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An Approach to Ship Water Ballast Management by Continuous Flow-through Method

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Preliminary note

An innovative concept is suggested for ship ballast water management using continuous flow-trough method in ships double bottom. The idea was to create a ship who will not carry ballast water containing invasive marine organisms from one destination to another but who will navigate through it keeping the necessary hydrostatic characteristics using always local ambient water. Authors have suggested the solution which can obtain satisfactory results based on tree-dimensional CFD simulations.

Pristup upravljanju balastnim vodama metodom kontinuiranog propuštanja

Prethodno priopćenje

Ovim se radom predlaže inovativni koncept upravljanja balastnim vodama korištenjem metode kontinuiranog propuštanja u brodskom dvodnu. Ideja je bila osmisliti brod koji neće prenositi balastne vode, a koje obično sadrže infektivne morske organizme, s jedne destinacije na drugu, nego će ploviti kroz balastne vode a da pritom zadrži potrebne hidrostatičke značajke koristeći isključivo okolišno more. Predloženo je rješenje koje temeljem tridimenzionalne CFD simulacije daje prihvatljive rezultate.

1. Introduction

Every year, ships transport over 80% of world goods, and in the same time approximately 3-5 billion tons of ballast waters. Ballast waters are necessary for safe and efficient exploitation of modern merchant ships by securing the stability of unloaded ships, but in the same time, ballast waters present a serious ecological threat to the seas. There are thousands of species of sea organisms that can be transported by ballast waters.

The sea pollution problem with water ballast bailed from the tankers and other cargo ships can be significant, especially for the closed seas. As this water contains some aquatic plants, animals and microbes while coming from distant and different environments, it can be dangerous for the new environment at ship destinations where they are bailed (Figure 1).

In general, IMO and various National jurisdictions have identified two main methods for ballast exchange: the sequential and flow-through method. Both methods come with limitations and require considerable amounts of fuel and staff time.

The authors worked on an alternative design based on exploitation of natural forces [1].

The method relies on natural forces of pressure differences to achieve ballast water exchange. Unlike the sequential and flow-trough methods, the proposed method would not require operation of auxiliary machinery.

This article is considering the case of changing water ballast within the tanks with continuous flow of seawater during navigation without using pumps. With suggested innovative continuous flow-through method, the ballast compositions in the tank is continuously changing, and differences of water composition in the tank and water composition of the surrounding seawater and in particular of the waters at ship destination port are equalized.

Analogue to this model, the ship is navigating through the sea, while the surrounding seawater passes through the ship, becoming water ballast in her tank/tanks.

In the article the principle of the innovative continuous flow-through method and its appertaining ship construction configuration is suggested. The results obtained with CFD simulations have shown possibilities and feasibility of such system.

Invasive sea organisms are one of the four greatest threats to the world oceans. Contrary to other types of pollution, such as pollution by oil, that can be cured by certain procedures, and the nature can recover in a reasonable time interval , the damage that can be done by such invasive organisms is often irreparable.

2. Innovative countinuous flow-through method

The existence of ballast tanks is necessary to insure ship's stability while navigating without cargo, securing optimal trim and draught for propulsion and lowering stress in the ship's structure. The problem of pollution of seas by ballast waters, especially the closed ones, which are disposed by tankers and other merchant ships during the loading of cargo, is very serious. The existing organic and inorganic matter and the organisms are taken from one ecosystem are disposed in another. This creates imbalance of ecosystem in which the ballast waters are disposed, and in certain cases irreparable damage.

In this article is being considered the case when the content of the ballast waters is being changed periodically or continuously by washing of ballast tanks during navigation in the open sea. The arguments for such approach are based on the understanding that disposal of the content of ballast waters in the closed sea during the loading of cargo, contrary to periodical or continuous replacement in navigation in ballast in the open sea, affects the ecosystem in a different way by significant relative concentrations of pollutants.

The technological solution is simple because the ballast water is being disposed from the specified ballast tanks of the existing ships by the computer-controlled system of pumps during the navigation without perturbation of stability. After that, the necessary amount of water is being pumped into specified empty ballast tanks until all water is being replaced in all the tanks for specified number of times.

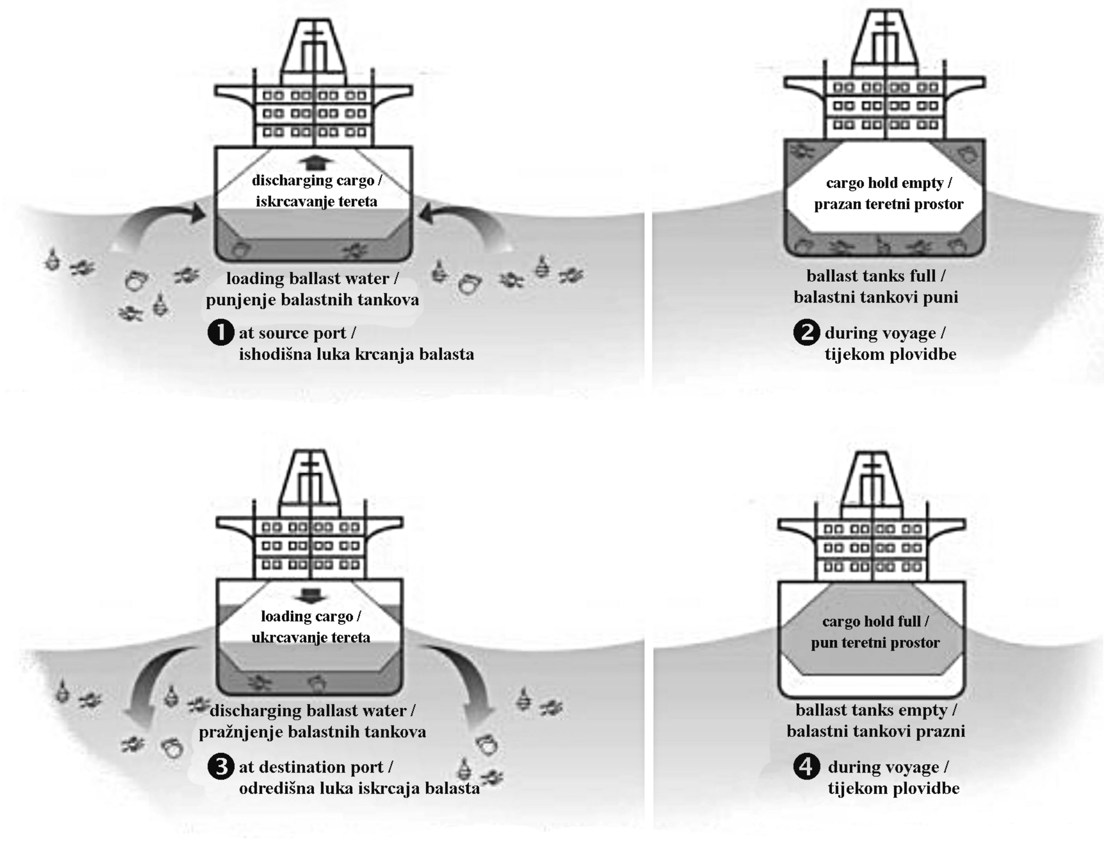

Figure 1. Process of exchanging marine organisms by conventional ballast water management (IMO)

Slika 1. Proces izmjene morskih organizama konvencionalnim upravljanjem balastnim vodama (IMO)

The reason for this logic is the fact that the ecosystems of geographically distant seas can differ significantly, and the ecosystem of closer ones can be similar. The possible difference is growing with the distance. Mixing of sea water of different systems significantly disturbs ecosystems of closed seas.

By continuous replacement of ballast water during the navigation the composition of pollutants in the tanks is also being continuously changed, but the differences are much smaller than in the case when loaded ballast is being transported from the place of loading to the ship's final destination.

Analogue to this model the ship navigates through the sea (ballast water) and during the whole navigation it is sucking in the surrounding sea which, caught by the ships volume, acts as ballast. By replacing that water in navigation, the disposal of waters of distant ecosystems into protected closed seas is being avoided. In the beginning of voyage ship ballast contains local sea water which is continuously exchanged, thus on the arrival ships ballast water is from close neighbouring environment, that can not endanger the ecosystem.

3. Analysis of pipe production process

Innovative continuous flow-through method without using pumps requires adjusting of ship's structure for the optimal flow of ballast through the double bottom. The problem was approached primarily from the aspect of environmental protection, but also minding that the adjustment of ship's construction doesn't significantly change the existing shipbuilding technologies. The authors have based their project of adjusting the ship's construction on the existing tanker ship.

The necessary optimization of the double bottom's structure for reducing the drag of ballast water flowing through it has resulted in the need for reducing the elements of structure inside the double bottom. The authors have accepted the use of sandwich panels for the bottom shell and tank top (Figure 2), which reduced the longitudinal elements of tank bottom and top [2], [3], [4]

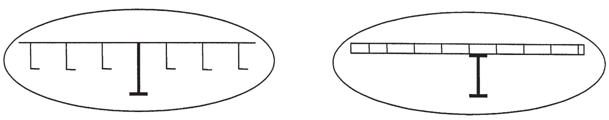

Figure 2. Conventional panel with longitudinal's (left) and proposed sandwich panel (right)

Slika 2. Konvencionalni panel s uzdužnjacima (lijevo) i predloženi "sendwich" panel (desno)

However, the greatest resistance to the flow of ballast water is being generated by the transversal elements in the structure of the double bottom, for which the authors have not yet found adequate replacement which could satisfy the necessary strength. The optimization of the transversal elements of the double bottom's structure, from the aspect of reducing the resistance of the ballast water flow, has resulted with design of additional openings on the floors (Figure 3), [5], [6] but with proposed use of sandwich panels, which compares the proposed and conventional double bottom structure. A rendered model in mid ship section of an isolated ballast tank rendering in (Figure 4).

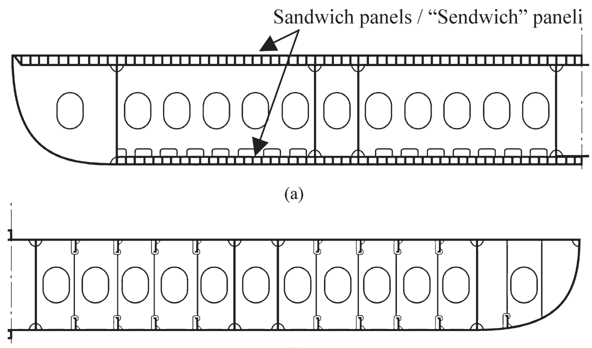

Figure 3. Proposed (a) and conventional (b) structure of tanker double bottom comparison

Slika 3. Usporedba predložene (a) i konvencionalane (b) strukture dvodnom tankeru

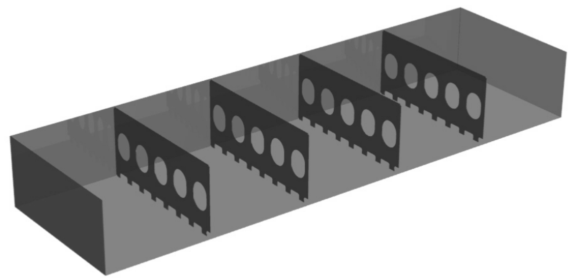

Figure 4. Isolated ballast tank in tanker double bottom

Slika 4. Izdvojeni balastni tank u dvodnu tankera

4. The physics of proposed continuous flow-through ballast system

Since the ship in its exploitation has many loading conditions, the ballast system must be constructed in a way that allows necessary trim for every loading condition. This request can be satisfied only if there are a large number of ballast tanks in the longitudinal and transversal way. This shows that for now the number of ballast tanks must be defined in a conventional way and that the application of the Continuous ballast replacement system has to be done separately for each tank. The authors have kept the present state of the ballast tank spacing on the existing ship and have proposed a solution that would secure full replacement of ballast water in the tank in a specified period of time without application of any pumps.

The solution was found in a special construction of intake basket for ballast intake and a special variation of ballast outlet opening from the tank which uses ship's surge, i.e. the velocity of flow around the ship to create increased pressure on the intake and the reduced pressure on the outlet of the ballast. The difference in pressures allows continuous replacement of ballast in navigation. The intake basket and the ballast outlet opening are to be placed on the shell.

5. Numerical considerations of CFD simulations

5.1. Simulation approach

By numerical simulation of innovative continuous flow-through ballast method on model (Figure 4.), the authors have conducted series of preliminary and full scale simulations. Before conducting full scale problem simulation there was a couple of scenarios that needed to be done previously. These preparatory problems were simulated on an isolated ballast tank computational domain (Figure 5a). Two locations of water intake and outlet openings were investigated. First proposal was to position the openings in the line of tank centreline (midline) and the second in the opposite tank corners (diagonally). The next step and the most important objective of this research involved identification of the minimal pressure difference on intake and outlet to obtain complete exchange within defined input parameters. The main input parameters, beside previously defined tank geometry, were: service speed of the ship and minimal time interval needed in which the complete exchange (min. 98 %) of ballast water should be done. Authors defined 18 hours time interval as minimal to prevent that ship moves away in different ecosystem with potentially critical ballast water content.

Full scale problem simulation involved modelling of sea current at the speed of ship below ballast tank (Figure 5b). This simulation was to determine flow behaviour at the tank openings due to the pressure difference generated between them. Furthermore, examination of orientation of intake and outlet baskets was performed to ensure maximum exchange in a given objective timeline.

All simulations were run on HP Cluster Platform 3000BL with 20 Intel Xeon Quad 2.66 GHz processors on Linux operating system. Mesh preparation and later analysis and visualization were performed on SUN graphical workstation with AMD Dual Opteron 2.8 GHz processor.

5.2. Model formulation

Three-dimensional CFD models of the fluid exchange process in an isolated ballast tank are described. Mesh and geometry builder CATIA and I-DEAS and commercially available Navier–Stokes code FLUENT were used to develop transient model of the flow exchange.

When ship departs from the port, its ballast tanks are filled with port seawater. In order to simulate time change of new water volume fraction while new water enters the tank, unsteady approach was introduced. Simulation process covers period of time when ship departs until its ballast tanks reach 98 % of exchange with fresh seawater.

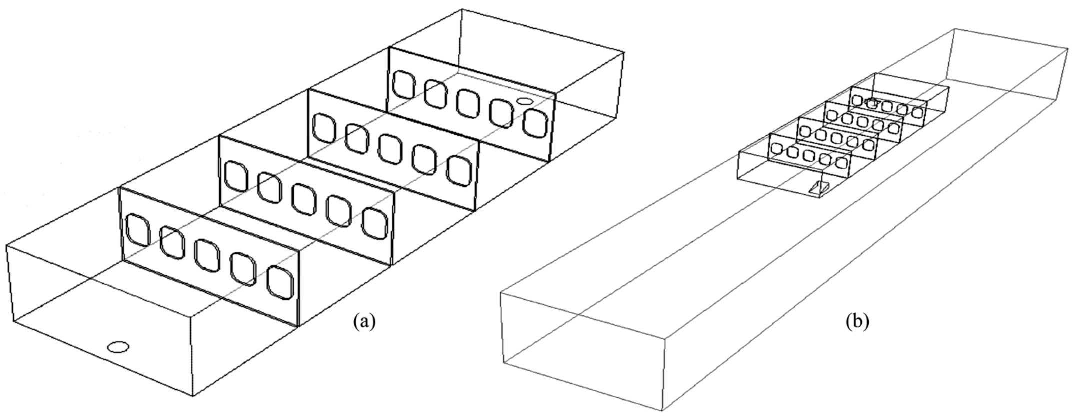

Figure 5. Computational domains of isolated ballast tank (for preliminary simulations) (a), Computational domain of ballast tank with seawater extension volume (full scale simulations) (b)

Slika 5. Računalna domena izoliranog balastnog tanka (preliminarne simulacije) (a), Računalna domena balastnog tanka na izdvojenoj cjelini broda s rubnim slojem morske vode uz oplatu broda (potpuna simulacija) (b)

To simulate such a process two fluids need to be defined. First one is old water inside tanks that was set with slight difference in density (1000 kg/m^3) while the new fresh seawater was set as boundary condition at the intake with the density of 998.2 kg/m3. As simulation proceeds new seawater was let inside so that exchange process can begin. To account for that process we used simplified Eulerian mixture model called multiphase model that is suitable for couple of fluids that penetrates deep inside each other and that moves by their own velocities. Other possible mixture models were VOF (volume-of-fluid) model that is constrained with the fact that fluids can not penetrate through boundary free surface between fluids and fully Eulerian mixture multiphase model that simulated each phase individually, hence being the most computationally expensive model. Following the fact that once filled in the port, ballast water must exit the tanks in short period of time. In such a timeline temperature change of ballast and sea water during exchange process is neglected. For that reason isothermal model was assigned.

5.3. Computational domain

Two simulation studies rely on two computational domains (Figure 7). First domain represent isolated ballast tank that was modelled in two variants. Each variant differ in the location of intake and outlet openings as stated previously (Figure 8). Size of isolated tank is 16 m in the ship moving direction (Global x-axis in this analysis), 4.6 m transverse (y-direction) and 2.1 m vertically (z-direction). Tank has rounded intake and outlet 0.4 m in diameter.

Second domain (Figure 7) incorporates isolated ballast tank but extends in all three directions in order to simulate seawater flow along the ship's hull and natural seawater flow in and out of the tank hull openings. It extends 5 m deep from the floor of the tank (- z-direction), 1.7 m transverse from the side walls of the tank in each direction and 17 m fore and aft to the rear and front tank wall. Total volume of such a domain is 50 m x 9 m x 7.1 m. Extending is done mostly in longitudinal and vertical direction to account for the effect of tank entrance and exit wake formations and to move seawater boundaries away from the tank openings and to obtain sufficient boundary layer velocity profiles in order to correspond to real boundary layer developed on the ship's hull.

5.4. Boundary conditions

For the isolated ballast tank, the only known mechanism of letting water through the tank is pressure difference between intake and outlet openings on the tank floor. Hence, PRESSURE INTAKE and PRESSURE OUTLET boundary condition were used at the tank intake and outlet, respectively.

Tank structural panels were modelled as no-slip WALL boundary condition.

Full scale simulation was performed on the extended domain. Extended fluid zone was initially set as new sea water (less dense fluid) and the fluid zone inside the tank as old port sea water (denser fluid). These fluid zones are connected with tank openings and separated with tank structure. Since the speed of the ship in known, it was assigned as boundary condition on the intake of extended domain as a VELOCITY INTAKE thus simulation flow past a tank's hull. On the exit of extended domain a zero-gradient outlet boundary condition was applied using OUTFLOW boundary condition. As in preliminary simulations all structural plates of the tank and ship's hull were modelled as no-slip WALL boundary conditions.

5.5. Computational meshes

The computational domain was discredited using the unstructured 3D tetrahedral mesh, (Figure 6). The mesh was generated such that its quality criteria (in terms of the skew ness, orthogonality and warp age) specified in FLUENT was satisfied. In the first stage, a study of mesh density was conducted using volume adaptation. This adaptation process was adopted for the reason that no irrelevant fluid domains exist in the complex geometry of tank interior for not to be adapted. Five different unstructured tetrahedral meshes were tested in order to define minimum mesh density for adequate mesh independent solution.

Table 1. Mesh size

Tablica 1. Veličina mreže

Mesh size / Veličina mreže	Time step / Vremenski korak (s)	Simulation time for 98% volume change / Simulacijsko vrijeme za 98%-tnu izmjenu volumena (s)	Computational time / Vrijeme računanja (h)
55000	0.2	**1688**	1
85000	0.2	**1893**	1.5
280000	0.15	**2418**	7
500000	0.1	**2418**	24 (1d)

Test was done using 100 kPa pressure differences at tank openings. Table.1. shows that for each rise in mesh size time step for precise simulation needed to be decreased according to CFL limited to 20-30 set by the FLUENT code for numerical stability. As a side effect total wall clock time rose 5-7 times from the initial mesh size. This study showed that solution independent mesh size could be chosen from 200 000 cells up shown above.

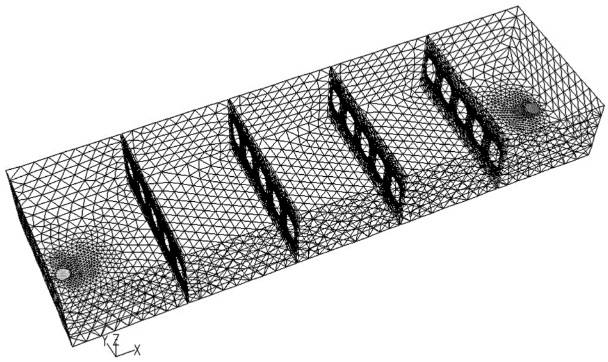

Figure 6. Initial 55000 cells mesh for preliminary simulations

Slika 6. Početna mreža sa 55000 ćelija za preliminarnu simulaciju

Full scale simulation domain was meshed using combined structured quadrilateral (seawater zone) and unstructured tetrahedral (tank) meshes (Figure 7). Seawater fluid zone was completely meshed with structured cells with higher mesh density at the longitudinal area of tank. Vertical distribution of cells was biased to the ship's hull to achieve better results in the boundary layer where flow at tank intake and outlet occurs. Interface was achieved at the tank intake and outlet faces. Ballast tank mesh was obtained in three stages (intake, middle and outlet zone). Intake and outlet volume zone that extends to the first structural plate was meshed with combination of quadrilateral and tetrahedral cells. Next three middle lames between inner plates were meshed with wedges extruded from the triangle mesh created at the surface of inner structural plates.

5.6. Discretization schemes

For transient simulations, the governing equations must be discretized in both space and time. Temporal discretization was performed using implicit first-order time stepping formulation. Cell centre scalar values were spatially discretized using second order upwind scheme while scalar and vector derivatives were obtained using cell-based averaging using neighbouring cell centre values. Body force weighted and second order pressure interpolation scheme were used for pressure gradient discretization in momentum equations. Coupling of pressure and velocity is achieved using SIMPLEC algorithm. Closure of governing equations was achieved by using the realizable k–ε turbulence model with standard wall functions in a vicinity of ship structure plates. This approach was chosen due to the fact that exchange of fluids takes place inside the tank where dominates laminar flow. Only in the region of tank intake and outlet there exist sudden changes of pressure. Turbulent kinetic energy and eddy dissipation were discretized using second-order upwind scheme.

5.7. Solution process

Simulations were performed with pressure-based segregated 3D solver with double precision numbers. The solution was converged to a normalized residual level of 10^{-4} every outer time step iteration. Time step was set to be 0.1 s for 200 000 cells thus preserving recommended CFL value of 20-30.

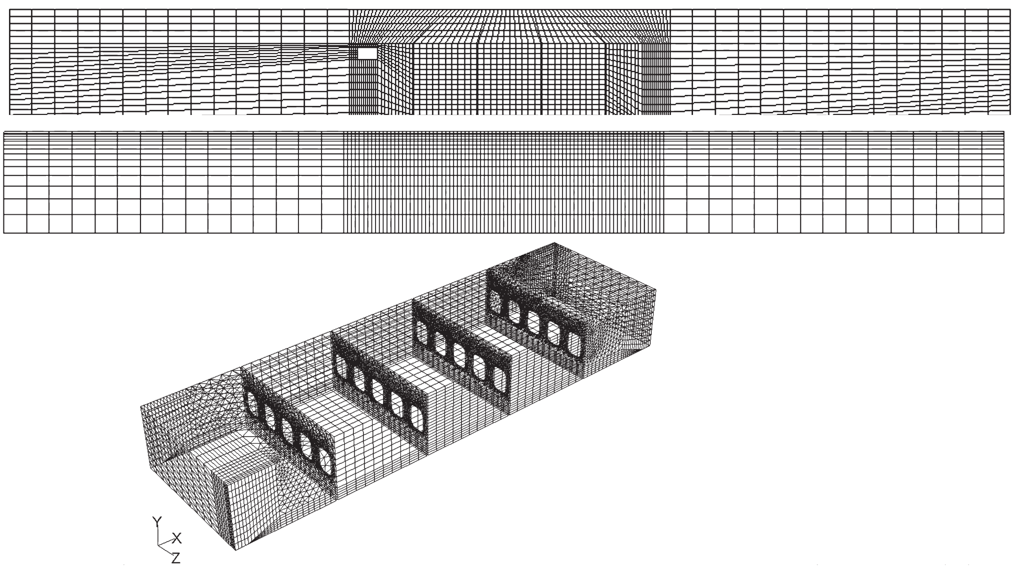

Figure 7. Full scale simulation structural quadrilateral mesh with 200 000 cells in longitudinal vertical and horizontal cross-sectional view (on top) and ballast tank (on bottom) in isometric view

Slika 7. Prikazi strukturirane kvadrilateralne mreže sa 200 000 ćelija za cjelokupnu simulaciju strujanja (na vrhu – tlocrtni i bočni prikaz domene rubnog sloja mora; na dnu – izometrični prikaz balastnog tanka)

6. Numerical simulation results of the proposed method

The first step consisted in finding optimal location for tank intake and outlet openings while holding pressure difference fixed at 100 kPa. Two locations were chosen after discussion: midline and diagonal variant (Figure 8). Diagonal variant has more advantage then midline one. Firstly, that flow will be more complex inside tank allowing faster exchange and secondly, that outlet flow, from the tank before, will not be sucked with intake opening of the next tank in longitudinal line of the ship.

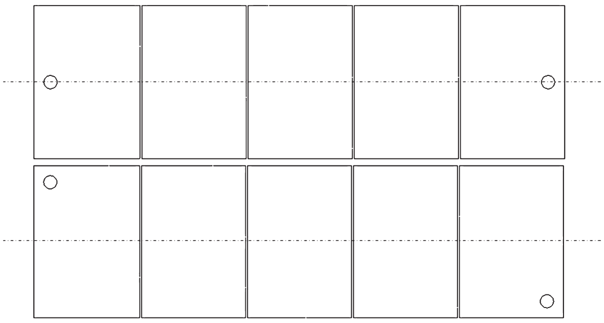

Figure 8. Location of intake and outlet openings: midline (up) and diagonal (down) variant

Slika 8. Varijante lokacija za ulazne i izlazne otvore: meridionalna (gore) i dijagonalna (dolje) varijanta

Numerical simulation has showed that diagonal variant has faster reached 98 % exchange point in time. Even though average inner tank velocity magnitudes are almost equal in size, difference in exchange time can be attributed to the fact that pressure drop of 1/5 of intake pressure is observed at diagonal variant, while for midline variant this drop was 1/3 of total intake pressure, hence resulting in longer exchange.

Flow path lines prove that, as predicted flow is more complex and stagnant in the diagonal variant. In Figure 9 it can be seen that flow from the leftmost compartment of the tank is passing to the end much faster in the midline variant thus providing less mixing. Colours on the path lines signify velocity magnitude.

Next, authors conducted series of simulations where intake pressure was varied for determination of minimal pressure for complete exchange in the given time period of 18 h. Boundary layer develops underneath the ship's hull and varies in the streamline direction defining sea velocity at the tanks' entrances. Therefore, the only way of maintaining given exchange time is by finding corresponding pressure difference. Following graph (Figure 10.) present time needed for 98 % exchange of fluids. It can be seen that for complete exchange inside 18 hours the pressure difference must be higher then 200 Pa.

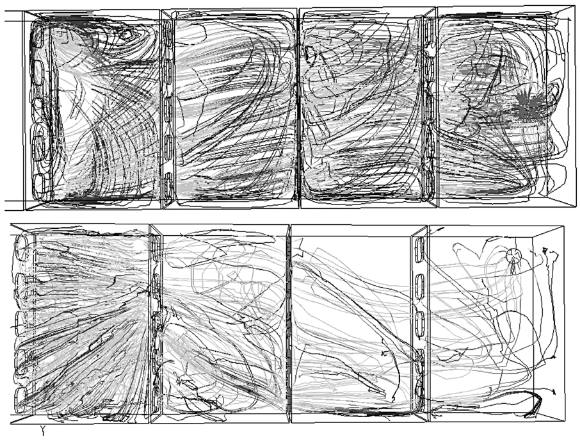

Figure 9. Flow pathlines coloured with velocity magnitude inside the isolated ballast tank (up - midline variant; down– diagonal variant)

Slika 9. Strujnice fluida unutar izoliranog balastnog tanka (gore- meridionalna varijanta; dolje- dijagonalna varijanta) obojane magnitudom brzine

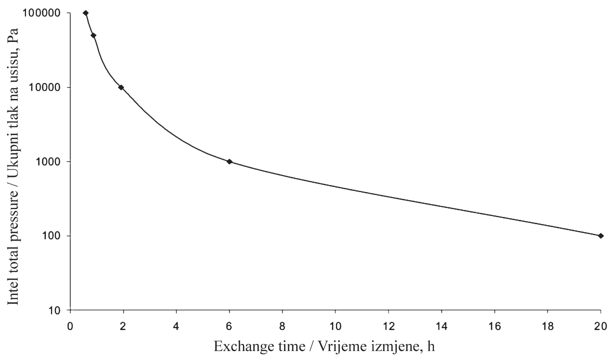

Figure 10. Intake and outlet total pressure difference versus 98 % exchange time

Slika 10. Razlika tlakova usisa i ispusta u odnosu na 98 %-tno vrijeme izmjene

Finally, intake and outlet baskets were introduced as potential solution for real implementation on the ship's hull. Such designs of baskets require detailed knowledge of flow pattern around them (boundary layer). As a natural step, a full scale simulation was performed. Simulation offered potential for optimization of basket orientation. First proposal was to sink intake basket below bottom to grab water and the outlet the opposite way to discharge ballast water. This solution led to the question of increased drag force. Better proposal was to open baskets above hull's bottom level (inside the tank) thus leading to smaller or even neglected increase in ship's drag force. The simulation was carried out for second proposal. Cruising speed was set to be 10 knots at the extended sea water velocity intake boundary. Moreover, two orientations of the baskets were simulated as shown in Figure 11. IN-OUT is the orientation mode in which flow is passing through the tank in the opposite direction to the ship's motion direction. Sea water enters at the intake basket at aft side of the tank and exits fore. OUT-IN orientation mode is just the opposite. See water enters at the fore of the tank and exits at the aft of the tank. In such way ballast water motion inside the tank is in the same direction of the ship.

Results shows, that complete exchange for both basket orientation modes eventually finishes nearly at the same time. For incomplete exchange situation is quite different. OUT-IN mode dominates all the exchange period. What is even more surprising is that for 50-70% exchange of ballast water, OUT-IN mode is three time faster.

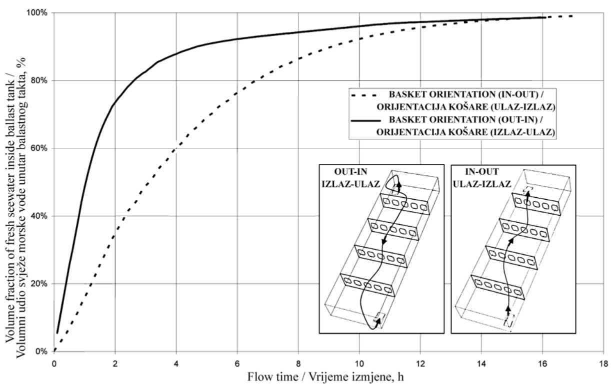

Figure 11. Volume fraction change over time for two basket orientation modes

Slika 11. Vremenska promjena volumnog udjela za dvije orijentacije usisnih i ispustnih košara

7. Conclusion

This article presents one of the solutions to the problem of transporting unwanted organisms in ballast waters from one ecosystem to another. The authors concluded that, using sandwich panels for the bottom shell and tank top structure, longitudinals of tank bottom and top can be significantly reduced thus reducing internal resistance of ballast water flow.

Regarding tank intake and outlet positions, two approaches were analyzed. Simulation has shown that a diagonal variant has reached complete exchange time faster than the variant with symmetrically positioned openings due to more efficient mixing of new incoming sea water.

The most important research objective was to obtain at least 98 % ballast water exchange within defined time interval and ship cruising speed. With diagonally positioned intake and outlet of isolated ballast tank, simulations of various pressure differences were performed. Results indicated that 200 Pa pressure difference is adequate for required ballast exchange within 18 hours that can be acceptable in ship exploitation. Due to the fact that developed boundary layer varies sea velocity profiles along ship's length for the constant cruising speed of the ship, designed pressure must be obtained at tank intake opening by optimizing position and shape of intake and outlet baskets for each individual ballast tank which is a topic for further research. However, in order to confirm this conclusion, a full scale simulation was introduced and performed for one segment of possible optimizations. Authors presented two basket configurations that result with ballast water flow motion in two different directions. First one was in direction of ship motion and other to the opposite. Moreover, this simulation provides an insight in the complexity of three-dimensional flow patterns in the vicinity of baskets and inside the tank, allowing further discussion and possible ballast flow motion control.

Further research and improvements are needed before practical application of proposed method that can prevent undesirable consequences of the mentioned problem which still has not found a totally efficient solution in ballast water treatment.

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