence on the effectiveness of the system's operation since the operation of the units inside the system should not affect each other.

Furthermore, as it was already mentioned in the previous sections, the system's operation does not employ chemicals and it includes the pre-treatment phase (separator) which allows the immediate return of organisms with density greater than water to its natural habitats, and at the same time it offers a high level of protection of marine ecosystem where the ballast water is discharged. Based on the previously mentioned facts, it is possible to conclude that claims from the third hypothesis were completely confirmed.

4.4.4 The findings on the validity of the "Hypothesis 4"

The presumption of the fourth hypothesis was that it is possible to generate the cavitation effect at the entrance to the vortex tube of the hydrocyclone.

According to the results of the hydraulic experiments, the hydrodynamic cavitation has been generated with the pilot system I (see section 4.1.1 and Table 15). At the entrance to the vortex tube which is situated in the central part of the hydrocyclone. In addition, the system was improved and two new pilot systems were constructed. The results of the hydraulic experiments performed with the pilot systems II and III confirmed the hypothesis, since the hydrodynamic cavitation occurred at the beginning of the central vortex tube in place of the rapid narrowing caused by the nozzle's construction. Moreover, the results of the experiments confirmed that the constructional changes of the pre-treatment unit where hydrocyclone was replaced with the separator will not affect to the occurrence of the hydrodynamic cavitation. According to the facts mentioned above, the fourth hypothesis was completely confirmed.

5 CONCLUSIONS

According to the main goals and hypothesis set at the beginning of this doctoral dissertation, the research conducted as part of dissertation should contribute to the ballast water treatment area in the way of developing innovative, highly effective, environmentally and safety acceptable technology whose operation relies on the use of thus far insufficiently researched and implemented technology - hydrodynamic cavitation.

With the aim of developing such technology, a detailed research of the existing applications of HC in different disinfection and other processes that include damaging the cells, particularly in ballast water treatment area, was performed. The results of the research were published in the article written by Cvetković et al. (2015). Based on the existing literature, the key parameters and constructional characteristics of the effective HC devices were selected and new pilot systems whose operation should include HC as a main step of the treatment were constructed. As the next steps of the research, hydraulic characteristics of the newly developed pilot systems were tested. After the hydraulic experiments were finished and the results of experiments processed, the pilot system which showed the highest working efficiency among the tested systems was selected for further biological tests. The primary purpose of the performed biological tests was to verify the effectiveness of the new technology on damaging the marine organisms.

5.1 General findings of the research results

During the development of the new ballast water treatment technology, three different pilot systems whose work consolidates separation (pre-treatment) and hydrodynamic (main treatment) phase to the common unit were constructed. While the hydraulic experiments with the pilot system I were concentrated on verifying the working concept of the new technology and selecting the key factors that influence its operation, the primary goal of the other two experiments (experiments with pilot system II and III) was to improve the working performances and to assess the influence of the changes in the design of the pilot systems on the hydraulic results.

After processing the results of all three sets of experiments, and also based on the visual observation of the performance of experiments, pilot system III proved to operate with the optimal values and relations of the key factors in comparison with the other two systems. Namely, when it comes to the generation of the HC, pilot system III needed lower pressures at the entrance to the system to induce cavitation than pilot system I and II, which is particularly important for further use of the system on ships where the operation of the system is often directly related to the properties of the ship's pumps.

Moreover, for the same pressures at the entrance of the system in the case of all three systems, pilot system III reached considerably higher flow rates and velocities of the liquid inside the nozzles. While energy (the pressure) loss was similar for the pilot system II and III, pilot system III had slightly higher power consumption. Higher power consumption in case of tested pilot systems yielded considerably higher overall working efficiency of the system. Moreover, when the power consumption of our pilot system was calculated to the higher dimensions suitable for the treatment of ballast water on the ships, our pilot system is still among the systems with the lowest power requirements. Since our technology does not include additional chemicals or expensive processes such as UV or ozone, and its constructional requirements are simple and relatively cheap in comparison with other technologies, it is possible to place our system in the category of cost-effective systems.

Biological experiments with pilot system III were performed to assess the morphological changes and viability of copepods and *A. salina* cysts, as well as the growth potential of heterotrophic marine bacteria after the treatment at different time of treatment (15, 30 and 60 minutes for zooplankton and 30 and 60 minutes for bacteria).

The results of the biological experiments confirmed significant efficiency of the treatment because more than 98% of the copepods and *A. salina* cysts were destroyed compared to the initial population. The efficiency increased with the duration of the treatment or in combination with the separation phase for cysts. The results also showed that after 48 h of the incubation of the samples in the thermostatic chamber, the number of hatched nauplii in the samples that were treated with the pilot system for 60 minutes was low, regardless of whether the separation phase was used or not.

Furthermore, there was also a significant decrease in bacterial abundance and growth rate, since only 1.7 to a maximum 30% of bacteria were able to grow, compared to the initial population growth potential. The results of the biological research related to our pilot system were published in the article by Cvetković et al. (in press).

All the results of this research, which include review of the existing literature about the use and effects of HC with the emphasis on the ballast water treatment area, and which were expanded by the experimental hydraulic and biological results performed in our laboratories as part of the doctoral research, enhanced the confirmation of our hypothesis.

To the best of the author's knowledge, it was the first comprehensive study of the effect of hydrodynamic cavitation on destroying the copepods and at the same time heterotrophic marine bacteria in lab-scale conditions. Therefore, it is considered that this study contributed to making a step forward in the application of hydrodynamic cavitation in the area of ballast water treatment, but also in expanding general knowledge about hydrodynamic cavitation and its properties and effects on marine organisms.

5.2 Further research

International requirements and standards relating to BWM were defined due to the increasing concern of the introduction of IAS to new environments, which could negatively affect the marine ecosystem, as well as the global economy. The installation of the systems that are environmentally and economically acceptable and secure should become mandatory in less than one year. So far different technologies whose operation includes the use of harmful chemicals or expensive and work limited technologies such as UV were used for the ballast water treatment. A new ballast water treatment system, whose work includes the combination of hydrodynamic cavitation and separation phase without the use of additional chemicals or other expensive technologies, was developed as part of the doctoral dissertation and its effectiveness on marine organisms was examined thus far.

Since the newly developed pilot system showed high effectiveness on copepods, cysts, and marine bacteria, the technology seems to be prospective for further development for ballast water area, as well as for very different areas of use that include the destroying of various organisms or the sterilization process. Since the primary aim of the experiments that have been performed until now is the proof of the concept of newly developed ballast water treatment technology, we believe that additional lab-scale tests with the pilot system, in order to be tested in full-scale conditions, are needed. Further lab-scale tests should include experiments with detailed evaluation of phytoplankton viability after treatment, the repetition of the experiments with nauplii hatching, as well as tests with the pathogenic microorganisms.

The system is also planned to be tested in the full scale conditions, where the above described modular concept should be used. As the system has not theoretically shown any technical obstacles for use in any phases of the voyage of the ship (during loading, discharging of ballast water or sailing), the full scale tests should also confirm the most appropriate time for the treatment of ballast water with the newly developed system.

SUMMARY

Apart from hull fouling and aquaculture, ballast water is considered as one of the most important vectors of transportation of invasive alien species (IAS) in aquatic ecosystems. Its harmful effects are recognized in all world seas, causing considerable economic, ecological and environmental consequences. With the aim of controlling and preventing further spread of invasive organisms, international regulations and guidelines related to the Ballast Water Management (BWM) issues were prepared. Such international regulation with a wide global application is IMO's "International Convention for the Control and Management of Ships' Ballast Water and Sediments".

In accordance with the requirements of IMO's Convention, very different technologies were approved for ballast water treatment on ships. Their working process frequently includes the use of the ultraviolet irradiation, de-oxygenation, heat treatment, ozonation, biocides and acoustic cavitation, by itself or in different combinations. Many of the existing technologies on the market have their advantages and disadvantages: usually environmentally dangerous effects, high installation costs, high energy consumption, complexity, etc. While the physical technology hydrodynamic cavitation proved to be effective in breaking the cells of many unicellular or multicellular organisms, which makes it widely used technology in the science, engineering and different industrial processes, it was still insufficiently explored and applied for the ballast water treatment area.

Based on the aims and hypotheses of the doctoral dissertation, the main contribution of the dissertation was research that should confirm the possibilities of application of hydrodynamic cavitation in ballast water treatment area, particularly without the combination with any environmentally harmful chemicals. As a part of the research, the key parameters that should affect effectiveness of the systems which use hydrodynamic cavitation as a main step of their operation and advancing their efficacy were determined. During the research, the constructional characteristics of the system which is supposed to be capable for the operation of high flow rates, and at the same time the demanding conditions of ships were also considered.

To confirm the hypotheses, three different pilot systems were developed so far and their hydraulic characteristics were tested. Experiments with the newly developed systems were divided into two phases: the first phase, verification of the working concept and adapting the key performances of the pilot systems that was performed at the Hydraulic laboratory of UL FGG, and the second phase, evaluation of the biological efficiency of the pilot system III, which according to the analyzed results showed the highest operating effectiveness. Both phases were carried out at the Marine Biology Station Piran.

The results of the biological experiments certified that the new ballast water treatment system provides an effective solution for destroying tested marine organisms - zooplankton, cysts and heterotrophic bacteria. In experiments with zooplankton, only 15 minutes of treatment was sufficient for significant decrease of the number of living copepods present in the samples (99.4% copepods were destroyed), while the 30 minute long treatment succeed to destroy all of the copepods. In the treatment of the *A. salina* cysts, the cavitation treatment alone or in combination with the separation phase was used. By the end of the experiments (60 minutes) 90.2% of cysts were destroyed using cavitation, and 98.2% of cysts were destroyed with the combination of cavitation and separation phase. The experiments where cavitation together with the separation phase was used had a better effect not only on breaking the cysts, but also on the required time - after only 30 minutes of the treatment same results were achieved as after 60 minutes of treatment using only cavitation. There was also considerable impact of the treatment on hatching of the nauplii, since after 48 h incubation of the treated samples with *A. salina* cysts only a few nauplii hatched. Furthermore, the experiments also showed a considerable impact of the treatment on natural population of heterotrophic bacteria, since the number of bacteria and BCP decreased after 30 and 60 minutes of the exposure to the treatment.

The newly developed ballast water treatment system satisfied the conditions for the generation of the hydrodynamic cavitation at relative low pressures at the entrance to the system (at already 1.5 bar) and at the same time achieved relative high flow rates, for which it needed the same or even lower power than in existing similar systems. Moreover, the new technology did not use any chemicals or active substances for its operation, which makes it safe for the crew and the environment. It has been theoretically proven that the technology is easily adaptable to full scale conditions where the large amount of the ballast water needs to be treated. Furthermore, laboratory tests confirmed that such system can be highly effective when it comes to the destruction of different marine organisms. Based on the aforementioned facts, it follows that the aims and hypotheses set at the beginning of this research were completely fulfilled.

POVZETEK

Poleg obraščanja ladijskih trupov in izvorov pri ribogojstvu so balastne vode med najpomembnejšimi dejavniki raznašanja invazivnih tujerodnih vrst v vodnih ekosistemih po svetu (David et al., 2013). V Sredozemskem morju je bilo na seznam takšnih vrst uvrščenih že več kot 986 neavtohtonih vrst (NIS, angl. IAS) (Zenetos et al., 2012), vendar pa je bilo le 12 vrst neposredno povezanih z ladijskim prometom. Kljub temu domnevamo, da je pomorstvo, prek balastnih voda ali obraščanja ladijskih trupov, vseeno pomemben vzrok za uvrstitev nadaljnjih 300 tujerodnih vrst na ta seznam.

Svetovni letni izpusti balastnih voda se za leto 2013 ocenjujejo na približno 3,1 milijarde ton (David, 2014). Ladijski balastni rezervoarji lahko prenesejo vsaj 10.000 različnih vrst (Faimali et al., 2006), med katerimi najdemo različne vrste tujerodnih organizmov, kot so vretenčarji, nevretenčarji, rastline in bakterije (Ruiz et al., 2000; Mimura et al., 2005; Khandeparkar in Anil, 2013). Vdor organizmov, povezanih z balastnimi vodami, postaja vse bolj ireverzibilen proces, kar pogosto negativno vpliva na vodne ekosisteme (Endresen et al., 2004; Migetalke in Abdulla, 2005; Migetalke et al., 2007; Gollasch, 2007; Kang et al., 2010). Poleg tega takšno širjenje deluje tudi kot mehanizem razpršitve različnih človeških patogenov, kot je npr. *Vibrio cholerae* (Seiden in Rivkin, 2014), zato so pomemben vir nevarnosti oz. ekoloških in človeških tveganj.

Eden najpomembnejših mednarodnih predpisov za ravnanje z balastnimi vodami (angl. Ballast Water Management, krajše BMW) je Konvencija za nadzor in ravnanje z ladijskimi balastnimi vodami in sedimenti (t. i. konvencija BWM), ki je nastala pod okriljem Mednarodne pomorske organizacije (angl. International Maritime Organisation - IMO). Konvencija ureja načine in metode za izpust balastnih voda in obenem predpisuje potrebne načine ravnanja z balastnimi vodami (IMO, 2004; Bakalar, 2014; IMO, 2014; Lloyd Register, 2014).

Standard o izmenjavi balastnih voda (angl. Ballast Water Exchange - BWE, uredba D-1) vsebuje smernice in zahteve za ladje, ki naj bi izpolnjevale pogoje za učinkovito izmenjavo balastnih voda z oceanskimi vodami (Andresen et al., 2004; ABS, 2010). V skladu z uredbo D-2 konvencije lahko ladje spustijo balastne vode, ko koncentracije organizmov velikih 50 μm ali več znašajo manj kot 10 živih organizmov v m^3, manj kot 10 živih organizmov po mL v velikosti med 50 in 10 μm, in manj, kot znašajo posebej predpisane koncentracije za indikatorske mikroorganizme (*Vibrio cholerae*, *Escherichia coli* in črevesni enterokoki).

Glede na to, da je konvencija BMW sicer pripravljena, a zaradi premajhnega števila držav podpisnic še ni začela veljati, je izmenjava balastnih voda z oceanskimi še vedno najbolj razširjeni način ravnanja z balastnimi vodami. Ta način sicer omejujejo določene varnostne zahteve in geografski pogoji, kljub temu pa to ni dovolj učinkovita zaščita vodnih ekosistemov pred tujerodnimi organizmi. Čeprav naj bi izmenjava balastnih voda z oceanskimi zmanjšala vnos nekaterih vrst planktona tudi za od 80 do 95 % (Seiden in Rivkin, 2014), ta način ni dovolj učinkovit pri zmanjševanju števila bakterij (Seiden et al., 2011; Drake et al., 2007; Hess-Erga et al., 2010; Fykse et al., 2012).

Različne študije poročajo o številčnosti heterotrofnih bakterij in virusov v balastnih vodah (Gollasch et al., 2000a; Ruiz et al., 2000; Burkholder et al., 2007; Ma et al., 2009;. Seiden et al., 2010; Seiden et al., 2011; Seiden in Rivkin, 2014) in prav tako o spremembah v sestavi mikrobnih združb (Drake et al., 2007; Mimura et al., 2005; Seiden et al., 2010; Seiden in Rivkin, 2014; Tomaru et al., 2010). Spremembe v sestavi mikrobne združbe je treba raziskovati za izboljšanje razumevanja morebitnih nevarnosti oz. tveganj, povezanih s prenosom mikroorganizmov v balastnih vodah, in zaradi kompleksnosti ravnanja z balastnimi vodami.

Raziskovalci si prizadevajo razviti različne tehnologije obdelave balastnih voda, da bi odkrili ustrezne načine, ki bi čim bolj zmanjšali tveganja zaradi pojava neželenih vdorov tujerodnih organizmov. Na tržišču obstajajo različni sistemi za obdelavo balastnih voda, z različnimi tehnologijami, ki se uporabljajo samostojno ali v kombinaciji z drugimi tehnologijami (Perrins et al., 2006; McCollin et al., 2007; Holm et al., 2008; Gregg et al., 2009; Liebich et al., 2012; IMO, 2014; Lloyd register, 2014). Večina teh tehnologij ima podobne prednosti in slabosti: tveganja za okolje, visoki obratovalni stroški, visoka poraba energije, kompleksnost postrojenja, težave pri vgradnji in navezavi na naprave v omejeno dosegljivih prostorih na ladjah, celo nezmožnost uničevanja nekaterih skupin organizmov in podobno (Gregg et al., 2009; Werschkun et al., 2014).

Ena izmed razmeroma novih metod, ki se uporablja pri obdelavi balastnih voda, je hidrodinamična kavitacija (Sawant et al., 2008; Cvetković et al., 2015). Kavitacija je fizikalni pojav, ki se zgodi v trenutku, ko pride do hitrih sprememb tlaka v tekoči vodi ali drugi tekočini (Jyoti in Pandit, 2001; Gogate in Pandit 2004; Al-Jubouri, 2010; Zupanc et al., 2013). Pri hitrih spremembah tlaka v tekočini, ta svoje stanje spremeni iz tekočega v plinasto in nato nazaj v tekoče stanje. Pri tem se pojavijo udarni valovi kot posledica znatnih količin ujete energije, ki se sprošča iz razpadlega mehurčka.

Kavitacija je lahko zelo uničujoča, zato je bila v preteklosti večinoma obravnavana kot nezaželen pojav (Knapp et al., 1970), ki lahko poškoduje različne površine, kot so ladijski propelerji, črpalke, ventili in cevi (Brennen, 1995; Brujan, 2011), saj na njih nastaja erozija, ki jo spremljajo vibracije in hrup (Kuiper, 2012; Moussou, 2004). V primerjavi z akustično kavitacijo, ki nastaja kot posledica prehoda ultrazvočnih valov skozi medij, hidrodinamična kavitacija nastaja kot posledica spreminjanja hitrosti toka (in s tem povezanimi spremembami lokalnega tlaka) tekočine, zato se lahko pojavlja pri spremembah geometrije ostenja, ki narekujejo tokovne razmere v tekočini (Arranjo in Benito, 2008; Gogate in Pandit, 2011; Joty in Pandit, 2001; Moholkar et al., 1999).

Na nastanek in različno jakost akustične in hidrodinamične kavitacije vplivajo trije ključni parametri (Moholkar et al., 1999):

a. intenzivnost in frekvenca ultrazvoka pri akustični kavitaciji,
b. obnovitveni tlak v tekočini, v območju dolvodno od ustja pri hidrodinamični kavitaciji, in
c. čas, potreben za ponovno zvišanje tlaka pri hidrodinamični kavitaciji.

Številne študije so dokazale, da so sistemi, katerih obratovanje temelji na hidrodinamični kavitaciji, učinkovitejši od sistemov, ki uporabljajo akustično kavitacijo (Gogate 2002; Joty in Pandit 2011; Moholkar et al., 1999; Chivate in Pandit, 1993; Pandit in Joshi, 1993). Na primer sistemi, ki uporabljajo hidrodinamično kavitacijo, so običajno energetsko precej učinkovitejši od sistemov, ki uporabljajo akustično kavitacijo. Energetska učinkovitost različnih hidrodinamičnih sistemov je med 54 % in 60 %, medtem ko je energetska učinkovitost različnih akustičnih sistemov med 3 % in 43 % (Arranjo in Benito, 2008; Chivate in Pandit, 1993; Gogate, 2002; Jyoti in Pandit, 2001; Pandit in Joshi, 1993). Poleg energetske učinkovitosti pa študije poročajo tudi o drugih prednostih hidrodinamične kavitacije pred akustično kavitacijo (Moholkar et al., 1999; Jyoti in Pandit, 2001): veliko preprostejša oprema, preprostost vzdrževanja, relativno enostavna nadgradnja (povečanje kapacitete) procesa itn.

Kljub dejstvu, da hidrodinamična kavitacija uničuje celice enoceličnih ali večceličnih organizmov in zato predstavlja dobro znano in razširjeno metodo v znanosti, inženirstvu in različnih industrijskih procesih (Gogate, 2002, Sawant et al., 2008; Brujan, 2011; Ozonek, 2012), pa je ta še vedno premalo raziskana in se premalo uporablja na področju obdelave balastnih voda. Do sedaj je le nekaj avtorjev (Kato, 2003; Sawant et al., 2008; Renade et al., 2009) izvedlo laboratorijske eksperimente z različnimi pilotnimi napravami v različnih delovnih pogojih, da bi določili učinkovitost hidrodinamične kavitacije pri uničevanju različnih vrst morskih organizmov.

Doslej je Uprava za vgradnjo sistemov na ladje odobrila le štiri vrste sistemov za obdelavo balastnih voda, ki v svojem obratovalnem procesu uporabljajo hidrodinamično kavitacijo (IMO, 2014; Lloyd register, 2014; Cvetković et al., 2015), pa še ti sistemi uporabljajo kavitacijo predvsem kot en korak obdelave, pri čemer se kavitacija običajno kombinira še z uporabo različnih kemikalij, ki naj bi povečale učinkovitost obdelave. Čeprav izpolnjujejo pogoje, ki jih določa IMO, pa ti načini, predvsem zaradi dodajanja kemikalij, lahko negativno vplivajo na okolje (vpliv na morske organizme), na gospodarnost (visoki stroški vzdrževanja, visoka poraba energije) in varnost pri obratovanju (potrebno je posebno izobraževanje posadke za ravnanje z napravami in kemikalijami) (Joo-Won, 2010; Lloyd's Register, 2014).

Na podlagi zgornjih ugotovitev, lastnih raziskav in idejne zasnove smo postavili glavne cilje doktorske disertacije in dosegli avtorske izvirne prispevke na področju obdelave balastnih voda. Ti cilji so naslednji:

a. Raziskati možnosti uporabe hidrodinamične kavitacije in narediti korak naprej pri uporabi hidrodinamične kavitacije za obdelavo balastnih voda;
b. Prepoznati/določiti optimalne konstrukcijske elemente, ki bi omogočali visoko učinkovit proces hidrodinamične kavitacije za poškodovanje oz. uničenje ciljnih (izbranih) morskih organizmov;
c. Dokazati enako ali celo večjo učinkovitost pilotnega sistema, ki uporablja zgolj hidrodinamično kavitacijo, tj. brez kombiniranja s katerimi koli aktivnimi snovmi v svojem delovanju, v primerjavi s sistemi za obdelavo balastne vode, ki uporabljajo hidrodinamično kavitacijo v kombinaciji z različnimi aktivnimi snovmi;
d. Razviti sistem za obdelavo balastnih voda, katerega delovanje na noben način ne bo vplivalo na morski ekosistem ali na zdravje ljudi;
e. Razviti energetsko učinkovit in varnostno sprejemljiv postopek obdelave, katerega značilnosti omogočajo prilagoditev na omejene delovne pogoje na ladjah (s posebnim poudarkom na nizkih delovnih tlakih, ki so neposredno odvisni od lastnosti že vgrajenih ladijskih črpalk).

Da bi upoštevali zgoraj naštete pogoje in cilje doktorske disertacije, smo v okviru doktorske disertacije najprej podrobno raziskali možnosti uporabe hidrodinamične kavitacije na področju obdelave balastnih voda, nato pa smo ključne parametre razvitega načina obdelave količinsko opredelili. Na podlagi teh izhodišč smo razvili učinkovitejši sistem, ki temelji na hidrodinamični kavitaciji brez dodajanja kemikalij, ki deluje tudi v zahtevnih, *in situ* ladijskih pogojih.

Raziskave za potrditev delovne hipoteze smo opravili na treh različnih pilotnih sistemih, na katerih smo najprej testirali njihove hidravlične značilnosti. Eksperimente z novo razvitimi sistemi smo razdelili v dve fazi. Prvo fazo, ki je obsegala preverjanje zasnove delovanja in opredelitev ključnih značilnosti pilotnih sistemov, smo opravili v hidravličnem laboratoriju na UL FGG. Druga faza raziskav pa je obravnavala biološko učinkovitost pilotnega sistem III, ki se je v prvi fazi izkazal kot najbolj učinkovit; to smo izvedli na Morski biološki postaji Piran.

Vsi trije pilotni sistemi so bili izgrajeni s kombinacijo pleksi stekla (osrednji del, cilindrični del in cev vrtinčnega nastavka) in jekla. Zasnova obratovalnega procesa pilotnih sistemov I in II je bila podobna, medtem ko smo pilotni sistem III zasnovali glede na hidravlične rezultate procesov v prvih dveh sistemih in je bil njegov delovni proces torej zasnovan drugače.

Znotraj ohišja pilotnih sistemov I in II je bila v smeri od vrha do dna ohišja vgrajena prozorna cev, t. i. cev vrtinčnega nastavka (6) (sliki 10 in 13). Ko voda tangencialno vstopa v sistem skozi vhod sistema na desni strani ohišja sistema (pravokotni prerez) (1), se vrtinči znotraj vrtinčnega nastavka (6). Zaradi centrifugalne sile je večina delcev z lastno gostoto, večjo od gostote vode, z vrtincem potisnjena k steni sistema. Delci potem naprej drsijo navzdol ob steni in so izvrženi skozi izhod na dnu sistema (4). Preostanek delcev z gostoto, večjo od gostote vode, ki še niso bili izvrženi na dnu sistema, zajame skupaj z delci z nižjo gostoto od gostote vode notranje vrtinčenje in nato prehajajo skozi vrtinčni nastavek (6) v odvodno cev (zgornji izhod), (5) umeščeno na vrhu pilotnega sistema. Ob koncu vrtinčnega nastavka je postavljena šoba z eno ali več lukenj, ki je v posameznih poskusih imela različne premere in obliko. Na mestu, kjer voda prehaja skozi šobo, prihaja do hidrodinamične kavitacije (slika 10). Razlog za njen nastanek je nenadno povečanje hitrosti pretoka vode čez zoženje, kar je posledica oblike šobe na vhodu v vrtinčni nastavek. Zaradi povečanja hitrosti pretoka vode pa se na mestu zoženja pojavlja nenadni padec tlaka (glej enačbo 2).

Čeprav je zasnova delovnih procesov v pilotnih sistemih I in II ostala nespremenjena, smo za večji učinek na pilotnem sistemu II naredili nekaj konstrukcijskih sprememb:

a. Zožitev vhodnega dela, da bi dosegli večji pospešek vode na vhodu v sistem;
b. Da bi omogočili lažje dviganje in izstop zračnih mehurčkov in delcev z gostoto, ki je nižja od gostote vode, je bila pravokotna geometrija zgornjega dela sistema (kjer je izstopna cev iz sistema) spremenjena v kupolasto obliko.

Pri tretjem pilotnem sistemu voda tangencialno vstopa v sistem istočasno in v isti osi, a v nasprotni smeri, skozi zgornji (1) in spodnji (2) vhod sistema (pravokotni prerez) in se zaradi centrifugalne sile vrti okoli zgornjega (7) in spodnjega dela (6) vrtinčnega nastavka. Posledično se oblikujeta dva vodna vrtinca (zgornji in spodnji), ki pa se združujeta v območju med vrtinčnima nastavkoma (6 in 7). Združitev vrtincev povečuje hitrosti vrtenja vodnega curka in posledično disperzijo delcev z gostoto, večjo od gostote vode, v smeri proti steni cilindričnega ohišja (5) (t. i. ločevalnik). Vsi delci z gostoto, večjo od gostote vode, so potisnjeni navzdol, proti stenam ohišja sistema in drsijo navzdol, do izhoda na dnu sistema (4). Ob koncu obeh vrtinčnih nastavkov sta postavljeni šobi (8 in 9), po ena šoba za vsak vrtinčni nastavek, ki sta pri poskusih imeli luknje različnih premerov in geometrij. Ko voda teče skozi šobo (8 in 9), se pojavi hidrodinamična kavitacija. Delci z gostoto, manjšo od gostote vode, so zajeti z vrtincem in so po prehodu skozi šobe, kjer se pojavlja hidrodinamična kavitacija, naprej potisnjeni skozi notranji del vrtinčnih nastavkov (6 in 7) (na zgornji in spodnji cevi), potem pa odhajajo iz sistema skozi zgornji oz. spodnji izhod (3 in 4). Hkrati skozi zgornji izstop iz sistema (3), skupaj z delci z gostoto, nižjo od gostote vode, izhajajo še zračni mehurčki iz sistema. Po prehodu območja s kavitacijo se obdelana voda vrne nazaj v rezervoar, iz katerega se, če je potrebna večkratna obdelava, ponovno vrača v pilotni sistem.

Sistem lahko deluje s fazo ločevanja ali brez nje (z vklopom/izklopom ločevalnika), kar se izvaja s pomočjo ventilov (odprt ventil pomeni vključen proces ločevanja).

Pri vseh poskusih v skupini C, tj. s pilotnim sistemom III, smo uporabili šobo z eno luknjo premera d_1 = 16 mm (slika 11). Ostali premeri šobe, tj. d_2 = 49,5 mm, d_3 = 51,5 mm in d_4 = 10 mm, so bili nespremenjeni za vse eksperimente skupine C. Razlike med posameznimi eksperimenti v skupini C smo dosegli z nastavitvijo razdalje med šobama (L_x) (preglednica 17), s spreminjanjem odprtosti zgornjih in spodnjih ventilov sistema in z vstavljanjem jeklene plošče z luknjo v območje med šobama oz. med vrtinčna nastavka (Slika 17 c). Vsi ostali tehnični pogoji izvajanja eksperimentov so bili enaki za vse eksperimente skupine C.

Da bi izboljšali učinkovitost zasnovanega sistema, je bil zgrajen še pilotni sistem III, katerega tehnologija obratovanja nadgrajuje tehnologiji, uporabljeni v predhodnih dveh sistemih. Konstrukcijske značilnosti pilotnega sistema III se v bistvu razlikujejo od tistih v sistemih I in II v naslednjem:

a. Ohišje pilotnega sistema, ki je bilo prej zasnovano v obliki hidrociklona, smo nadomestili z novim v obliki ločevalnika (separatorja). Osnovna funkcija ohišja pilotnega sistema, to je ločevanje delcev z gostoto, večjo od gostote vode, je ostala enaka;
b. Da bi povečali hitrosti vodnega toka v vrtincu, smo pilotni sistem nadgradili z dodatnim, novim vhodom, torej ima pilotni sistem III dva simetrična tangentna vhoda (zgornjega in spodnjega) in prav tako dva izhoda (zgornjega in spodnjega);
c. Da bi izboljšali intenzivnost oz. učinek hidrodinamične kavitacije v sistemu, sta zdaj dva vrtinčna nastavka nameščena simetrično, eden nasproti drugemu na razdalji, ki je bila določena z vhodnimi parametri v sistemu za posamezno serijo poskusov.

V vsakem posameznem naboru poskusov znotraj skupine eksperimentov A in B so se spreminjale lastnosti šob z različnimi oblikami in dimenzijami. Pri tem so bili merjeni naslednji parametri: temperatura zraka (T_{zraka}), temperatura vode (T_{vode}), pretok (Q_0), zračni tlak (p_0), tlak na vhodu tekočine v sistem (p_1), tlak v kotanji sistema (p_5), tlak na notranjem ostenju sistema (p_6), tlak na ostenju vrtinčnih nastavkov (p_7), tlak na mestu nastanka hidrodinamične kavitacije (p_8), tlak na odvodni cevi (p_9) in tlak na izstopni cevi (p_{10}).

Merjeni parametri za pilotni sistem III so bili delno enaki. Zaradi spremembe v konstrukciji sistema pa smo dodatno merili vrednosti tlakov na naslednjih delih sistema: tlak med šobami (p_2), tlak na spodnjem izstopu iz sistema (p_3), tlak na zgornjem izstopu iz sistema (p_4), tlak na ostenju vrtinčnih nastavkov (p_5), tlak na notranjem robu spodnje šobe (p_6), tlak na zunanjem robu spodnje šobe (p_7), tlak na notranjem robu zgornje šobe (p_8) in tlak na zunanjem robu zgornje šobe (p_9).

Za vse tri sisteme smo z uporabo enačb št. 1, 3, 7, 14, 15, 16 izračunali naslednje teoretične vrednosti: površina šobe (S), površina vrtinčnih nastavkov (S_{cevi}), hitrost vode v odvodni cev ($v_{\text{odvodne cevi}}$), hitrost vode znotraj šobe ($v_{\text{šobe}}$), kavitacijsko število (σ), relativna debelina (α), število toka (β), izguba tlaka (Δp) in poraba energije (P).

Po izračunanih teoretičnih vrednostih je izmed treh raziskanih sistemov najboljše hidravlične lastnosti delovnega procesa pokazal pilotni sistem III. Šoba z eno luknjo premera 16 mm in brez dodatnih nastavkov je pokazala najboljše rezultate glede na vse izvedene eksperimente na vseh treh pilotnih sistemih. Zato smo to šobo izbrali za nadaljevanje eksperimentov, tj. za drugo, biološko fazo eksperimentalnega dela, v kateri smo raziskali učinkovitost pilotnega sistema pri uničevanju izbranih morskih organizmov.

Glavne rezultate primerjave delovanja pilotnih sistemov I, II in III oz. izmerjenih vrednosti pri poskusih iz skupin A, B in C, v katerih je bila uporabljena ista šoba (tj. šoba z eno luknjo premera 16 mm brez dodatkov), povzemamo v preglednici 23. Primerjavo smo izvedli med podskupinami znotraj poskusov A, B in C, pri katerih se je zaradi zagotavljanja primerljivosti ročno nastavljalo približno enake vrednosti tlaka na vhodu v sistem za vse tri pilotne sisteme. To pomeni, da so bili vrednosti pretoka (Q_0), kavitacijski števili (σ_1 in σ_2), razlike tlaka (Δp) in poraba energije (P) izmerjeni za vrednosti tlaka na vhodu v sistem po naslednjem zaporedju: p_1 ~ 1,5 bar, p_1= 2 bar in p_1= 3,75 bar, za vse tri skupine eksperimentov.

V primeru enakega tlaka na vhodu v sistem, ki je znašal okoli 1,5 bar, preglednica 23 pokaže, da je pilotni sistem III deloval s skoraj 3 m^3/h višjimi pretoki kot pilotna sistema I in II. Prav tako se izkaže, da tlak na vhodu v sistem okoli 1,5 bar ni dovolj visok, da bi povzročil nastanek hidrodinamične kavitacije v ohišju sistemov I in II. Enak tlak na vhodu pilotnega sistema III pa je zadoščal za pridobivanje hidrodinamične kavitacije v sistemu.

Čeprav smo enako šobo uporabili v poskusih B4 in C4, pa slika 34 pokaže precejšnje razlike v vrednosti parametrov (Q_0 in $v_{\text{šobe}}$) pri opravljenih poizkusih. Medtem ko pretok v eksperimentu B4 ni presegel vrednosti 11,6 m^3/h pri vrednosti tlaka 3,76 bar na vhodu v sistem (p_1), pa je bil najvišji doseženi pretok za eksperiment C4 pri skoraj enaki vrednosti tlaka 3,75 bar na vhodu v sistem (p_1) kar za 5 m^3/h (16,30 m^3/h) višji kot v eksperimentu B4 (slika 34a, preglednica 23). Podobno zvezo opazimo med vrednostmi hitrosti tekočine v šobi ($v_{\text{šobe}}$) za poskusa B4 in C4, kjer je bila za enako vrednost vhodnih tlakov (okoli 3,75 bar) hitrost v šobi pri poskusu C4 bistveno višja (22,5 m/s) kot pri poskusu B4 (16,1 m/s) (slika 34b, preglednica 23).

Ko gre za izmerjene razlike tlaka v sistemu (Δp), preglednica 23 pokaže, da sta pilotna sistema II in III v primeru uporabljenih enakih tlakov na vhodu v sistem obratovala s približno enakima razlikama tlaka. Sistem z največjo porabo energije je bil pilotni sistem III, ki pa je pri tem obratoval z znatno višjimi vrednostmi pretokov in večjimi hitrostmi tekočine v šobi v primerjavi z drugima pilotnima sistemoma (preglednica 23, slika 34). Večja poraba energije se je tako izkazala kot pogoj za pridobitev boljših rezultatov, tj. boljše učinkovitosti celotnega sistema.

Za nadaljevanje eksperimentalnega dela smo nato pilotni sistem III prestavili iz hidravličnega laboratorija UL FGG v Ljubljani na dvorišče Morske biološke postaje Piran (Nacionalni inštitut za biologijo). Eksperimentalno konstrukcijo pilotnega sistema za izvajanje poskusov, s katerimi bi ovrednotili biološko učinkovitost sistema, so sestavljali naslednji deli (slika 18): posode za shranjevanje morske vode (t. i. modelni ekosistem), centrifugalna črpalka, cevi za krožni tok vode in ohišja za hidrodinamično kavitacijo. Skupna količina morske vode, ki je bila obdelana v pilotnem sistemu, je bila 150 L (100 L v modelnem ekosistemu in 50 L v ohišju in ceveh). Morska voda iz modelnega ekosistema je bila po cevovodih črpana v ohišje za obdelavo vode (pilotni sistem III) (slika 18) in se je po vsakem zaključenem ciklu obdelave vračala nazaj v posodo.

Vrednosti ključnih parametrov pri delovanju pilotnega sistema so bile naslednje: tlak na vhodu v komoro se je gibal med 1,8 in 2,8 bar, pretok morske vode skozi sistem je bil pribl. 15 m^3/h, vsak cikel obdelave pa je trajal okrog 0,6 minute (glej enačbo 5). Celotna količina morske vode (150 L) se je pretočila skozi sistem v času trajanja enega poskusa, pri čemer je bilo za vsak poskus opravljenih 100 ciklov kavitacijske obdelave v eni uri (glej enačbo 4).

Učinkovitost pilotnega sistema za obdelavo balastne vode smo testirali na naravni populaciji planktonskih morskih organizmov (zooplankton in heterotrofne morske bakterije) v morski vodi, zajeti v Tržaškem zalivu (severno Jadransko morje). Pred vsakim eksperimentom so bili pilotni sistem in cevi (slika 18) napolnjeni s svežo morsko vodo (skupaj 150 L) s pomočjo laboratorijskega črpalnega sistema za dovod morske vode. Vzorce zooplanktona smo zbrali s planktonsko mrežo (velikost por 50 μm) na postaji 00BF (45° 32.93 N, 13° 33.03 E), nato pa dodali v taki količini, da je bila dosežena njihova testirana koncentracija v modelnem ekosistemu z morsko vodo.

Vzorci za analizo zooplanktona in cist so bili odvzeti iz posode (modelnega ekosistema) pred obdelavo (t0), po 15 minutah (t15), 30 minutah (t30) in po 60 minutah (t60) obdelave v vsakem poskusu. Za bakteriološke analize so bili odvzeti vzorci za iste časovne intervale, razen pri t15. Za vse analize in vsak korak obdelave so bili odvzeti vzorci v triplikatih. Poskuse smo izvedli med oktobrom 2013 in majem 2014. Skupno smo opravili pet raziskav z vzorci zooplanktona, šest raziskav s cistami *Artemia salina* (Crustacea, Anostraca) in šest raziskav, pri katerih smo ugotavljali spremembe v številčnosti bakterij in stopnji njihove rasti (bakterijska produkcija ogljika).

Separacijo kot način predobdelave (slika 18, črtkana črta) smo uporabili le pri poskusih s cistami, ki imajo lastno gostoto večjo od morske vode (Van Stanpen, 1996; Vos in de la Rosa, 1980). Za ostale testne organizme pa smo privzeli, da faza separacije ne bi bila dovolj učinkovita zaradi lastne gostote manjše od gostote vode ali pa zaradi njihove plovnosti.

Glede na to, da smo raziskave z zooplanktonom izvedli v različnih letnih časih, se je začetna številčnost zooplanktona bistveno razlikovala od poskusa do poskusa (Dodatek H). Rezultati vseh petih raziskav kažejo, da je številčnost preživelega zooplanktona (kopepodov) hitro padla po samo 15 minutah obdelave s kavitacijskim pilotnim sistemom, torej s 346,5 ± 216,3 na 2,53 ± 2,12 organizmov/L (Priloga H). To pa pomeni, da je bilo doseženih do 99,4 % poškodovanih organizmov (Priloga H).

Za določitev učinka obdelave s hidrodinamično kavitacijo pri cistah so bili izvedeni trije poskusi s cistami vrste *Artemia salina*. Število celih cist se je po 15 minutah obdelave z zasnovanim sistemom značilno znižalo s 527,3 ± 161,2 na 190,3 ± 130,0 organizmov/L (Priloga H). To pomeni, da je bilo doseženih do 66,7 % poškodovanih cist. Število nepoškodovanih cist se je v naslednjih minutah (do 60) obdelave še zmanjševalo in je na koncu obdelave znašalo le še 49,9 ± 23,4 organizmov/L, kar pomeni, da je bilo v vzorcih 90,2 % poškodovanih cist (Priloga H). Poleg tega smo s cistami *Artemia salina* izvedli še dodatne tri poskuse, pri katerih smo uporabili kombinacijo hidrodinamične kavitacije in predobdelave s postopkom ločevanja (separacije). Rezultati so pokazali, da je pri teh treh eksperimentih število celih cist padlo z začetnih 560,4 ± 174,1 na 152,8 ± 102,6 organizmov/L v prvih 15 minutah obdelave, nato pa se je število še naprej zmanjševalo na komaj 8,4 ± 5,9 organizmov/L po 60 minutah obdelave vzorcev morske vode s cistami (Priloga H). Torej je bilo po 15 minutah poškodovanih do 69,9 % cist oz. je bilo po končanih 60 minutah obdelave vzorcev poškodovanih 98,2 % cist.

Ti rezultati dokazujejo, da je sistem še bolj učinkovit, če je v delovni proces sistema kot faza predobdelave vključena tudi faza ločitve (preglednica 24, 2-way ANOVA, faktorja »obdelava« (C in CS) in »čas« (t0, t15, t30, t60)).

Vzorci z bakterijami, pripravljeni za obdelavo s pilotnim sistemom, so vsebovali povprečno 0,9 do 3,1 x 10^8 bakterij/L v posodi (modelnem ekosistemu), kar smo upoštevali kot začetno koncentracijo pred obdelavo. To število približno sovpada s povprečnimi mesečnimi koncentracijami bakterij v Tržaškem zalivu v jesenskem obdobju (Tinta et al., 2015).

Po 60 minutah obdelave s pilotnim sistemom se je število bakterij zmanjšalo in je bilo v razponu od 0,26 do 0,92 × 10^8 celic/L, različno po posameznih poskusih (slika 40). Koncentracija bakterij je bila višja v drugem in tretjem poskusu, z začetno vrednostjo 3,1 × 10^8 celic/L. Pri teh poskusih je bilo obenem izmerjeno največje znižanje števila bakterij po končani obdelavi (t60). Število morskih bakterijskih celic se je zmanjšalo vse do 80 % (slika 40). Istočasno je bila merjena tudi stopnja rasti bakterij (BCP) z dodajanjem ^{3}H-levcina v novosintetizirane proteine v bakterijskih celicah (Kirchman et al., 1985) pri vseh podvzorcih. Stopnja bakterijske rasti se je spreminjala od začetne vrednosti 0,7 do 2,1 × 10^7 celic/liter/uro na začetku eksperimentov in ni presegla vrednosti 0,013 do 0,43 × 10^7 celic/liter/uro po končani obdelavi (slika 41).

V primerjavi z začetno stopnjo rasti se je po 60 minutah obdelave s kavitacijskim pilotnim sistemom BCP, ki je v povprečju znašala 86 %, znižala. V primerjavi s potencialom rasti bakterijske populacije rezultati pri vseh poskusih pokažejo, da je samo 1,7 % do največ 30 % bakterij lahko raslo naprej. Vendar pa je bila splošna učinkovitost obdelave vzorcev z zasnovanim sistemom v glavnem odvisna od časa trajanja obdelave.

Rezultati hidravličnih eksperimentov in prav tako nadaljevalni biološki testi o doseženi učinkovitosti novo izdelanega sistema potrjujejo, da je inovativni koncept lahko učinkovit kot zgolj kavitacijski sistem in da se lahko uspešno uporablja za uničevanje različnih vrst morskih organizmov. Poleg tega se je izkazalo, da na učinkovitost tehnologije pomembno vplivata tudi zasnova in oblikovanje elementov pilotnega sistema, kar pomeni, da še vedno ostajajo odprte možnosti za nadaljnje raziskave in izboljšanje tehnologije glede na trende, ki smo jih prepoznali v naših raziskavah.

Primerjava obstoječih laboratorijskih pilotnih sistemov za obdelavo balastne vode (Kato, 2003; IMO, 2006; Sawant et al., 2008; Ranade, 2009) in našega pilotnega sistema je bila zelo zahtevna, saj so nekateri ključni podatki o sistemih, opisanih v literaturi, nedosegljivi (npr. detajlni tehnični podatki, natančna prepoznava opazovanih organizmov, na primer planktona na splošno). Kljub temu pa je mogoče prikazati nekaj pomembnih prednosti našega sistema pred obstoječimi sistemi:

- V primerjavi s sistemom, ki ga je zasnoval Sawant s sodelavci (2008), je bila z našim sistemom dosežena približno 17 % večja poškodovanost zooplanktona. Za približno enako trajanje obeh obdelav (15 minut) smo namreč z našim sistemom dosegli poškodovanje približno 99,4 % zooplanktona v primerjavi s stopnjo, doseženo s sistemom Sawanta in sodelavcev (2008), ki je znašala do 82 % poškodovanosti prisotnega zooplanktona v vzorcih pri nastavitvi za 75 % odprte plošče šobe pilotnega sistema, kar je bil obenem njihov najvišji doseženi rezultat z navedeno pilotno napravo. Poleg tega je naš sistem dosegel bistveno višje količine pretoka (15 m^3/h) z uporabljenimi enakimi ali celo manjšimi delovnimi tlaki (1,8-2,8 bar) kot sistem Sawanta in sodelavcev (2008), ki so pri svojih poizkusih uporabljali tlak 2,9 bar za doseganje pretoka 4,68 m^3/h;

- Primerjava z rezultati laboratorijskega sistema, ki so ga zasnovali Ranade in sodelavci (2009), pokaže, da naš sistem doseže približno 23 % večja znižanja števičnosti morskih bakterij in obenem enako učinkovitost poškodovanega zooplanktona (več kot 99 % pri obeh sistemih). Najboljši doseženi rezultat Ranade in sodelavcev (2009) pri redukciji bakterijskih celic je bil 46 %, za kar so potrebovali tlak 6,9 bar in pretoke 2,95 m^3/h. Naš sistem pa je bil uspešen tako pri zmanjšanju števila bakterijskih celic kot pri inhibiciji bakterijske rasti, z uporabo bistveno nižjih delovnih tlakov (1,8-2,8 bar) in doseženim bistveno večjim pretokom (15 m^3/h);

- Primerjava s sistemom, ki so ga zasnovali Kato in sodelavci (2003), pokaže, da je naš pilotni sistem poškodoval večino cist *Artemia salina* med izpostavljenostjo vhodnemu tlaku v sistem, ki je bil v razponu med 1,8 in 2,8 bar in s pretokom 15 m^3/h, medtem ko je laboratorijski sistem Katoa s sodelavci (2003) potreboval bistveno višji tlak (10 bar) in imel občutno manjšo količino pretoka (1,13 m^3/h). Po njihovih navedbah so dosegli le delno učinkovitost pri poškodbi cist, žal pa v omenjenem besedilu odstotek učinkovitosti ni bil podan.

Kljub visoki učinkovitosti novega pilotnega sistema pri poškodovanju testiranih organizmov, zlasti kopepodov, kjer je že 30 minut obdelave zadostovalo za izpolnitev zahtev standarda D-2 v kategoriji organizmov $\geq$ 50 um, pa v tej fazi razvoja pilotnega sistema ni mogoče trditi, da bi testirani pilotni sistem lahko izpolnjeval vse omejitve iz standarda D-2. Čeprav je bila dosežena skoraj 99-% stopnja inaktivacije cist *Artemia salina*, pa je bila koncentracija testiranih organizmov v vzorcih še vedno prenizka (rezultati so bili izraženi v številu cist/10 ml, tj. 10^{-5} m^3), kar pomeni, da je bilo teoretično število cist *Artemia salina* še nekoliko prenizko, da bi bile izpolnjene zahteve iz standarda D-2. Nadaljnje izboljšave novega sistema in podrobnejši eksperimenti naj bi bili usmerjeni v eksperimente z višjimi koncentracijami različnih mikroorganizmov, poseben poudarek pa naj bi bil na eksperimentih s fitoplanktonom, zooplanktonom (kopepodi in ciste) in s patogenimi bakterijami.

Da bi sistem lahko zasnovali za prototipno velikost, tj. za uporabo na ladjah, bi ta moral imeti možnost modularne zasnove (slika 42). Natančneje, posamezni modul naj bi bil sestavljen iz več manjših enot, tj. takšnih, kot je bil preizkušani pilotni sistem. Točno število enot, vključenih v posamezni modul, bo odvisno od količine in pretoka balastne vode, ki bi jo bilo treba obdelati. Poleg tega pa bi modularna zasnova pilotnega sistema omogočala, da bi bil ta prilagodljiv na različne prostorske zahteve in tehnične omejitve na različnih tipih ladij. Zasedba prostora (tloris, »footprint«) testiranega pilotnega sistema s pretokom do 20 m^3/h (tj. ene enote modularnega sistema za obdelavo balastne vode) znaša 0,12 m^2. Če je takšnih pet enot povezanih v enem krožnem modulu, bi lahko modul obdelal pretok 100 m^3/h, pri tem pa bi zasedel približno 2,00 m^2 tlorisne površine (slika 42).

Izračunana tlačna razlika za eno enoto našega sistema za obdelavo balastnih voda, ki deluje s tlakom na vhodu v sistem 2,8 bar in s pretokom 15 m^3/h, znaša 1,63 bar. Glede na to, da naj bi bila modularna zasnova sistema za obdelavo balastnih voda sestavljena iz niza povezanih kavitacijskih enot brez medsebojnega vpliva, ki bodo napajane s skupno centrifugalno črpalko, naj bi razlika tlaka znotraj modularnega sistema ostala enaka za celotni sistem (Δp = 1,63 bar). Poraba energije za eno enoto takšnega modularnega sistema (testirani pilotni sistem) znaša 600 W, kar pomeni, da bi bila za celotni modul, sestavljen iz petih enot, potrebna moč 3 kW.

Vsi rezultati te raziskave, ki vključujejo pregled obstoječe literature o uporabi in učinkih hidrodinamične kavitacije s poudarkom na obdelavi balastnih voda in ki so pomembno razširjeni z rezultati hidravličnih in bioloških raziskav, opravljenimi v naših laboratorijih kot del doktorske raziskave, potrjujejo vse delovne hipoteze, zastavljene na začetku raziskovalnega dela.

Kolikor je znano avtorici te študije, gre za prvo celovito raziskavo o vplivu hidrodinamične kavitacije na poškodovanost predstavnikov zooplanktona in obenem heterotrofnih morskih bakterij v obsegu laboratorijskih pogojev. Zato menimo, da ta študija predstavlja pomemben napredek k uporabi hidrodinamične kavitacije na področju obdelave balastnih voda, hkrati pa ponuja nova znanja tudi o hidrodinamični kavitaciji ter njenih lastnostih in učinkih pri uničevanju/poškodovanju različnih morskih organizmov.

Novo razviti pilotni sistem je pokazal visoko učinkovitost pri uničevanju predstavnikov zooplanktona, cist in morskih bakterij, zato je ta tehnologija obetavna za nadaljnji razvoj in uporabo na področju balastnih voda. Prav tako je tehnologija uporabna na številnih različnih področjih, kjer je potrebno poškodovanje različnih mikroorganizmov oziroma postopek sterilizacije. Glavni cilj eksperimentov, ki so bili opravljeni do sedaj, je bil dokazati učinkovitost novo razvite delovne zasnove in novo razvite tehnologije obdelave balastnih voda.

V nadaljevanju bodo potrebni tudi dodatni laboratorijski poskusi z drugačnimi parametri in poskusi na prototipni velikosti razvitega pilotnega sistema. Pri preizkušanju prototipnih rešitev bodo obravnavani še širši, dejanski obratovalni pogoji na plovilu in pogoji obratovanja zgoraj opisane modularne zasnove. Zasnovani sistem teoretično ne kaže tehničnih ovir za uporabo v vseh fazah potovanja ladje (med plovbo, v času natovarjanja ali praznjenja balastnih voda iz rezervoarjev), zato naj bi s prototipnimi poskusi preučili tudi najprimernejši čas za obdelavo balastnih voda z novo razvitim sistemom.

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Appendix A: Extended Table 10 with all the values of main parameters measured in set A of experiments with pilot system I

Priloga A: *Razširjena Tabela 10 z vsemi vrednostimi glavnih parametrov izmerjenih v skupini A eksperimentov z pilot sistemom I*

Experiment	T_{air}	T_{water}	Q_0 [m^3/h]	p_0 [bar]	p_1 [bar]	p_2 [bar]	p_3 [bar]	p_4 [bar]	p_5 [bar]	p_6 [bar]
A1	20.40	19.03	2.77	0.98	1.44	1.44	0.98	1.44	0.98	0.97
A2	20.50	19.03	2.74	0.98	1.44	1.50	1.02	1.44	0.98	1.05
A3	20.10	19.03	2.72	0.98	1.44	1.43	0.99	1.44	1.00	0.75
A4	20.10	19.03	2.62	0.98	1.44	1.44	0.99	1.44	0.98	0.93
A5	20.40	19.03	4.57	0.98	1.43	1.41	1.90	1.43	0.84	0.69
A6	20.10	19.03	4.00	0.98	1.43	1.42	0.99	1.44	0.99	0.56
A7	20.10	19.03	5.96	0.98	1.42	1.41	0.99	1.42	0.91	0.64
A8	20.40	19.03	4.55	0.98	1.43	1.41	0.99	1.43	1.00	0.98
A9	20.00	19.43	5.55	0.98	1.42	1.40	0.78	1.42	0.74	0.62
A10	20.10	19.03	5.40	0.98	1.42	1.40	0.90	1.43	0.85	0.74
A11	20.10	19.03	8.88	0.98	1.38	1.34	0.82	1.39	0.75	0.72
A12	21.00	19.43	8.92	0.98	1.38	1.33	0.83	1.39	0.74	0.59
A13	20.00	19.03	8.50	0.98	1.39	1.36	0.76	1.40	0.74	0.78
A14	20.10	19.03	8.34	0.98	1.40	1.36	0.82	1.37	0.74	0.77

Appendix B: The values of main parameters measured in set B of experiments with pilot system II

Priloga B: *Vrednosti glavnih parametrov merjenih v skupini B eksperimentov z pilot sistemom II*

Experiment	T_{air}	T_{water}	Q_0 [m^3/h]	Q_0 [l/s]	p_0 [bar]	p_1 [bar]	p_5 [bar]	p_6 [bar]	p_8 [bar]	p_9 [bar]	p_{10} [bar]	Δ p_7-p_8 [bar]
B1.1	21.30	19.40	0.00	0.00	0.98	1.06	1.04	1.04	1.05	1.06	1.04	0.07
B1.2	21.30	19.40	0.00	0.00	0.98	1.30	1.23	1.23	0.92	0.82	0.99	0.02
B1.3	21.30	19.40	0.00	0.00	0.98	1.50	1.46	1.47	0.91	1.01	0.95	-0.01
B1.4	21.30	19.40	4.40	1.22	0.98	1.92	1.90	1.92	0.77	0.92	1.01	-0.18
B1.5	21.70	19.40	4.85	1.35	0.98	2.29	2.26	2.26	0.71	1.05	1.05	-0.25
B1.6	21.70	19.40	5.43	1.51	0.98	2.64	2.59	2.62	0.62	1.06	1.07	-0.34
B1.7	21.70	19.40	5.79	1.61	0.98	2.96	2.92	2.94	0.59	1.11	1.11	-0.46
B1.8	21.70	19.60	6.50	1.81	0.98	3.53	3.46	3.51	0.56	1.15	1.16	-0.49
B1.9	21.60	19.60	6.70	1.86	0.98	3.74	3.65	3.70	0.53	1.17	1.16	-0.53
B1.10	21.60	19.60	6.66	1.85	0.98	3.86	3.81	3.85	0.54	1.19	1.20	-0.56
B2.1	20.90	19.50	0.00	0.00	0.98	1.08	1.08	1.08	1.08	1.09	1.08	0.02
B2.2	20.90	19.50	0.00	0.00	0.98	1.16	1.15	1.14	1.07	1.07	1.08	0.01
B2.3	20.90	19.50	0.00	0.00	0.98	1.46	1.47	1.47	0.99	0.99	1.08	-0.03
B2.4	20.90	19.50	0.00	0.00	0.98	2.03	2.01	2.01	0.86	1.08	1.08	-0.11
B2.5	20.90	19.50	0.00	0.00	0.98	2.34	2.31	2.32	0.77	1.08	1.08	-0.16
B2.6	20.80	19.60	4.65	1.29	0.98	2.50	2.47	2.49	0.73	1.09	1.09	-0.21
B2.7	20.80	19.60	5.25	1.46	0.98	2.91	2.88	2.89	0.58	1.10	1.11	-0.40
B2.8	20.80	19.60	5.94	1.65	0.98	3.49	3.46	3.47	0.44	1.13	1.14	-0.61
B2.9	20.80	19.50	6.22	1.73	0.98	3.67	3.64	3.66	0.34	1.16	1.16	-0.64
B2.10	21.20	19.60	6.30	1.75	0.98	3.82	3.79	3.82	0.30	1.19	1.18	-0.68
B2.11	21.20	19.60	6.50	1.81	0.98	3.90	3.87	3.88	0.30	1.17	1.17	-0.73
B3.1	21.60	19.20	0.00	0.00	0.97	1.17	1.17	1.17	1.17	1.17	1.17	0.00
B3.2	21.60	19.20	0.00	0.00	0.97	1.58	1.51	1.52	1.01	1.13	1.13	-0.10
B3.3	21.60	19.20	6.10	1.69	0.97	2.01	1.97	2.01	0.72	1.12	1.12	-0.31
B3.4	21.60	19.20	7.40	2.06	0.97	2.54	2.44	2.50	0.60	1.10	1.10	-0.44

Appendix B(continued)

Experiment	T_{air}	T_{water}	Q_0[m^3/h]	Q_0 [l/s]	p_0 [bar]	p_1 [bar]	p_5 [bar]	p_6 [bar]	p_8 [bar]	p_9 [bar]	p_{10} [bar]	Δp_7-p_8 [bar]
B3.5	21.60	19.30	8.70	2.42	0.97	3.13	3.03	3.09	0.51	1.18	1.19	-0.56
B3.6	21.70	19.30	9.42	2.62	0.97	3.57	3.46	3.53	0.48	1.29	1.29	-0.70
B3.7	21.70	19.30	9.93	2.76	0.97	3.99	3.85	3.96	0.47	1.38	1.38	-0.76
B4.1	20.80	19.40	0.00	0.00	0.99	1.09	1.09	1.09	1.09	1.09	1.09	0.00
B4.2	20.80	19.40	0.00	0.00	0.99	1.18	1.17	1.17	1.06	1.09	1.09	-0.02
B4.3	20.80	19.40	4.80	1.33	0.99	1.45	1.40	1.43	0.96	1.09	1.09	-0.10
B4.4	20.80	19.40	4.98	1.38	0.99	1.50	1.44	1.50	0.93	1.09	1.09	-0.01
B4.5	20.80	19.40	7.40	2.06	0.99	1.98	1.84	1.94	0.68	1.09	1.09	-0.03
B4.6	20.80	19.40	8.50	2.36	0.99	2.28	2.11	2.22	0.59	1.09	1.09	-0.04
B4.7	20.80	19.40	9.50	2.64	0.99	2.53	2.33	2.47	0.51	1.09	1.09	-0.04
B4.8	21.20	19.60	9.99	2.78	0.99	2.91	2.68	2.86	0.41	1.09	1.09	-0.05
B4.9	21.20	19.60	11.00	3.06	0.99	3.52	3.21	3.45	0.28	1.09	1.09	-0.06
B4.10	21.20	19.60	11.55	3.21	0.99	3.73	3.40	3.66	0.23	1.10	1.10	-0.06
B4.11	21.20	19.60	11.64	3.23	0.99	3.76	3.42	3.69	0.23	1.10	1.10	-0.06
B5.1	21.50	19.20	0.00	0.00	0.98	1.09	1.09	1.09	1.09	1.09	1.09	-0.02
B5.2	21.50	19.20	4.92	1.37	0.98	1.41	1.37	1.39	0.79	0.97	0.96	-0.11
B5.3	21.50	19.20	5.85	1.63	0.98	1.59	1.71	1.71	0.86	1.09	1.09	-0.22
B5.4	21.50	19.20	6.99	1.94	0.98	2.00	1.95	1.97	0.75	1.07	1.09	-0.25
B5.5	21.50	19.20	7.86	2.18	0.98	2.24	2.19	2.20	0.63	1.08	1.04	-0.27
B5.6	21.50	19.40	8.85	2.46	0.98	2.59	2.53	2.55	0.45	1.09	1.09	-0.39
B5.7	21.40	19.40	9.81	2.73	0.98	2.92	2.82	2.87	0.23	1.01	1.01	-0.62
B5.8	21.40	19.40	11.08	3.08	0.98	3.54	3.40	3.44	0.20	1.07	1.06	-0.64
B5.9	21.40	19.40	11.40	3.17	0.98	3.73	3.61	3.66	0.17	1.07	1.06	-0.60
B6.1	22.00	19.40	0.00	0.00	0.98	1.00	0.96	0.96	0.97	0.97	0.96	0.06
B6.2	22.00	19.40	7.50	2.08	0.98	1.50	1.42	1.45	0.95	0.95	1.00	0.10
B6.3	22.00	19.40	11.80	3.28	0.98	2.11	1.99	1.99	0.85	0.84	0.95	0.19
B6.4	22.00	19.40	13.60	3.78	0.98	2.44	2.22	2.33	0.74	0.75	0.91	0.22
B6.5	21.80	19.40	15.90	4.42	0.98	2.99	2.78	2.86	0.76	0.71	0.93	0.31

Appendix B(continued)

Experiment	T_{air}	T_{water}	Q_0[m^3/h]	Q_0 [l/s]	p_0 [bar]	p_1 [bar]	p_5 [bar]	p_6 [bar]	p_8 [bar]	p_9 [bar]	p_{10} [bar]	Δ p_7-p_8 [bar]
B6.6	21.80	19.50	17.50	4.86	0.98	3.49	3.13	3.33	0.76	0.74	0.99	0.35
B6.7	21.80	19.50	18.00	5.00	0.98	3.66	3.28	3.47	0.79	0.76	1.01	0.37

Appendix C: The values of main parameters measured in set C of experiments with pilot system III

Priloga C: *Vrednosti glavnih parametrov merjenih v skupini C eksperimentov z pilot sistemom III*

Experiment	T_{air}	T_{water}	Q_0 [m^3/h]	Q_0 [l/s]	p_0 [bar]	p_1 [bar]	p_2 [bar]	p_3 [bar]	p_4 [bar]	p_5 [bar]	p_6 [bar]	p_7 [bar]	p_8 [bar]	p_9 [bar]	p_{10} [bar]
C1.1	21.20	19.00	0.00	0.00	0.98	1.13	no data	no data	no data	1.12	1.11	no data	1.12	1.13	1.08
C1.2	21.20	19.00	8.20	2.28	0.98	1.48	no data	no data	no data	1.47	1.46	no data	1.44	1.11	1.09
C1.3	21.20	19.00	13.30	3.69	0.98	2.10	no data	no data	no data	2.07	2.08	no data	1.97	1.11	1.09
C1.4	21.20	19.00	15.78	4.38	0.98	2.53	no data	no data	no data	2.47	2.47	no data	2.37	1.11	1.09
C1.5	21.30	19.00	18.00	5.00	0.98	3.04	no data	no data	no data	2.97	2.98	no data	2.82	1.11	1.09
C1.6	21.30	19.10	19.45	5.40	0.98	3.51	no data	no data	no data	3.43	3.43	no data	3.26	1.13	1.10
C2.1	20.90	18.80	0.00	0.00	0.99	1.05	no data	no data	no data	1.05	1.05	no data	1.05	1.05	1.06
C2.2	20.90	18.80	7.00	1.94	0.99	1.40	no data	no data	no data	1.36	1.35	no data	1.31	1.07	1.05
C2.3	21.00	18.80	12.95	3.60	0.99	2.11	no data	no data	no data	2.06	2.07	no data	1.95	1.07	1.05
C2.4	21.00	18.80	15.85	4.40	0.99	2.75	no data	no data	no data	2.70	2.70	no data	2.50	1.20	1.18
C2.5	21.00	19.00	17.45	4.85	0.99	3.11	no data	no data	no data	3.05	3.04	no data	2.82	1.19	1.17
C2.6	21.00	19.00	19.00	5.28	0.99	3.50	no data	no data	no data	3.43	3.44	no data	3.17	1.22	1.20
C3.1	20.40	19.00	0.00	0.00	1.00	1.11	0.94	1.01	0.98	1.02	1.02	1.03	1.02	1.01	1.09
C3.2	20.40	19.00	8.43	2.34	1.00	1.56	1.05	0.96	0.91	1.25	0.95	1.02	1.03	1.04	0.99
C3.3	20.40	19.00	10.32	2.87	1.00	2.07	1.13	0.95	0.91	1.47	0.91	1.03	1.00	1.02	1.05
C3.4	20.40	18.70	13.30	3.69	1.00	2.60	1.17	0.96	0.91	1.73	0.92	1.01	1.01	1.03	1.00
C3.5	20.40	18.70	14.70	4.08	1.00	2.99	1.27	1.00	0.93	1.87	1.00	1.01	1.01	1.04	1.07
C3.6	20.60	18.70	16.30	4.53	1.00	3.49	1.36	0.97	0.92	1.88	0.99	1.02	1.00	1.04	1.08
C3.7	20.60	18.70	17.10	4.75	1.00	4.29	1.40	0.99	0.95	2.29	0.94	1.00	0.97	1.01	1.08
C4.1	20.40	18.70	0.00	0.00	0.94	1.09	0.95	0.96	0.91	0.95	0.96	0.96	0.96	0.96	1.02
C4.2	20.40	18.70	7.45	2.07	0.94	1.53	1.03	0.94	0.96	1.47	1.01	0.83	0.98	0.98	0.91
C4.3	20.40	18.80	11.10	3.08	0.94	2.03	1.05	0.92	0.92	0.93	1.96	0.60	0.66	0.79	0.90
C4.4	20.40	18.80	13.30	3.69	0.94	2.56	1.18	0.96	0.97	2.57	1.64	0.50	0.45	0.79	0.93
C4.5	20.50	18.80	14.70	4.08	0.94	3.12	1.37	1.10	1.11	3.10	1.24	0.51	0.91	0.92	1.08
C4.6	20.50	18.80	16.30	4.53	0.94	3.75	1.58	1.14	1.14	3.71	1.33	0.42	0.81	0.90	1.12
C5.1	21.80	19.00	0.00	0.00	0.94	1.09	0.95	0.96	0.91	0.95	0.96	0.96	0.96	0.96	1.02

Appendix C (continued)

Experiment	T_{air}	T_{water}	Q_0 [m^3/h]	Q_0 [l/s]	p_0 [bar]	p_1 [bar]	p_2 [bar]	p_3 [bar]	p_4 [bar]	p_5 [bar]	p_6 [bar]	p_7 [bar]	p_8 [bar]	p_9 [bar]	p_{10} [bar]
C5.4	21.70	19.00	12.00	3.33	0.94	2.52	1.54	1.13	1.15	2.36	1.19	0.78	0.75	0.96	1.11
C5.5	21.70	19.20	12.66	3.52	0.94	2.97	1.69	1.14	1.15	2.78	1.23	0.64	0.75	0.89	1.13
C5.6	21.70	19.20	14.80	4.11	0.94	3.77	2.04	1.17	1.18	3.51	1.29	0.54	0.73	0.91	1.15

Appendix D: The calculation of the key values for the operation of the pilot system II (S nozzle. v_{nozzle}. v_{tube}. σ_1 and σ_2) on the basis of pressures measured inside the system and diameter of the nozzles (d_1) for different flow rates (Q_0)

Priloga D: *Izračun ključnih vrednosti za delovanje pilotnega sistema II ($S_{šobe}$, $v_{šobe}$, v_{cevi}, σ_1 and σ_2) na podlagi tlakov zmerjenih znotraj sistema in premera šob (d_1) za različne pretoke (Q_0)*

Experiment	S_{nozzle} [m^2]	S_{tube} [m^2]	v_{nozzle} [m/s]	$v_{outlet\ pipe}$ [m/s]	σ_1	σ_2
B1.1	0.00	0.00	0.00	0.00	no data	no data
B1.2	0.00	0.00	0.00	0.00	no data	no data
B1.3	0.00	0.00	0.00	0.00	no data	no data
B1.4	0.00	0.00	10.81	0.58	0.81	0.40
B1.5	0.00	0.00	11.91	0.64	0.80	0.33
B1.6	0.00	0.00	13.34	0.72	0.74	0.27
B1.7	0.00	0.00	14.22	0.77	0.73	0.25
B1.8	0.00	0.00	15.96	0.86	0.69	0.20
B1.9	0.00	0.00	16.46	0.89	0.69	0.19
B1.10	0.00	0.00	16.36	0.88	0.72	0.20
B2.1	0.00	0.00	0.00	0.00	no data	no data
B2.2	0.00	0.00	0.00	0.00	no data	no data
B2.3	0.00	0.00	0.00	0.00	no data	no data
B2.4	0.00	0.00	0.00	0.00	no data	no data
B2.5	0.00	0.00	0.00	0.00	no data	no data
B2.6	0.00	0.00	11.42	0.62	0.95	0.35
B2.7	0.00	0.00	12.89	0.70	0.87	0.29
B2.8	0.00	0.00	14.59	0.79	0.81	0.24
B2.9	0.00	0.00	15.28	0.83	0.78	0.21
B2.10	0.00	0.00	15.47	0.84	0.79	0.20
B2.11	0.00	0.00	15.96	0.86	0.76	0.20
B3.1	0.00	0.00	0.00	0.00	no data	no data
B3.2	0.00	0.00	0.00	0.00	no data	no data
B3.3	0.00	0.00	11.01	0.81	0.82	0.41
B3.4	0.00	0.00	13.35	0.98	0.70	0.28
B3.5	0.00	0.00	15.70	1.16	0.63	0.21
B3.6	0.00	0.00	17.00	1.25	0.61	0.20
B3.7	0.00	0.00	17.92	1.32	0.62	0.19
B4.1	0.00	0.00	0.00	0.00	no data	no data
B4.2	0.00	0.00	0.00	0.00	no data	no data
B4.3	0.00	0.00	6.63	0.64	1.62	1.18
B4.4	0.00	0.00	6.88	0.66	1.56	0.98
B4.5	0.00	0.00	10.22	0.98	0.93	0.33
B4.6	0.00	0.00	11.74	1.13	0.82	0.22
B4.7	0.00	0.00	13.12	1.26	0.73	0.15
B4.8	0.00	0.00	13.80	1.33	0.76	0.11
B4.9	0.00	0.00	15.20	1.46	0.76	0.07
B4.10	0.00	0.00	15.96	1.53	0.73	0.05

Appendix D (continued)

Experiment	S_{nozzle} [m2]	S_{tube} [m2]	v_{nozzle} [m/s]	$v_{outlet\ pipe}$ [m/s]	σ_1	σ_2
B5.1	0.00	0.00	0.00	0.00	no data	no data
B5.2	0.00	0.00	6.80	0.65	1.50	0.94
B5.3	0.00	0.00	8.08	0.78	1.20	0.81
B5.4	0.00	0.00	9.66	0.93	1.06	0.52
B5.5	0.00	0.00	10.86	1.04	0.94	0.37
B5.6	0.00	0.00	12.23	1.18	0.86	0.27
B5.7	0.00	0.00	13.55	1.30	0.79	0.22
B5.8	0.00	0.00	15.31	1.47	0.75	0.17
B5.9	0.00	0.00	15.75	1.51	0.75	0.15
B6.1	0.00	0.00	0.00	0.00	no data	no data
B6.2	0.00	0.00	8.29	1.00	1.07	0.75
B6.3	0.00	0.00	13.04	1.57	0.61	0.30
B6.4	0.00	0.00	15.03	1.81	0.54	0.21
B6.5	0.00	0.00	17.57	2.11	0.48	0.17
B6.6	0.00	0.00	19.34	2.32	0.46	0.14
B6.7	0.00	0.00	19.89	2.39	0.46	0.14

Appendix E: Calculation of the pressure loss (Δp), loss coefficient (ξ) and power requirements (P) for the set B experiments for the pilot system II

Priloga E: *Izračun izgub tlaka (Δp), koeficienta izgube (ξ) in porabe energije (P) za poskuse v skupini B za pilotni sistem II*

Experiment	Q_0 [m^3/h]	Q_0 [l/s]	p_1 [bar]	p_{10} [bar]	Δp [bar]	Δp [Pa]	ξ	P [W]
B1.1	0.00	0.00E+00	1.06	1.04	0.01	1060.00	no data	0.00
B1.2	0.00	0.00E+00	1.30	0.99	0.32	31690.00	no data	0.00
B1.3	0.00	0.00E+00	1.50	0.95	0.55	54990.00	no data	0.00
B1.4	4.40	1.22E-03	1.92	1.01	0.91	91260.00	534.30	111.54
B1.5	4.85	1.35E-03	2.29	1.05	1.24	124250.00	598.72	167.39
B1.6	5.43	1.51E-03	2.64	1.07	1.57	156880.00	603.09	236.63
B1.7	5.79	1.61E-03	2.96	1.11	1.85	185270.00	626.41	297.98
B1.8	6.50	1.81E-03	3.53	1.16	2.37	236770.00	635.20	427.50
B1.9	6.70	1.86E-03	3.74	1.16	2.57	257230.00	649.51	478.73
B1.10	6.66	1.85E-03	3.86	1.20	2.66	266280.00	680.46	492.62
B2.1	0.00	0.00E+00	1.08	1.08	0.00	160.00	no data	0.00
B2.2	0.00	0.00E+00	1.16	1.08	0.07	7350.00	no data	0.00
B2.3	0.00	0.00E+00	1.46	1.08	0.38	37710.00	no data	0.00
B2.4	0.00	0.00E+00	2.03	1.08	0.95	94700.00	no data	0.00
B2.5	0.00	0.00E+00	2.34	1.08	1.25	125060.00	no data	0.00
B2.6	4.65	1.29E-03	2.50	1.09	1.41	140690.00	737.52	181.72
B2.7	5.25	1.46E-03	2.91	1.11	1.80	180260.00	741.30	262.88
B2.8	5.94	1.65E-03	3.49	1.14	2.35	235080.00	755.19	387.88
B2.9	6.22	1.73E-03	3.67	1.16	2.51	250640.00	734.32	433.05
B2.10	6.30	1.75E-03	3.82	1.18	2.64	263770.00	753.28	461.60
B2.11	6.50	1.81E-03	3.90	1.17	2.73	273030.00	732.48	492.97
B3.1	0.00	0.00E+00	1.17	1.17	0.00	-470.00	no data	0.00
B3.2	0.00	0.00E+00	1.58	1.13	0.44	44350.00	no data	0.00
B3.3	6.10	1.69E-03	2.01	1.12	0.89	89200.00	271.72	151.14
B3.4	7.40	2.06E-03	2.54	1.10	1.43	143450.00	296.93	294.87
B3.5	8.70	2.42E-03	3.13	1.19	1.95	194530.00	291.31	470.11

Appendix E (continued)

Experiment	Q_0 [m^3/h]	Q_0 [l/s]	p_1 [bar]	p_{10} [bar]	Δp [bar]	Δp [Pa]	ξ	P [W]
B4.1	0.00	0.00E+00	1.09	1.09	0.00	-350.00	no data	0.00
B4.2	0.00	0.00E+00	1.18	1.09	0.09	8660.00	no data	0.00
B4.3	4.80	1.33E-03	1.45	1.09	0.36	35690.00	175.58	47.59
B4.4	4.98	1.38E-03	1.50	1.09	0.41	40890.00	186.88	56.56
B4.5	7.40	2.06E-03	1.98	1.09	0.88	88430.00	183.04	181.77
B4.6	8.50	2.36E-03	2.28	1.09	1.19	118540.00	185.97	279.89
B4.7	9.50	2.64E-03	2.53	1.09	1.44	144180.00	181.08	380.48
B4.8	9.99	2.78E-03	2.91	1.09	1.82	182310.00	207.06	505.91
B4.9	11.00	3.06E-03	3.52	1.09	2.43	242510.00	227.17	741.00
B4.10	11.55	3.21E-03	3.73	1.10	2.63	263380.00	223.79	845.01
B4.11	11.64	3.23E-03	3.76	1.10	2.66	266290.00	222.77	861.00
B5.1	0.00	0.00E+00	1.09	1.09	-0.01	-560.00	no data	0.00
B5.2	4.92	1.37E-03	1.41	0.96	0.45	44800.00	209.78	61.23
B5.3	5.85	1.63E-03	1.59	1.09	0.50	49710.00	164.64	80.78
B5.4	6.99	1.94E-03	2.00	1.09	0.91	90810.00	210.67	176.32
B5.5	7.86	2.18E-03	2.24	1.04	1.21	120520.00	221.12	263.14
B5.6	8.85	2.46E-03	2.59	1.09	1.50	150200.00	217.37	369.24
B5.7	9.81	2.73E-03	2.92	1.01	1.91	190640.00	224.54	519.49
B5.8	11.08	3.08E-03	3.54	1.06	2.49	248660.00	229.58	765.32
B5.9	11.40	3.17E-03	3.73	1.06	2.67	267090.00	232.95	845.79
B6.1	0.00	0.00E+00	1.00	0.96	0.05	4580.00	no data	0.00
B6.2	7.50	2.08E-03	1.50	1.00	0.49	49390.00	99.52	102.90
B6.3	11.80	3.28E-03	2.11	0.95	1.16	115590.00	94.10	378.88
B6.4	13.60	3.78E-03	2.44	0.91	1.53	152830.00	93.66	577.36
B6.5	15.90	4.42E-03	2.99	0.93	2.06	206030.00	92.37	909.97
B6.6	17.50	4.86E-03	3.49	0.99	2.50	249850.00	92.47	1214.55
B6.7	18.00	5.00E-03	3.66	1.01	2.64	264340.00	92.48	1321.70

Appendix F: Theoretical values for the operation of the pilot system III (S_{nozzle}, v_{nozzle}, v_{tube} and σ) on the basis of pressures measured inside the system and dimensions of the nozzles for different flows (Q_0)

Priloga F: *Teoretične vrednosti za delovanje pilotnega sistema III ($S_{šobe}$, $v_{šobe}$, v_{cevi} and σ) na podlagi tlakov izmerjenih znotraj sistema in dimenzij šob (d_1) za različne pretoke (Q_0)*

Experiment	Q_0 [m^3/h]	S_{nozzle} [m^2]	S_{tube} [m^2]	v_{nozzle} [m/s]	$v_{outlet\ pipe}$ [m/s]	σ
C1.1	0.00	2.01E-04	2.09E-03	0.00	0.00	no data
C1.2	8.20	2.01E-04	2.09E-03	11.33	1.09	0.57
C1.3	13.30	2.01E-04	2.09E-03	18.37	1.77	0.31
C1.4	15.78	2.01E-04	2.09E-03	21.80	2.10	0.26
C1.5	18.00	2.01E-04	2.09E-03	24.87	2.39	0.24
C1.6	19.45	2.01E-04	2.09E-03	26.87	2.58	0.24
C2.1	0.00	2.01E-04	2.09E-03	0.00	0.00	no data
C2.2	7.00	2.01E-04	2.09E-03	9.67	0.93	0.73
C2.3	12.95	2.01E-04	2.09E-03	17.89	1.72	0.33
C2.4	15.85	2.01E-04	2.09E-03	21.90	2.11	0.28
C2.5	17.45	2.01E-04	2.09E-03	24.11	2.32	0.27
C2.6	19.00	2.01E-04	2.09E-03	26.25	2.52	0.25
C3.1	0.00	2.01E-04	2.09E-03	0.00	0.00	no data
C3.2	8.43	2.01E-04	2.09E-03	11.65	1.12	0.57
C3.3	10.32	2.01E-04	2.09E-03	14.26	1.37	0.50
C3.4	13.30	2.01E-04	2.09E-03	18.37	1.77	0.38
C3.5	14.70	2.01E-04	2.09E-03	20.31	1.95	0.36
C3.6	16.30	2.01E-04	2.09E-03	22.52	2.17	0.34
C3.7	17.10	2.01E-04	2.09E-03	23.62	2.27	0.38
C4.1	0.00	2.01E-04	2.09E-03	0.00	0.00	no data
C4.2	7.45	2.01E-04	2.09E-03	10.29	0.99	0.71
C4.3	11.10	2.01E-04	2.09E-03	15.34	1.47	0.43
C4.4	13.30	2.01E-04	2.09E-03	18.37	1.77	0.38
C4.5	14.70	2.01E-04	2.09E-03	20.31	1.95	0.38
C4.6	16.30	2.01E-04	2.09E-03	22.52	2.17	0.37
C5.1	0.00	2.01E-04	2.09E-03	0.00	0.00	no data
C5.2	5.70	2.01E-04	2.09E-03	7.87	0.76	1.23
C5.3	8.97	2.01E-04	2.09E-03	12.39	1.19	0.67
C5.4	12.00	2.01E-04	2.09E-03	16.58	1.59	0.45
C5.5	12.66	2.01E-04	2.09E-03	17.49	1.68	0.48
C5.6	14.80	2.01E-04	2.09E-03	20.45	1.97	0.45

Appendix G: Calculation of the pressure loss (Δp), loss coefficient (ξ) and power requirements (P) for the set C experiments for the pilot system III

***Priloga G:** Izračun izgub tlaka (Δp), koeficienta izgube (ξ) in porabe energije (P) za poskuse v skupini C za pilotni sistem III*

Experiment	Q_0 [m^3/h]	Q_0 [l/s]	p_1 [bar]	p_{10} [bar]	Δp [bar]	Δp [Pa]	ξ	P [W]
C1.1	0.00	0.00E+00	1.13	1.08	0.05	4540.00	no data	0.00
C1.2	8.20	2.28E-03	1.48	1.09	0.40	39730.00	66.97	90.50
C1.3	13.30	3.69E-03	2.10	1.09	1.02	101810.00	65.24	376.13
C1.4	15.78	4.38E-03	2.53	1.09	1.44	144400.00	65.73	632.95
C1.5	18.00	5.00E-03	3.04	1.09	1.95	194630.00	68.09	973.15
C1.6	19.45	5.40E-03	3.51	1.10	2.41	241050.00	72.22	1302.34
C2.1	0.00	0.00E+00	1.05	1.06	-0.01	-1050.00	no data	0.00
C2.2	7.00	1.94E-03	1.40	1.05	0.34	34150.00	79.00	66.40
C2.3	12.95	3.60E-03	2.11	1.05	1.06	105590.00	71.37	379.83
C2.4	15.85	4.40E-03	2.75	1.18	1.57	157430.00	71.03	693.13
C2.5	17.45	4.85E-03	3.11	1.17	1.95	194510.00	72.40	942.83
C2.6	19.00	5.28E-03	3.50	1.20	2.30	230200.00	72.28	1214.94
C3.1	0.00	0.00E+00	1.11	1.09	0.02	1830.00	no data	0.00
C3.2	8.43	2.34E-03	1.56	0.99	0.57	57170.00	91.19	133.87
C3.3	10.32	2.87E-03	2.07	1.05	1.02	101660.00	108.19	291.43
C3.4	13.30	3.69E-03	2.60	1.00	1.60	159850.00	102.43	590.56
C3.5	14.70	4.08E-03	2.99	1.07	1.91	191300.00	100.34	781.14
C3.6	16.30	4.53E-03	3.49	1.08	2.41	240980.00	102.81	1091.10
C3.7	17.10	4.75E-03	4.29	1.08	3.21	320950.00	124.41	1524.51
C4.1	0.00	0.00E+00	1.09	1.02	0.07	6660.00	no data	0.00
C4.2	7.45	2.07E-03	1.53	0.91	0.62	62410.00	127.45	129.15
C4.3	11.10	3.08E-03	2.03	0.90	1.13	113130.00	104.07	348.82
C4.4	13.30	3.69E-03	2.56	0.93	1.63	163320.00	104.65	603.38
C4.5	14.70	4.08E-03	3.12	1.08	2.04	203540.00	106.76	831.12
C4.6	16.30	4.53E-03	3.75	1.12	2.63	262770.00	112.10	1189.76
C5.3	8.97	2.49E-03	2.07	1.12	0.95	95280.00	134.22	237.41
C5.4	12.00	3.33E-03	2.52	1.11	1.40	140320.00	110.45	467.73
C5.5	12.66	3.52E-03	2.97	1.13	1.84	184460.00	130.45	648.68
C5.6	14.80	4.11E-03	3.77	1.15	2.62	261820.00	135.49	1076.37

Appendix H: The effectiveness of the system on destroying the organisms (zooplankton (copepods) and *A. salina* cysts without and with separation)

Priloga H: *Učinkovitost sistema na poškodovanje organizmov (zooplankton (kopepodi) in A. salina ciste, z in brez ločevanja)*

			The average number of whole organisms and duration of the treatment				% of destroyed organisms		
		Experiment	0 min	15 min	30 min	60 min	15 min	30 min	60 min
Zooplankton	(No/L)	Z1	471.7 ± 36.1	4.0 ± 1.0	0	0	99.2	100	100
		Z2	551.3 ± 197.1	4.3 ± 2.1	0	0	99.2	100	100
		Z3	483.0 ± 85.0	3.7 ± 1.5	0	0	99.2	100	100
		Z4	141.0 ± 5.0	0.3 ± 0.6	0	0	99.8	100	100
		Z5	85.3 ± 8.3	0.3 ± 0.6	0	0	99.6	100	100
Cysts (without separation)	(No/10 mL)	C1	376.7 ± 97.1	111.7 ± 53.2	68.7 ± 31.5	47.7 ± 6.7	70.4	81.8	87.3
		C2	479.3 ± 43.0	99.7 ± 11.8	130.7 ± 24.8	39.7 ± 9.5	79.2	72.7	91.7
		C3	726.0 ± 49.7	359.7 ± 65.0	304.3 ± 5.5	62.3 ± 42.4	50.5	58.1	91.4
Cysts (with separation)	(No/10 mL)	Cs1	492.0 ± 25.5	287.7 ± 59.0	85.7 ± 13.8	15.0 ± 2.6	41.5	82.6	97.0
		Cs2	400.3 ± 16.9	82.0 ± 15.1	41.7 ± 12.5	9.0 ± 1.0	79.5	89.6	97.8
		Cs3	789.0 ± 63.3	88.7 ± 7.1	5.0 ± 3.5	1.3 ± 0.6	88.8	99.4	99.8