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STUDY OF FOULING COMMUNITIES SUCCESSION UNDER CONDITIONS OF THE DEVICE OF CONTROLLED WATER FLOW

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For testing the anticorrosive and antifouling protective coatings, a ground stand is developed: the device of controlled water flow. The relevance of the study is undeniable, given the practical significance of the problem. The stand is connected to the main of sea running water. The device makes it possible to imitate the motion of aqueous flow around the vessel, thus simulating the conditions of moving amphibious facility. The aim of this work is to present for the first time the new device, created by us, which received a positive decision of Rospatent (Federal Service for Intellectual Property). For two months, full-scale field tests were carried out. They have showed essential qualitative and quantitative differences in the composition of fouling communities on the experimental plates, placed into the device of controlled water flow and suspended in the water column on the pier of the Zapad marine biological station of the National Scientific Center of Marine Biology, FEB RAS. Benthic diatoms predominate in the periphyton community under the conditions of the device of controlled water flow; there is practically no zoofouling. Phytocenosis of green algae, which is common for a vessel variable loadline or a hydraulic structure drainage zone, is presented on the plates from the open bay. The efficiency of using the device of controlled water flow, created by us, is shown for studying the patterns of formation of the fouling communities in different hydrodynamic flows. The main practical conclusion is that the device can be used to verify the properties of protective coatings on the substrates tested, *inter alia* antifouling and anticorrosive coatings.

Keywords: device, controlled flow, fouling community, green algae, diatoms

The study of formation of fouling communities is one of the necessary aspects of identifying the patterns of their functioning. In world practice, a detailed description of methods for investigating the periphyton of experimental plates is possible only in a large analytical review; its compilation is not the aim of this work. The importance of analyzing the dynamic aspect of the fouling communities of operating vessels is obvious, since the problem is of high practical significance. To the middle of the XX century, the annual damage from vessels fouling was estimated at millions of dollars (Marine Fouling and Its Prevention, 1952); to date, the values are only increasing. The Institute of Marine Biology of the Far Eastern Branch of the Russian Academy of Sciences (FEB RAS) has developed a methodology for studying the fouling communities succession of operating vessels afloat using surface-supplied diving equipment. To study the dynamic aspects of the fouling, the surface of the vessel's hull was used. Significant results have already been obtained by this methodology (Zvyagintsev, 2005). In 1986, specialists of both the Institute of Marine Biology and Central Research Institute “Prometey” manufactured a ship device for biological and corrosion tests (Ostrikov et al., 1998), intended for exposing removable plates on the vessel’s hull during its operation. The device was successfully tested during the Vietnamese cruise of the RV “Akademik Aleksandr Nesmeyanov” in 1986.

In world practice, the devices of controlled water flow have been used for many times to solve mariculture problems, as well as for other purposes (Fitzsimmons, 2000 ; Patent no. US8245440B2, 2012 ; Pearce et al., 2002 ; etc.). The aim of this work is to present for the first time a new device, developed by us, which received a positive decision of Rospatent (Federal Service for Intellectual Property) (Patent no. 2728490, 2019). The objectives set were as follows: to give an illustrated description of the device of controlled water flow (hereinafter DCWF); to describe the hydrological conditions of the testing both in the device and in the open bay area; to give the readings of average water flow velocities for each gradation of the device electric motor; to carry out a comparative analysis of the structure of the fouling communities in the DCWF and in the open bay; to substantiate the effectiveness of using our device to identify the patterns of formation of the fouling communities in different hydrodynamic flows; and to provide practical conclusions and recommendations for using the DCWF.

MATERIAL AND METHODS

Design of the device of controlled water flow. A method for testing the properties of protective coatings in seawater flow and the device for its simulating have been developed by us (Fig. 1).

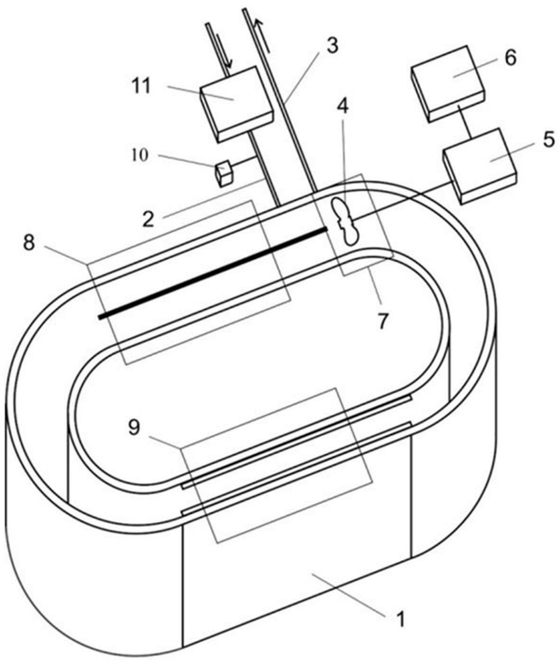

Fig. 1. Device of controlled water flow:
1 – o-shaped container of variable cross-section;
2 – water supply pipe;
3 – spillway drain pipe;
4 – main screw propeller;
5 – electric motor power plant;
6 – electric motor on-off control unit with electric motor speed control unit;
7 – screw-steering group zone;
8 – imitation of screw-steering group surfaces;
9 – midship and different foreship areas, *inter alia* bulbous bow;
10 – continuous salinometer and thermometer;
11 – seawater conduit with specified parameters of purification and treatment or without purification

Together with specialists from the Institute of Chemistry, FEB RAS, design proposals and a draft study of a year-round marine stand were made for testing the peculiarities of the fouling formation on the plates with different composition of coatings, the adhesion of marine organisms on the surface at different water flow velocities, and the effect of coatings on the occurrence of turbulent flows. The device of controlled water flow (the stand) is a complex of technical devices for simulating seawater flow with as complete set of factors as possible, including biotic and abiotic components. The DCWF can be used for testing and verifying the properties of protective coatings on various substrates, *inter alia* antifouling and anticorrosion coatings. Moreover, it allows to carry out experiments on the effect of the water flow velocity and its duration both on attachment and development of separate hydrobionts and peculiarities of the fouling community formation and functioning. The device can be used for load testing of installations and mechanisms in seawater flow of constant and variable force, as well as for modeling storm load and currents (tidal, wind, and constant ones). Successful testing of the DCWF operation on experimental plates has been carried out; preliminary results have been obtained.

The device, developed by us (Patent no. 2728490, 2019), consists of: underwater intake from a pumping station (centrifugal pump, 12.5 $m^3 \cdot h^{-1}$, 900 W); seawater conduit with specified parameters of purification and treatment or without purification; spillway drain pipe; electric motor on-off control unit; control unit of electric motor speed and seawater supply and discharge valves; o-shaped container of variable cross-section for modeling areas with different water flow velocities; main screw propeller; imitators of steering column and vessel side from a given material with any protective coating or protector (see Fig. 1). The DCWF allows to simulate all conditions of a moving vessel simultaneously, with imitation of the surfaces of screw-steering group, midship, and bulbous bow.

Hydrological conditions of the test. The research was carried out in the Tikhaya Zavod Bay, Vostok Bay (Peter the Great Bay, the Sea of Japan). Seawater characteristics were measured by SeaGuard RCM system (Aanderaa). The device was installed on the pier of the eastern cape of the Tikhaya Zavod Bay at the depths of 1.0–1.5 m. The average long-term values of water temperature and salinity are given for the middle area of Vostok Bay; seasonal and diurnal – for the Tikhaya Zavod Bay. Variations in tide rise are given for Vladivostok.

This area of the bay is characterized by significant thermohaline fluctuations in the surface and bottom water layers, especially in rainy years. In Vostok Bay, water temperature in the 0–6-m layer varies +7.4 to +25.9 °C June to September (Grigoryeva & Kashenko, 2010). By the surface, salinity values vary in a wide range of 0.5–34.0 ‰; at the bottom, they are slightly less: 19.2–35.2 ‰. Long-term periods of desalination were recorded during two or three summer months, as in other Peter the Great Bay shallow areas.

The pattern of Vostok Bay currents is determined by wind, drift, and tidal currents. The Primorsky Current affects this pattern as well, which is manifested in the stability of quasi-stationary flows in the water area. In Peter the Great Bay, irregular semidiurnal tides are registered, with maximum fluctuations of 40–50 cm (Sostoyanie i ustoichivost’ ekosistem…, 2001). Data about constant currents in Vostok Bay are rather contradictory (Ivashchenko, 1993 ; Khristoforova et al., 2004). According to one data, the main water transfer is carried out west to east and is of anticyclonic character; according to others, it is of cyclonic one. According to our archival material, water movement in the Tikhaya Zavod Bay has a predominantly cyclonic direction. The velocity of currents here varies 2–18 $cm \cdot s^{-1}$, increasing up to 6–26 $cm \cdot s^{-1}$ towards the bay exit.

During the period of experiments, we have carried out three series of measurements of flow velocities, generated in the device, on 11 and 22 October. All the measurements were carried out both near the outlet and at a distance of 1.0–1.5 m. In separate series, flow velocities were determined in the main (VIII) mode. In addition, we have carried out measurements when immersing the upper part of the device only, where the sensor is located.

Four steel rectangular plates, 20×20 cm each, were simultaneously installed vertically on the buoy in the Tikhaya Zavod Bay at a depth of 1 m and in the DCWF. The plates were exposed for 2 months (early September to late October 2019). On each plate, macrofouling samples were collected on an area of 10×10 cm in triplicate. A total of 24 quantitative samples were collected and processed. Macrofouling samples were treated by the generally accepted procedure for processing benthic samples in laboratory conditions (Zhadin, 1969). During laboratory processing of fresh living material, all components of zoo- and phytoperiphyton were extracted and counted; then, they were divided into separate groups. After samples treating, macrophytes were placed in the herbarium or fixed with 4 % formalin, and zoofouling – with 70 % alcohol; later, they were transferred to specialists for determination. The taxonomic affiliation of the foulers was established by the staff of the National Scientific Center of Marine Biology, FEB RAS. Animals, identified to species lever or to higher taxonomic rank, were counted and weighed to the nearest 0.01 g after drying on filter paper. Sedentary polychaetes in tubes and amphipods in shells were weighed with these formations, which are the products of their vital activity. After the identification of systematic groups was completed, lists of species were compiled, with the quantitative indicators of each species and its location.

Laboratory and microscopic processing of microperiphyton on the experimental plates was carried out according to generally accepted methods (Ryabushko, 2013 ; Ryabushko & Begun, 2015) at the marine microbiota laboratory of the National Scientific Center of Marine Biology. The quantitative abundance of microalgae was assessed by the Visloukh scale. Identification of the species composition was carried out on temporary aqueous preparations under an Olympus BX41 light microscope, using a UPLanFl 100×/1.30 objective (Japan) and oil immersion (Guiry & Guiry, 2020).

Statistical processing of the material. The samples were grouped using Ward's method of cluster analysis (ward.D2) based on the Bray – Curtis metric and the subsequent application of the bootstraping to assess the probability of a node appearing on the dendrogram (Shitikov & Rozenberg, 2013). Unbiased bootstrap probabilities were estimated by fitting parametric models using the maximum likelihood estimation. To check the reliability of the appearance of the tree structure fragments, the ANOSIM procedure was applied with the calculation of the general statistics (global R, *GR*). For the selected groups, species contribution to intragroup similarity and intergroup dissimilarity was determined (the SIMPER procedure). Pairwise comparison of various quantitative characteristics of the fouling (average species number in a sample; biomass; the Margalef species diversity index; the Pielou evenness index; and the Shannon – Wiener diversity index) was carried out by the Mann – Whitney test [a nonparametric analogue of the Student's *t*-test (null hypothesis H_0: there is no relative shift in distributions)].

RESULTS AND DISCUSSION

Hydrological monitoring in the area of the device testing. The data of a diurnal survey in October 2019 indicate as follows: in the area of the eastern cape of the Tikhaya Zavod Bay, velocities of currents by the water surface varied 0.02 to 9.7 $cm \cdot s^{-1}$, averaging 1.1 $cm \cdot s^{-1}$; at low tide, the currents were of northern and northeastern directions, while at high tide – of southeastern, southern, and southwestern (Fig. 2). Water temperature and salinity values changed as well: temperature decreased by 2.2 °C at night, and salinity increased by 1.5 ‰ with the tide.

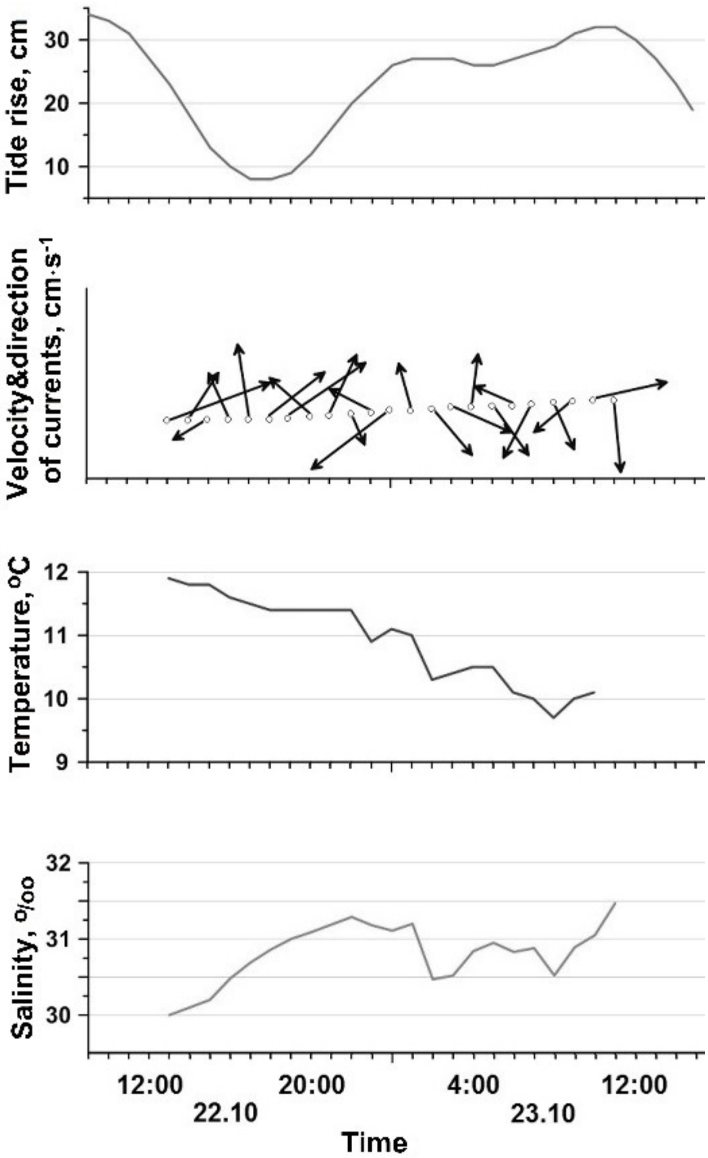

Fig. 2. Daily variations of indicators in tide rise (cm), velocity (cm·s^{-1}) and direction of currents (degrees), temperature (°C), and water salinity (‰) near the eastern cape of the Tikhaya Zavod Bay on 22–23 October, 2019

The readings of the average flow velocities for each power gradation (mode) are shown in Fig. 3. On 11 October, the series of measurements showed good convergence of the results; on 22 October, some instability of the flow was noted in the VI, VIII, and X modes. The minimum average velocities were 2.6–2.7 cm·s^{-1}; the maximum ones – 55.1–65.0 cm·s^{-1}. When carrying out a series of measurements with variable mode switching, the velocity in the VIII mode varied 21.0–32.7 cm·s^{-1}, averaging 24.5, 22.0, and 29.0 cm·s^{-1} (the values correspond to the numbers of the series of experiments). The average velocity of the main mode (VIII) with a separate long exposition was 51.7 cm·s^{-1}. It should be noted that the velocity is underestimated by the case of the device itself. To eliminate this interference, measurements were carried out when immersing the upper part of the device only. The average flow velocity at a distance of 1.0–1.5 m was 78.8 cm·s^{-1}, and near the outlet – 84.3 cm·s^{-1}. The maximum recorded value was 91.2 cm·s^{-1}.

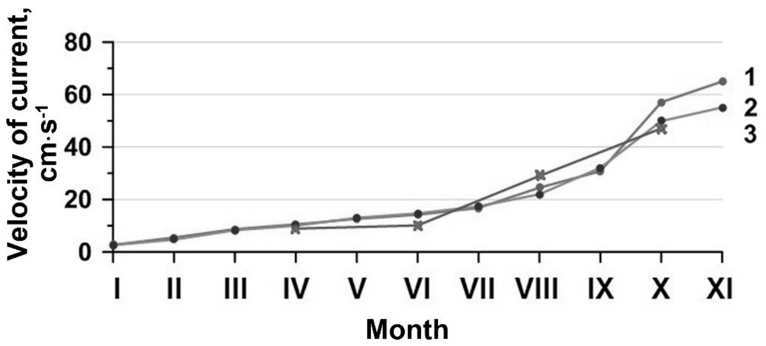

Fig. 3. Changes in flow velocities depending on the set power. 1, 2 – series of the measurements on 11.10.2019; 3 – series of the measurements on 22.10.2019

During the 3-month period of studying the fouling formation (September to November), temperature and salinity of water, entering the device, were measured hourly (Fig. 4). Temperature naturally decreased +22.0 to +1.9 °C (water was gradually cooling down). In the first half of September, salinity underwent significant fluctuations (26.2–33.7 ‰) due to rains; then, the general background levelled off, and indicator varied in a range of 31.2–34.1 ‰.

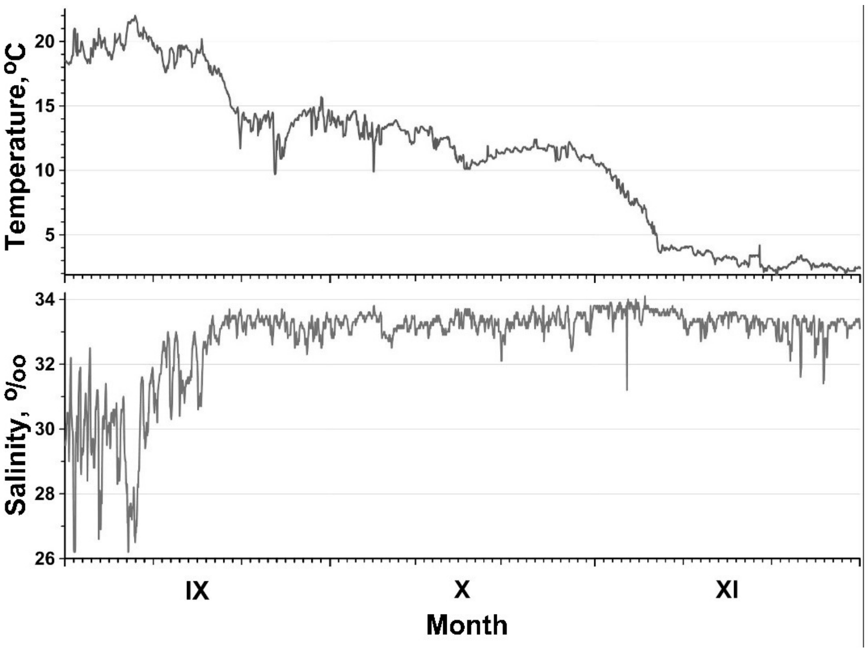

Fig. 4. Fluctuations of temperature (°C) and salinity (‰) of water, entering the device on September – November

Comparative analysis of the fouling communities on the experimental plates under conditions of the device of controlled water flow and the open Tikhaya Zavod Bay. During the period of experiments, 12 hydrobiont species were recorded on the plates from different areas of exposition, 2 of which were green algae (Table 1). Of the attached forms of zoofouling, bay barnacle *Amphibalanus improvisus* (Darwin, 1854) was recorded, as well as polychaetes *Hydroides ezoensis* Okuda, 1934 and *Neodexiospira alveolata* (Zachs, 1933). In addition to macroalgae development, mass diatom development was registered in the fouling on the plates from both biotopes studied; a total of 16 Bacillariophyta species were identified (see Tables 5, 6).

Table 1. Taxonomic composition of macrofouling on the plates from the device of controlled water flow and under the conditions of open Tikhaya Zavod Bay

	Device of controlled water flow	Open Tikhaya Zavod Bay
Algae		
Ulva linza Linnaeus, 1753	+	+
Ulva fenestrata Postels & Ruprecht, 1840	+	+
Animalia		
Hydroides ezoensis Okuda, 1934	–	+
Neodexiospira alveolata (Zachs, 1933)	–	+
Amphibalanus improvisus (Darwin, 1854)	–	+
Caprella cristibrachium Mayer, 1903	–	+
Caprella acanthogaster Mayer, 1890	–	+
Caprella algaceus Vassilenko, 1967	–	+
Ampithoe lacertosa Spence Bate, 1858	–	+
Pontogeneia intermedia (?) Gurjanova, 1938	–	+
Monocorophium acherusicum (Costa, 1853)	–	+
Lacuna turrita A. Adams, 1861	–	+

We attributed green algae *Ulva linza* Linnaeus, 1753 and *Ulva fenestrata* Postels & Ruprecht, 1840, as well as bay barnacles *Amphibalanus improvisus*, to background-forming macrofouling species. Taxonomic composition and quantitative distribution of the fouling communities from the DCWF and from the open Tikhaya Zavod Bay differ significantly (see Figs 5, 6). Thus, on the plates from the device, diatoms predominated, forming the basis of biomass; on the plates from the open bay, green algae *Ulva linza* prevailed. The mobile forms, represented by gastropods and amphipods, were of minimal biomass or were found in qualitative samples only.

Results of the statistical analysis. The analyzed sample is clearly divided into two groups with a very high intragroup similarity of 91.2 and 94.7 %, with an intergroup dissimilarity of 70.8 % (Fig. 7, Table 2): group I – samples from the plates exposed in the Tikhaya Zavod Bay (Z1–Z12); group II – samples from the DCWF (U1–U12). In the group I, the main contributor to the similarity of the samples is *Ulva linza* (52.8 %); it is followed by *Amphibalanus improvisus*, the contribution of which is 2.7 times less (19.4 %). In the group II, the main contributor is the complex of diatoms (66.9 %); the contribution of *U. linza* is two times less (32.9 %). The same organisms determine group dissimilarity: the contribution of diatoms is 31.1 %; *U. linza* – 26.8 %; *A. improvisus* – 16.2 %. The isolation of these groups is significant from the standpoint of statistics, as evidenced by the results of the ANOSIM procedure (*GR* (1.000 ± 0.120); quantile of permutations is ± 95 %; $p = 0.001$; number of permutations is 999).

The fouling associations on the plates, exposed in the Tikhaya Zavod Bay and on the DCWF, are statistically significantly different in all quantitative indicators (Table 3). The first association is characterized by larger values of the average biomass, species number in the sample, and value of the Margalef index, while the second one – by higher values of the Pielou and Shannon – Wiener indices. The latter indicates that the second group has greater species distribution evenness by ranks and species diversity from the standpoint of information theory; this is an "artifact", which is explained by a much smaller number of settled organisms and a lower biomass of the dominant species (the complex of diatoms, in this case). It should be emphasized as follows: the absolute values of all ecological indices, *inter alia* the average species number, are extremely low in comparison with those of both most natural communities and the fouling associations with a longer duration of development.

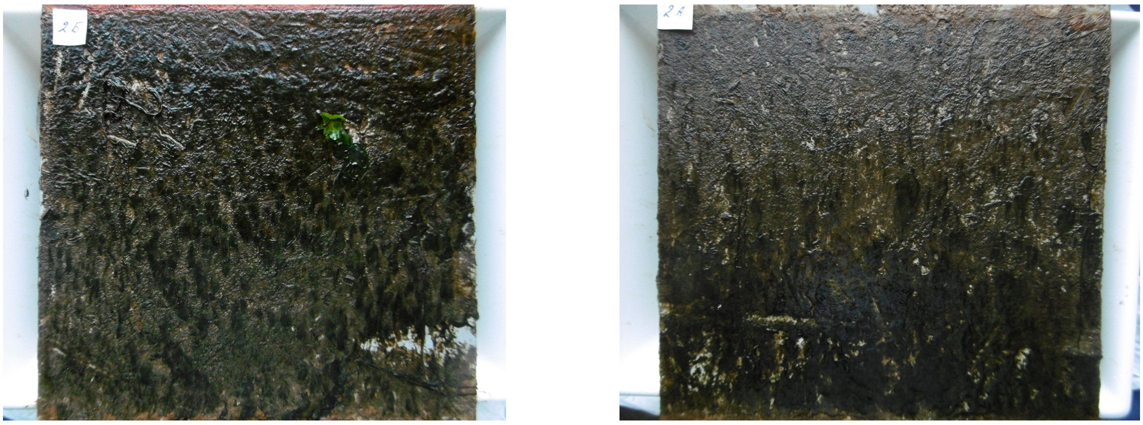

Fig. 5. View of fouling on the plates from the device of controlled water flow. Diatom taxocen in the form of macrocolonies

Fig. 6. View of fouling on the plates from the open Tikhaya Zavod Bay. *Ulva linza* + *Amphibalanus improvisus* community

Table 2. Distribution of average similarity (dissimilarity) within (between) groups based on contribution of each fouling species on the plates from the device of controlled water flow and from the open Tikhaya Zavod Bay

Taxon	I/II	$\bar{\delta}_i$	$\bar{\delta}_i / SD(\delta_i)$	CN, %	CCN, %
		Group I. Average similarity: 91.2			
Ulva linza	5148	48.14	21.38	52.82	52.82
Amphibalanus improvisus	99.7	17.70	22.25	19.42	72.23
Hydroides ezoensis	16.3	10.48	8.90	11.49	83.72
Neodexiospira alveolata	7.8	9.20	13.62	10.09	93.82
		Group II. Average similarity: 94.7			
Bacillariophyta	1983	63.30	19.85	66.86	66.86
Ulva linza	115	31.13	16.88	32.88	99.74
		Groups I–II. Average dissimilarity: 70.8			
Bacillariophyta	0.15/1983	21.99	20.56	31.08	31.08
Ulva linza	5148/115	18.93	12.67	26.75	57.84
Amphibalanus improvisus	99.7/0.0	11.47	16.39	16.21	74.04
Hydroides ezoensis	16.3/0.0	7.14	7.35	10.10	84.14
Neodexiospira alveolata	7.83/0.0	6.05	10.32	8.55	92.69

Note: species are arranged in decreasing order of percent contribution; δ_i — measure of similarity (dissimilarity); *SD* – standard deviation; CN – percent contribution; CCN – accumulated percent.

Table 3. Quantitative characteristics of fouling communities on the plates from the device of controlled water flow and from the open Tikhaya Zavod Bay and results of pairwise comparison of indicators (Mann – Whitney test; probability of H_0 validity is shown)

Group	*S* ± *SE*	B ± *SE*, g·m^{-2}	*R* ± *SE*	*e* ± *SE*	*H'* ± *SE*, bit·g^{-1}
I. *Ulva linza*	6.4 ± 0.3	5277 ± 209	0.63 ± 0.03	0.073 ± 0.004	0.19 ± 0.01
II. Diatomea	2.2 ± 0.1	2101 ± 108	0.15 ± 0.01	0.299 ± 0.019	0.32 ± 0.02
Mann – Whitney test	0.000	0.000	0.000	0.000	0.000

Note: *S* – average species number in the sample; B – biomass; *R* – Margalef index; *e* – Pielou evenness index; *H'* – Shannon – Wiener diversity index; *SE* – standard error.

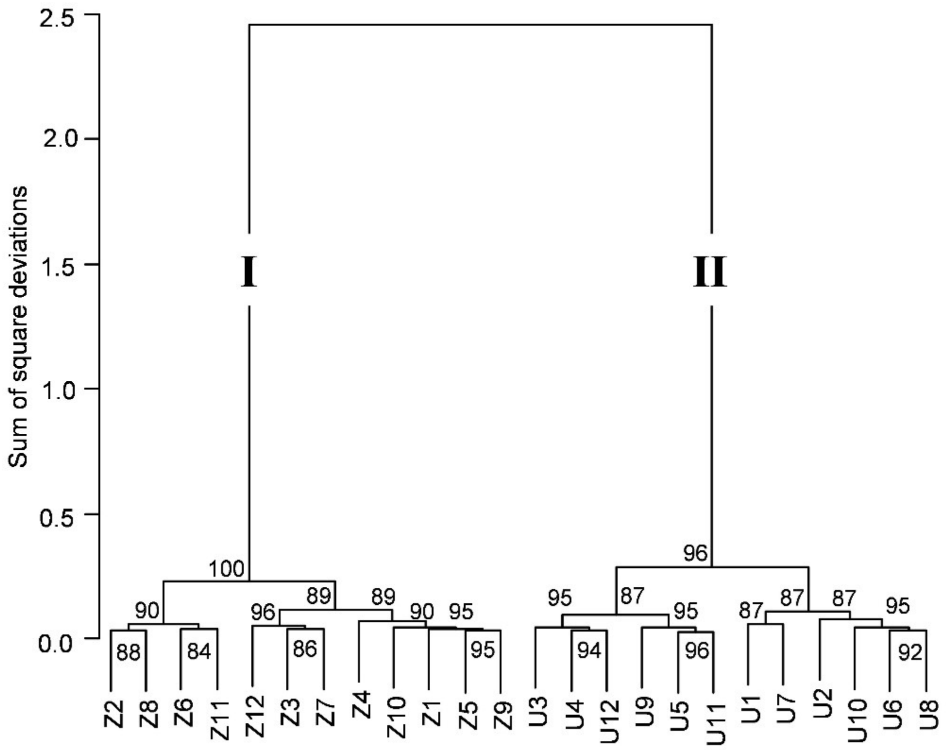

Fig. 7. Dendrogram of the plates similarity (ward.D2 method) with Bray – Curtis similarity index (the fourth-root transformation) based on phyto- and zoofouling biomasses. The best estimations of unbiased bootstrap probabilities are shown in dendrogram nodes (number of permutations is 1000). Roman numerals denote allocated groups

The identified associations have only three common components: the complex of diatoms, *U. linza*, and *U. fenestrata*. The first two were found in all samples; the third one was recorded with a frequency of 50 and 17 % in the first and second groups, respectively. The average biomass of microalgae on the plates, exposed on the DCWF, was thousands of times higher than in natural conditions, while that of *U. linza* macrophytes, on the contrary, was almost 45 times lower. Naturally, such differences are significant from the standpoint of statistics (the results of the Mann – Whitney test: the probability of H_0 validity $p = 0.000$) (Fig. 8, Table 4). Biomass of *U. fenestrata* in both cases was approximately the same ($p = 0.260$). Another difference, qualitative one, is the complete absence of macrozoobenthos on the plates from the DCWF, whereas in natural conditions, 10 macrozoobenthos species were found on the plates, and *A. improvisus* can be considered as a subdominant species (taking into account 100 % occurrence and high biomass).

Thus, the statistical analysis proves cardinal differences (qualitative and quantitative ones) in the fouling associations on the plates, exposed in the Tikhaya Zavod Bay and on the DCWF. These differences, in fact, are of a succession nature. It is known that on objects, that have gotten to the sea, bacteria and microalgae settle in the first phases of succession; they form a mucous film, which facilitates the subsequent colonization of the substrate by various hydrobionts (Zvyagintsev, 2005). Our experiment clearly shows the "delay" of the succession under conditions of the DCWF.

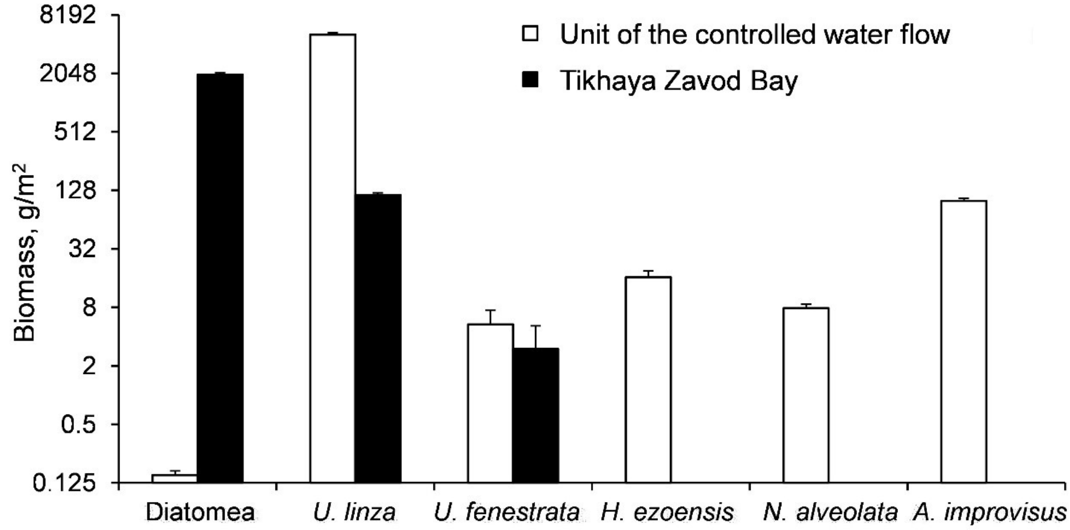

Fig. 8. Biomass of some foulers on the plates from the device of controlled water flow and from the open Tikhaya Zavod Bay (logarithmic scale). Error bars denote standard error

Table 4. Taxonomic composition and biomass (± standard error) of fouling communities on the plates from the device of controlled water flow and from the open Tikhaya Zavod Bay

Taxon	Device of controlled water flow	Open Tikhaya Zavod Bay
	Microalgae	
Bacillariophyta	1983 ± 107	0.15 ± 0.02
	Algae	
Ulva linza Linnaeus, 1753	115 ± 6	5148 ± 210
Ulva fenestrata Postels & Ruprecht, 1840	3.0 ± 2.1	5.3 ± 2.1
	Animalia	
Hydroides ezoensis Okuda, 1934	–	16.3 ± 2.7
Neodexiospira alveolata (Zachs, 1933)	–	7.8 ± 0.8
Amphibalanus improvisus (Darwin,1854)	–	100 ± 6
Caprella cristibrachium Mayer, 1903	–	0.03 ± 0.01
Caprella acanthogaster Mayer, 1890	–	0.02 ± 0.01
Caprella algaceus Vassilenko, 1967	–	0.01 ± 0.01
Ampithoe lacertosa Spence Bate, 1858	–	0.02 ± 0.01
Pontogeneia intermedia (?) Gurjanova, 1938	–	0.01 ± 0.01
Monocorophium acherusicum (Costa, 1853)	–	0.01 ± 0.01
Lacuna turrita A. Adams, 1861	–	0.01 ± 0.01

Note: a dash (–) means that no organisms were found.

Diatoms of microperiphyton on the experimental plates. On the surface of the experimental plates under conditions of the DCWF, the presence of dark brown microperiphyton was noted, with the predominance of macrocolonies of diatoms, forming the basis of the biomass of the fouling. In the microperiphyton community, 14 species were identified, represented by different life forms: mobile and immobile; attached and free-living; and solitary and colonial (Table 5). In relation to water salinity, marine forms predominated (7 species), as well as brackish-water and marine ones; in relation to active reaction of the environment, alkaliphiles prevailed (Fitzsimmons, 2000). In the phytogeographic aspect, widespread cosmopolitan species predominated (Ryabushko & Begun, 2015).

Table 5. Composition, ecological and geographical characteristics, and relative quantitative abundance of diatoms of microperiphyton from the device of controlled water flow (November 2019)

Taxon	Ecological characteristic			Phytogeographical characteristic	Quantitative abundance
	Life form	Salinity	Saprobity		
Berkeleya rutilans (Trentepohl ex Roth) Grunow, 1880	B	BM	–	C	ms
Cylindrotheca closterium (Ehrenberg) Reimann & J. C. Lewin, 1964	BP	BM	β	C	r
Gomphonemopsis pseudexigua (Simonsen) Medlin in Medlin & Round, 1986	B	M	–	ABT	of
Licmophora abbreviata C. Agardh, 1831	B	M	β	AB	ms
Licmophora flabellata (Greville) C. Agardh, 1831	B	M	β	BT	of
Melosira lineata (Dillwyn) C. Agardh, 1824	BP	BM	α	ABT	r
Melosira moniliformis var. *subglobosa* (Grunow) Hustedt, 1927	BP	BM	α	AB	of
Navicula directa (W. Smith) Ralfs, 1861	B	BM	–	C	r
Nitzschia hybrida f. *hyalina* Proschkina-Lavrenko, 1963	BP	BW	–	Bo	of
Nitzschia longissima (Brébisson) Ralfs, 1861	B	M	–	C	r
Odontella aurita (Lyngbye) C. Agardh, 1832	BP	M	–	C	r
Parlibellus delognei (Van Heurck) E. J. Cox, 1988	B	M	–	C	r
Rhabdonema arcuatum (Lyngbye) Kützing, 1844	BP	M	–	C	r
Tabularia tabulata (C. Agardh) Snoeijs, 1992	B	BM	α	C	of

Note. Confinement to habitat: B – benthic; BP – benthic and planktonic. Confinement to salinity: M – marine; BM – brackish-water and marine; BW – brackish-water. Confinement to saprobiology: α – alpha-mesosaprobiont; β – beta-mesosaprobiont. Phytogeographic characteristics: C – cosmopolitan; AB – arctic-boreal; ABT – arctic-boreal-tropical; BT – boreal-tropical; Bo – boreal. Relative quantitative abundance is given according to the Visloukh scale (Diatomovye vodorosli SSSR…, 1974): ms – mass; l – a lot of; of – often; r – rarely.

Two colonial diatom species were characterized by the maximum quantitative development: *Berkeleya rutilans*, which forms tubular mucous microcolonies, and *Licmophora abbreviata*, which develops on a substrate with stems of a polysaccharide matrix (Fig. 9). The quantitative abundance of these species in the fouling on the plates from the DCWF was assessed as "mass". Both of these species are typical epiphytes, which form in natural conditions a mutual connection with the phorophyte – the same as in terrestrial plants with their epiphytes (Ryabushko, 2013). The above-mentioned species are the main component of diatom periphyton of anthropogenic substrates in the water of Peter the Great Bay (the Sea of Japan), as well as in the coastal areas of Japan (Kasim & Mukai, 2006), China (Checklist of Marine Biota of Chinese Seas, 2008), and Korea (Lee et al., 2015).

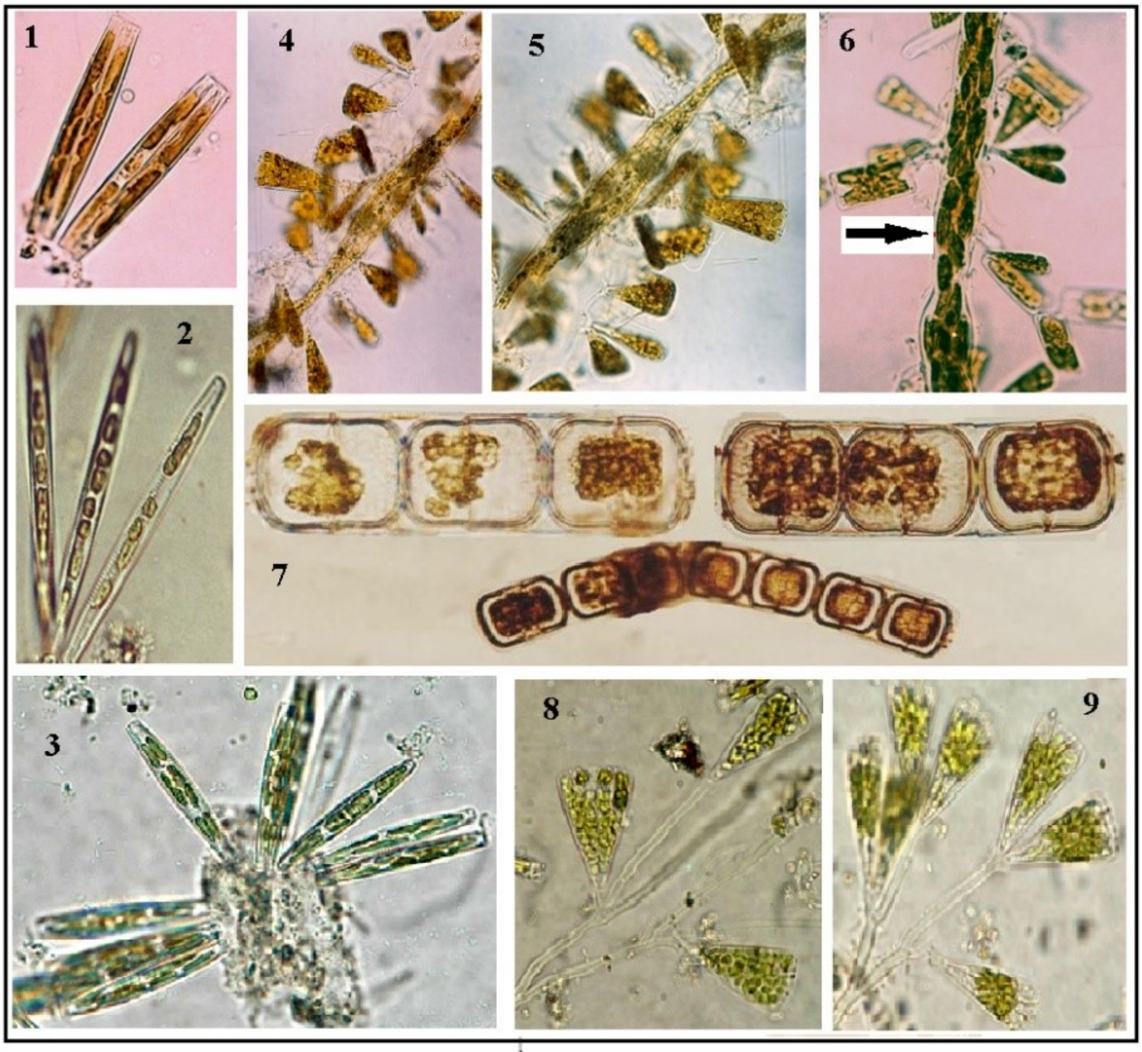

Fig. 9. View of the mass colonial forms of diatoms from microperiphyton on the experimental plates from the device of controlled water flow and the Tikhaya Zavod Bay in November 2019: 1–3 – *Tabularia tabulata*; 4, 5, 8, 9 – *Licmophora abbreviata*; 6 – *Berkeleya rutilans* (the arrow indicates the tubular mucous macrocolony of this species); 7 – *Melosira lineata*

High quantitative indicators of diatoms *B. rutilans* and *L. abbreviata* on the experimental plates from the DCWF are determined, first of all, by the presence of favorable hydrological and hydrochemical conditions. Thus, in the late autumn period, in most of the shallow bays of Peter the Great Bay, the maximum concentrations of nitrites, nitrates, phosphates, and silicon are recorded, which are the most important biogenic elements, limiting the development of diatoms.

Diatom species, found in the microperiphyton on the plates from the DCWF, are eurythermal – occurring year-round regardless of water temperature, since water masses are subject to significant convective mixing in the coastal area of Peter the Great Bay in late autumn (Ryabushko & Begun, 2015).

Of all the mass species with a known saprobiological characteristic, in the microperiphyton on the plates from the DCWF, diatom *L. abbreviata* is recorded: a beta-mesosaprobiont and an indicator of moderate organic pollution of water. Mass development of this species and the absence of indicators of high organic pollution of water is primarily associated with no desalination and no anthropogenic load during the research period, since water intake for the DCWF was carried out at a greater depth at a distance of about 100 m from the pier.

On the surface of macrofouling on the experimental plates, exposed on the pier of the Zapad marine biological station of the National Scientific Center of Marine Biology in the coastal area of the Tikhaya Zavod Bay, a light brown plaque about 1 mm thick was observed. Microscopy showed that the plaque consists entirely of macrocolonies of diatoms. In total, 12 diatom species and intraspecific taxa were registered, represented by various life forms: mobile and immobile; attached and free-living; and solitary and colonial (Table 6). A quantitative analysis of the microperiphyton on the experimental plates showed that two colonial diatom species, *Melosira lineata* and *Odontella aurita*, reached their maximum development; their relative abundance was estimated as "mass" (Fig. 9). These species are benthic and planktonic, or tychopelagic, capable of dwelling both in phytoplankton and microphytobenthos, in fouling of stony soils and macrophytes, reaching mass development in late autumn and winter (Ryabushko, 2013). According to the data of previous studies in the water of Peter the Great Bay (the Sea of Japan), these microalgae are an integral component of the periphyton of the experimental plates, made of different materials (Ryabushko & Begun, 2015). The remaining 10 diatom species, recorded in the microperiphyton on the plates from the Tikhaya Zavod Bay (Table 6), are typical epiphytes, developing on macrophytes or solid substrates.

Table 6. Species list, ecological-geographical characteristics, and relative abundance of diatoms from microperiphyton on the plates from the Tikhaya Zavod Bay (November 2019)

Taxon	Ecological characteristic			Phytogeographical characteristic	Quantitative abundance
	Life form	Salinity	Saprobity		
Arachnodiscus ehrenbergii J. W. Bailey ex Ehrenberg, 1849	BP	M	–	C	r
Berkeleya rutilans (Trentepohl ex Roth) Grunow, 1880	B	BM	–	C	of
Cocconeis stauroneiformis H. Okuno, 1957	B	M	–	AB	of
Gomphonemopsis pseudexigua (Simonsen) Medlin in Medlin & Round, 1986	B	M	–	ABT	r
Licmophora abbreviata C. Agardh, 1831	B	M	β	AB	of
Licmophora flabellata (Greville) C. Agardh, 1831	B	M	β	BT	r
Melosira lineata (Dillwyn) C. Agardh, 1824	BP	BM	α	ABT	ms
Navicula directa (W. Smith) Ralfs, 1861	B	BM	–	C	of
Nitzschia longissima (Brébisson) Ralfs, 1861	B	M	–	C	r
Odontella aurita (Lyngbye) C. Agardh, 1832	BP	M	–	C	ms
Rhabdonema arcuatum (Lyngbye) Kützing, 1844	BP	M	–	C	r
Tabularia tabulata (C. Agardh) Snoeijs, 1992	B	BM	α	C	l

Note: as for Table 5.

Of all the species with a known saprobiological characteristic, in the microperiphyton on the plates from the Tikhaya Zavod Bay, two alpha-mesosaprobiont species were registered – indicators of high organic pollution of water. These are *M. lineata* and *T. tabulata*; the quantitative abundance of the latter was assessed at the level of "a lot of". These are brackish-water and marine ubiquist species with high saprobity indices, tolerant to adverse environmental conditions (oil, chemical, and thermal pollution) and capable of switching from autotrophic nutrition to heterotrophic or mixed one (Mitra et al., 2014).

In this paper, for the first time, the new device of controlled water flow, developed by us, is presented, for which a positive decision of Rospatent has already been received. Our experiment is an illustration of the capabilities of the DCWF. The results of its testing in biotopes of different abiotic conditions were obtained in just two months. Such a huge difference in the composition of the fouling on the plates under conditions of the DCWF and the open Tikhaya Zavod Bay can be explained as follows. It is known that the fouling of operating vessels forms most rapidly during anchorages in ports, where fouling larvae successfully settle on the vessel's hull (Marine Fouling and Its Prevention, 1952). Zoofouling is practically absent on the plates under conditions of a controlled water flow; only 2 green algae species and 12 diatom species are registered in phytoperiphyton. It should be concluded that for successful settling of macrofouling larvae, it is necessary to periodically stop the water flow, simulating a vessel anchorage. But this is already the task of our subsequent work.

The possibility of an "artifact", introduced by the device itself, has to be taken into account, in particular the negative effect of the pump on the fouling larvae. An indirect confirmation of their survival after passing through the water intake pumps of thermal power stations, as well as after passing ballast water, is the subsequent formation of a full-fledged fouling. At the same time, numerous literature data indicate that a significant part of zooplankton is injured when water passes through industrial cooling systems. However, the results of studies, carried out at the cooling ponds of the Kursk, Kalinin, and Smolensk Nuclear Power Plants (Suzdaleva et al., 2007), indicate that a noticeable number of injured individuals is registered not in every zooplankton sample, collected in a discharge area. The total ratio of injured zooplankton individuals in a water supply system, which is very high at the beginning of a cooling reservoir operation, is gradually decreasing. For example, at present, zooplankton die-off in the cooling system of the Kursk NPP, as a rule, does not exceed 45 % of the abundance of organisms at the water intake. In most cases, the ratio is significantly lower. In some periods, zooplankton die-off is only 3–5 %, which is less than when eaten by fish in natural conditions. Thus, at the beginning of operation, the ratio of dead zooplankton in the cooling system of the Zmievskaya Power Plant (Ukraine) was 75–80 %; in the subsequent period, it decreased to 20 %. None of the researchers registered 100 % die-off of fouling larvae. This fact can serve as an explanation for the mass development of macrofouling of the cooling systems of enterprises after passing through the pumps: for its formation, a limited number of larvae is enough. In our experiment, we do not yet have an idea of how the device affects fouling larvae; therefore, we cannot ignore the probability of mass die-off of meroplankton after passing through the pumps. In this situation, more research is required on the adequacy of our device. The study of plankton survival after passing through the pumps of the DCWF, developed by us, is planned to be carried out in the near future.

Conclusion. A new device of controlled water flow, developed by us, is presented, which received a positive decision of Rospatent; its capabilities are described. During 2-month experiment on testing the DCWF in biotopes with different abiotic conditions, results were obtained, that demonstrate significant differences in the composition of the fouling on the plates under conditions of the device and the open Tikhaya Zavod Bay.

Diatoms predominate in the fouling community under conditions of the DCWF; zoofouling is practically absent. On the plates from the open bay, there is a community of green algae *Ulva linza* and bay barnacles *Amphibalanus improvisus*, which is common for a vessel variable loadline or a hydraulic structure drainage zone. The latter is an introduced species; it has been successfully acclimatized in Peter the Great Bay. The statistical analysis proves cardinal differences (qualitative and quantitative ones) in the fouling associations on the plates, exposed in the Tikhaya Zavod Bay and on the DCWF; in fact, these differences are of a succession nature.

A developed microperiphyton community was registered on the experimental plates from both areas studied, and there were significant differences in the composition of dominant taxa, their quantitative indicators, and saprobiological characteristics. This is mainly due to different hydrodynamics of the controlled water flow and open water, as well as level of eutrophication, which determines the development of taxa, tolerant to high nutrient load. Based on the foregoing, it can be argued about the effectiveness of using our DCWF for studying the patterns of formation of the fouling communities in different hydrodynamic flows. The main practical conclusion is as follows: the device is recommended to verify the properties of protective coatings on the substrates tested, *inter alia* antifouling and anticorrosive coatings.

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ИССЛЕДОВАНИЕ ФОРМИРОВАНИЯ СООБЩЕСТВ ОБРАСТАНИЯ В УСЛОВИЯХ УСТАНОВКИ РЕГУЛИРУЕМОГО ПОТОКА ВОДЫ

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Для испытания противокоррозионных и антиобрастающих защитных покрытий разработан наземный стенд — установка регулируемого потока воды. С учётом практической значимости проблемы актуальность проведённого исследования не вызывает сомнений. Стенд подключён к магистрали морской проточной воды. Устройство позволяет имитировать движение водного потока вокруг судна, тем самым моделирует условия движущегося плавающего средства. Цель настоящей работы — впервые представить созданную нами новую установку, на которую получено положительное решение Роспатента. Проведены натурные полевые испытания, продолжавшиеся два месяца. Они показали существенные качественные и количественные различия в составе сообществ обрастания на экспериментальных пластинах, помещённых в установку и подвешенных в толще воды в бухте Тихая Заводь (залив Восток) на пирсе МБС «Запад» Национального научного центра морской биологии ДВО РАН. В условиях установки регулируемого потока воды в сообществе перифитона доминируют бентосные диатомовые водоросли; зоообрастание практически отсутствует. На пластинах из открытой бухты представлен обычный для переменной ватерлинии судов либо осушной зоны гидротехнических сооружений фитоценоз зелёных водорослей. Показана эффективность использования созданной нами установки для исследования закономерностей формирования сообществ обрастания в разных гидродинамических потоках. Основной практический вывод — то, что установку можно использовать для испытания и проверки свойств защитных покрытий на тестируемых субстратах, включая противообрастающие и антикоррозийные покрытия.

Ключевые слова: установка, регулируемый поток, сообщество обрастания, зелёные водоросли, диатомовые водоросли